Copyright Undertaking

This thesis is protected by copyright, with all rights reserved.

By reading and using the thesis, the reader understands and agrees to the following terms:

1. The reader will abide by the rules and legal ordinances governing copyright regarding the use of the thesis.

2. The reader will use the thesis for the purpose of research or private study only and not for distribution or further reproduction or any other purpose.

3. The reader agrees to indemnify and hold the University harmless from and against any loss, damage, cost, liability or expenses arising from copyright infringement or unauthorized usage.

If you have reasons to believe that any materials in this thesis are deemed not suitable to be distributed in this form, or a copyright owner having difficulty with the material being included in our database, please contact lbsys@polyu.edu.hk providing details. The Library will look into your claim and consider taking remedial action upon receipt of the written requests.

Pao Yue-kong Library, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong

http://www.lib.polyu.edu.hk
VEHICULAR EMISSIONS AND FUEL CONSUMPTION AT
URBAN TRAFFIC SIGNAL CONTROLLED JUNCTIONS

By

TONG Hing-yan

A Thesis submitted to
Department of Civil and Structural Engineering

for the degree of
Doctor of Philosophy

at
The Hong Kong Polytechnic University

in
March 2001
DECLARATION

I hereby declare that this thesis "Vehicular Emissions and Fuel Consumption at Urban Traffic Signal Controlled Junctions" has not been previously submitted to any other institution for a degree or other qualification, and contains no material previously published or written by another person, except where due reference is made in the text.

Tong, Hing-yan
ACKNOWLEDGEMENTS

During the past few years, under the supervision of my chief supervisor, Dr. Hung Wing-tat, I have been consistently enriched with his mind-stimulating inspiration and warm-hearted encouragement, and I would very much like to take this opportunity to express my truest gratitude to him. It would have been very difficult, if not impossible, to finish this study should I have failed to receive his enthusiastic and kind guidance. I would also like to thank my co-supervisor, Dr. Li, C.W., for his kind support.

A special note of thanks goes to Dr. Cheung, C.S. and Dr. Zhao, H., who devoted their time and sincere concern to advice me on vehicle emission and fuel consumption data collections and analysis. Their assistance has definitely contributed a lot to this project.

I would like to thank Miss Tian, F. as well as a number of my classmates and colleagues, who kindly helped me to collect traffic data.

Grateful acknowledgements should be given to Mrs. Elaine Anson for her whole effort in revising the language of this thesis.

Finally, I would also like to thank my family for every dedication I can never forget nor aptly express.
Abstract of thesis entitled

VEHICULAR EMISSIONS AND FUEL CONSUMPTION AT URBAN TRAFFIC
SIGNAL CONTROLLED JUNCTIONS

submitted by

TONG Hing-yan

for the degree of

Doctor of Philosophy at the Hong Kong Polytechnic University

in

October 2001
ABSTRACT

This research intends to develop a simulation model that predicts vehicular delay, emissions and fuel consumption of individual vehicles travelling in a selected urban signal controlled road network.

ON-ROAD emission and fuel consumption data are collected by instrumented test vehicles travelling along selected routes in the urban areas. Average and modal emission and fuel consumption factors are derived. Based on the collected emission and fuel consumption data, an ON-ROAD modal emission and fuel consumption model for vehicles travelling in the urban areas has also been developed. Piecewise interpolation and negative exponential functions are employed to model instantaneous emission and fuel consumption rates. In the mean time an urban driving cycle has been for the first time developed for Hong Kong in the present study based on on-the-road speed data.

To simulate the modal movements of vehicles at signal controlled junctions, a new approach adopting the neural network technique was employed. A discharge headway model (NNDHM) was developed. The NNDHM model estimates discharge headway of individual vehicle queued at signal controlled junctions. It is an ideal tool to investigate the effect of variables on saturation flows and capacities that would not be easily characterised by direct measurement.

Finally, a microscopic traffic simulation model, TREFSIM, was developed for the estimation of vehicle journey time, average speed, delay, fuel consumption and
emissions in urban traffic signal controlled road network. It is a time-based microscopic traffic simulation model. The TREFSIM model incorporated the ONROAD emission and fuel consumption model as well as the NNDHM model and other algorithms governing vehicle movements. The microscopic structure of the model makes the simulated vehicle emissions and fuel consumption sensitive to changes in vehicle behaviours due to traffic signals.

The TREFSIM model was compared with SATURN and PARAMICS in a selected urban network. It produces comparative flow, delay, emissions and fuel consumption results.
LIST OF PUBLICATIONS

Journal Papers:


3. Tong, H.Y. and Hung, W.T. "Neural Network Modeling of Vehicle Discharge Headway at Signalized Intersection: Model Description and Results". *Transportation Research A*, In press.

Conference Papers:


# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>DECLARATION</td>
<td>i</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>ii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>iii</td>
</tr>
<tr>
<td>LIST OF PUBLICATIONS</td>
<td>vi</td>
</tr>
<tr>
<td>TABLE OF CONTENTS</td>
<td>viii</td>
</tr>
</tbody>
</table>

## CHAPTER 1  INTRODUCTION

1.1 Background ...................................................................... 1
1.2 Aims and Objectives...................................................... 3
1.3 Outline of Thesis.......................................................... 5

## CHAPTER 2  LITERATURE REVIEW

2.1 Introduction ..................................................................... 8
2.2 Factors Affecting Vehicle Emissions and Fuel Consumption... 11
  2.2.1 Technical factors..................................................... 11
  2.2.2 Operational factors................................................ 13
  2.2.3 Cold start emissions............................................... 15
  2.2.4 Evaporative emissions.............................................. 15
  2.2.5 Considerations in modelling at urban signal controlled junction 16
2.3 Emission and Fuel Consumption Modelling Techniques........ 17
  2.3.1 Emission factor models............................................ 18
  2.3.2 Average speed models.......................................... 19
  2.3.3 Modal models....................................................... 21
  2.3.4 Fuel consumption models..................................... 24
2.4 Traffic Modelling Techniques......................................... 25
  2.4.1 Macroscopic models............................................... 27
  2.4.2 Microscopic models.............................................. 42
2.5 Traffic Signal Control Systems....................................... 56
  2.5.1 SCOOT Architecture............................................... 58
  2.5.2 SCATS Architecture............................................ 59
  2.5.3 RHODES Architecture........................................... 60
2.6 Approaches for Model in this Study ................................................. 62
2.6.1 Emissions and fuel consumption ................................................. 62
2.6.2 Traffic simulations ................................................................. 63

CHAPTER 3 EMPIRICAL INVESTIGATIONS OF URBAN DRIVING
CHARACTERISTICS

3.1 Introduction .............................................................................. 66
3.2 In-Use Driving Cycles .............................................................. 68
3.3 Methodology in Developing Driving Cycles ............................... 69
3.4 Speed Data Collection ............................................................... 72
3.5 Results from Field Data ............................................................ 75
3.5.1 Stability of data ...................................................................... 76
3.5.2 The driving characteristics in Hong Kong .............................. 78
3.5.3 Comparison of driving data .................................................... 79
3.6 Development of the Driving Cycle ............................................ 84
3.6.1 Development of the cycle ....................................................... 84
3.6.2 Comparison with other cycles ............................................... 87
3.7 Concluding Remarks ............................................................... 88

CHAPTER 4 ON-ROAD EMISSION AND FUEL CONSUMPTION
MODEL

4.1 Introduction .............................................................................. 90
4.2 Data Collection Methods .......................................................... 90
4.3 On-Road Emission and Fuel Consumption Testing .................. 92
4.3.1 Test vehicle specification ...................................................... 92
4.3.2 Test routes ........................................................................... 93
4.3.3 Experimental set-up ............................................................. 94
4.4 Data Handling Method ............................................................. 96
4.5 Empirical Results and Analysis ............................................... 98
4.5.1 Description of the data sample .............................................. 99
4.5.2 Global analysis ................................................................. 100
4.5.3 Modal analysis ................................................................. 111
4.6 Emissions and Fuel Consumption Modelling ............................ 115
4.6.1 Idling emissions and fuel consumption ........................................ 115
4.6.2 Non-idling emissions and fuel consumption .............................. 118
4.6.3 The mathematical model ............................................................. 122
4.7 Comparison of the Measured and Predicted Values of Emissions and Fuel Consumption ........................................................... 123
  4.7.1 The instantaneous results .................................................................. 123
  4.7.2 The trip based results ...................................................................... 127
  4.7.3 Model evaluation ............................................................................ 128
4.8 Concluding Remarks ........................................................................... 131

CHAPTER 5 DEVELOPMENT OF THE SIMULATION MODEL

5.1 Introduction ...................................................................................... 133
5.2 Model Overview ................................................................................. 133
5.3 Network Representation ..................................................................... 136
  5.3.1 Nodes ............................................................................................ 136
  5.3.2 Links ............................................................................................ 136
  5.3.3 Lanes ........................................................................................... 137
  5.3.4 Movements .................................................................................... 138
5.4 Signal Operation ................................................................................ 138
5.5 Vehicle Arrival Headways ................................................................. 140
  5.5.1 Neural network discharge headway model (NNDHM) ...................... 142
5.6 Vehicle Generations .......................................................................... 160
5.7 Vehicle/Driver Attributes ................................................................. 162
  5.7.1 Brake reaction time ........................................................................ 163
  5.7.2 Length .......................................................................................... 165
  5.7.3 Safety distance .............................................................................. 165
  5.7.4 Desired speed ............................................................................... 166
  5.7.5 Minimum stopping distance ........................................................... 167
  5.7.6 Acceleration/Deceleration capability .............................................. 167
  5.7.7 The critical gap ............................................................................. 169
5.8 Vehicle Movements ............................................................................ 170
  5.8.1 Vehicle loading ............................................................................ 171
  5.8.2 Car following model ..................................................................... 171
5.8.3 Responses to traffic signal .............................................. 176
5.8.4 Right turning logic ...................................................... 178
5.8.5 Left turning logic ........................................................ 178
5.8.6 Speed adjustment ....................................................... 179
5.9 Lane Changing Model ..................................................... 179
5.9.1 Selection of desired lane .............................................. 181
5.9.2 Lane changing factor (LCF) .......................................... 181
5.9.3 Initial gap acceptance check ....................................... 183
5.9.4 Final gap acceptance check ....................................... 185
5.9.5 Speed adjustment ....................................................... 185
5.10 Model Outputs ............................................................ 186
5.10.1 Delay .................................................................. 186
5.10.2 Journey time .......................................................... 188
5.10.3 Average speed ........................................................ 189
5.10.4 Emissions and fuel consumption ................................. 189
5.11 Concluding Remarks .................................................... 189

CHAPTER 6 NNDHM MODEL CALIBRATION, VALIDATION AND SENSITIVITY ANALYSIS

6.1 Introduction ................................................................ 191
6.2 Data Collection .......................................................... 191
6.2.1 Data characteristics .................................................. 193
6.2.2 Starting reaction time distribution ............................... 195
6.3 Training of the NNDHM Model ..................................... 196
6.4 Comparison with Other Models ...................................... 199
6.4.1 Average discharge headway comparison ....................... 200
6.4.2 Individual discharge headway comparison .................... 201
6.5 Sensitivity Analysis ....................................................... 201
6.5.1 Geometrical variables .............................................. 203
6.5.2 Attributes of subject vehicle .................................... 205
6.5.3 Attributes of preceding vehicle .................................. 206
6.6 Concluding Remarks .................................................... 209
CHAPTER 1
INTRODUCTION

1.1 Background

Air pollution problems have attracted worldwide attention in recent years. Of all the sources of air pollution, the motor vehicle is the most significant contributor of Carbon Monoxide (CO), Nitrogen Oxides (NOx), Hydrocarbon (HC) and Particulate (PM) emissions in urban areas (Stead, 1999). These pollutants are not only harmful to the health of human beings (for instance, particulates can cause respiratory diseases) but also affect the global climates (for instance, CO contributes to global warming and NOx produces acid rain and secondary pollutants like ozone).

In the United States, motor vehicle emissions account for 30% to 50% of HC, 80% to 90% of CO and 40% to 60% of NOx emissions (Huang, et. al., 2000; Recker and Parimi, 1999). The relative contributions in other parts of the developed world, such as Europe and Japan are similar (Touaty and Bonsang, 2000; Stead, 1999). In many large cities of China, such as Beijing, Shanghai and Guangzhou, the problem is even more serious (Hao, et. al., 2000). In 1996, automobiles were responsible for 86%, 96% and 56% of CO, NOx and HC emissions respectively in the central city of Shanghai and it is estimated that the number of these emissions will continue to increase until 2010 (Ye, et. al., 1999).

In Hong Kong, according to the Environmental Protection Department, CO, NOx and particulate emissions mainly come from motor vehicles. In 1998, particulates
and NOx emissions remained at a rather high level and exceeded the Hong Kong Air Quality Objective (HKAQO) at both general and roadside stations. The highest annual average particulate level measured at roadside station was almost double the annual HKAQO (Chang, 1999). Owing to the proximity of the toxic pollutants to human beings, it is necessary to reduce vehicle emissions in the urban areas.

Emission control devices like catalytic converters have achieved highly positive results in reducing emissions. Recker and Parimi (1999) reported that since the passage of the first Clean Air Act in 1970, tailpipe emissions have been greatly reduced by about 90%. However, the rapid increase in vehicle populations and total vehicle miles (VMT) travelled offset the emission reduction. In China, the average annual growth rate of the vehicle population is about 15% (Ye, et. al., 1999). Therefore, other control methods, like traffic signal control schemes, can be helpful in soothing the problem.

At the same time, the heavy reliance of road transport on conventional fossil energy resources such as petrol and diesel is very risky. Undoubtedly, fossil energy may be used up in the future and growing of vehicle population may speed up the evolution of fuel shortage. Therefore, it is necessary to improve the utilisation efficiency of conventional fossil energy until it can be substituted by new energy resources.

In urban areas, traffic signals have become the commonest method of controlling traffic at busy junctions, to safely separate conflicting traffic movements. The signal settings have great influences on the level of traffic congestion as well as vehicle emissions and fuel consumption. Poor signal settings will lead to congestion and thus
increase emissions and fuel consumption. It has been found that signal timing optimisation schemes and traffic control measures are effective methods to improve traffic movements and thus alleviate congestion as well as reducing emissions and fuel consumption. However, it is an expensive operation, if not impossible, to have real life studies of the effects of these measures. Computer simulation models of traffic flow are useful tools in this respect.

There have been a number of simulation models developed for assisting the testing and improvement of proposed traffic management and control strategies. These models simulate the interactions between vehicle movements and operations of traffic signals. Proposed traffic control schemes are then evaluated based on the measures of effectiveness (MOE) of the junction (e.g. vehicle delay, travel time as well as vehicle emissions and fuel consumption).

1.2 Aims and Objectives

The evaluation of traffic control schemes currently rely on the mobile source emission factor models, such as MOBILE (developed by the US Environmental Protection Agency) and MVEI (Motor Vehicle Emission Inventory model, developed by the California Air Resources Board), which are not sensitive to vehicle modal operations (i.e. acceleration, cruising, deceleration and idling). These behaviours occur frequently at urban signal controlled junctions and contribute significantly to the total vehicle emissions and fuel consumption (Barth, et. al., 2000; An, et. al., 1997). These emission models are also developed on the basis of
laboratory collected data, which may not be representative of actual driving conditions (Touaty and Bonsang, 2000).

The main aim of this research is to develop a traffic simulation model which can estimate vehicle emissions and fuel consumption at urban signal controlled junctions, and the estimated emissions and fuel consumption are sensitive to the interaction between vehicles and operations of traffic signals. The emission and fuel consumption model is developed based on ON-ROAD data. This has required work to be undertaken towards the following objectives:

1. To reveal the current practice of motor vehicle emissions and fuel consumption modelling as well as traffic flow simulation techniques and then evaluate in terms of the efficiency and capability for application at urban signal controlled junctions.

2. To develop an urban driving cycle for Hong Kong, which can provide a general understanding of the driving characteristics in the urban areas of Hong Kong.

3. To perform ON-ROAD vehicle tests to collect instantaneous (second-by-second) speed, emissions and fuel consumption data.

4. To develop an ON-ROAD vehicle emission and fuel consumption model which is sensitive to modal changes of vehicles at signal junctions.
5. To develop a time-based microscopic traffic signal simulation model that deals with individual vehicles in the network. The instantaneous speed and position of each vehicle in the road network are calculated for each time step.

6. To integrate the models developed in 4 and 5, to provide estimates of instantaneous emissions and fuel consumption rates at urban signal controlled junctions.

The microscopic structure of the resultant model makes the simulated vehicle emissions and fuel consumption sensitive to changes in vehicle behaviours due to traffic signals.

1.3 Outline of Thesis

This thesis is concerned with the simulation of vehicle emissions and fuel consumption at signal controlled junctions in Hong Kong. In chapter 2, a critical review of the currently available models is considered in detail. The review includes a discussion on the factors affecting vehicle emissions and fuel consumption, a description and evaluation of microscopic and macroscopic emission/fuel consumption modelling techniques as well as mandatory traffic signal simulation models. Some incisive conclusions are drawn from the review regarding the shortcomings of the methodology used in the development of the current models.
Chapter 3 describes the empirical investigation of the urban driving conditions in Hong Kong. Details of the development of an urban driving cycle are given in this chapter.

Chapter 4 presents the development of the ON-ROAD emission and fuel consumption model. Details of data collections are also included.

Chapter 5 contains a detailed description of the TREFSIM model, which is a combination of a number of algorithms and sub-models. It includes vehicle generations (vehicle arrival headway distribution), vehicle movements (car following and lane changing algorithms as well as generation of vehicle driver characteristics) and the modal emission and fuel consumption model.

Chapter 6 describes the neural network discharge headway (NNDHM) model calibration, validation and sensitivity analysis. The NNDHM model is developed to model the arrival pattern at the simulation network boundary. The calibration process consists of experimental investigations and model parameter calibrations. The validation process is based on comparisons of results from the model output against field data as well as results from mandatory models.

Chapter 7 presents the results and analysis of model output from simulation experiments. It includes comparisons of results from the developed model and some mandatory models.
Finally, a general summary and final conclusions are presented in Chapter 8. The main achievements of the research, the model limitations and possible further developments are briefly discussed.
CHAPTER 2

LITERATURE REVIEW

2.1 Introduction

Modelling the effect of traffic management schemes (such as traffic signals) on air quality and energy use requires a chain of different models — from land use, travel demand and traffic simulation models, which are used to generate traffic activity data, to emission, dispersion, and energy models that are used to estimate the impacts of changes in traffic activity on emission levels and energy use, respectively (Figure 2.1, from TRB, 1995). Lane use and travel demand models are critical to forecasting changes in travel demand from traffic management schemes. Traffic simulation models, as mathematical representations of real-world phenomena, provide sophisticated analyses of the impacts of traffic flow improvements on roadway vehicle performance. The outputs from traffic simulation models are then plugged into emission and atmospheric dispersion models to assess the impacts of motor vehicle travel on pollutant emissions and concentrations. Emission models estimate emission levels while atmospheric dispersion or diffusion models translate emission levels into atmospheric concentrations of pollutants. Fuel consumption is estimated by energy models using outputs from traffic simulation models. As shown in Figure 2.1, the current study is focused on the development of a traffic signal simulation model and its interface to emission and fuel consumption models to estimate pollutant emission and fuel consumption levels.
Figure 2.1 Modelling chain for estimating impacts of changes in travel activity on emissions and pollutant concentrations and energy use (TRB, 1995).

As shown in Figure 2.2, traffic simulation models/data vary in terms of their inherent temporal resolution. Macroscopic traffic simulation models typically provide
aggregated parameters, such as total vehicle volume and average speed over an entire regional network, for emission models to estimate average emission and fuel consumption levels. Microscopic traffic simulation models, however, produce second-by-second vehicle trajectories (locations, speed and acceleration) for modal emission models to estimate detailed second-by-second emission and fuel consumption rates.

Figure 2.2 Traffic simulation / emission model interface.

This chapter gives a critical review of a number of traffic modelling techniques and the interface with emission and fuel consumption models. In the following sections, the factors affecting vehicle emissions and fuel consumption are discussed first. Those traffic related factors are elaborated in greater detail. Different emission and fuel consumption modelling techniques are then revealed. These modelling techniques are evaluated in terms of the capability of simulating the effect of traffic flow improvements on emission and fuel consumption levels at signal controlled junctions. A review of the traffic modelling techniques is then given. Models selected for review are based on the availability of explanation documents. A number of widely publicised models are reported. Finally, based on the above review, the modelling approach adopted in this study is outlined.
2.2 Factors Affecting Vehicle Emissions and Fuel Consumption

In order to determine the effect of traffic control and management schemes on vehicle emissions and fuel consumption, it is important to understand the relationships between traffic characteristics, vehicle operations as well as exhaust emissions and fuel consumption rates. Vehicle emissions and fuel consumption rates depend on a large number of factors which can be divided into two broad categories (Cloke, et. al., 1998):

1. technical factors relating to the design and engineering of the vehicle;
2. operational factors relating to the way in which the vehicle is used.

2.2.1 Technical factors

A list of the technical factors that are known to affect vehicle emissions and fuel consumption are listed in Table 2.1. It is acknowledged that this list is not exhaustive and that other factors may have impacts on emission and fuel consumption rates. Furthermore, only factors considered to be potentially important for modelling in this study are discussed.

Engine type Most vehicles are powered by either petrol or diesel engines. In general, diesel engines have a fuel economy advantage over petrol engines, owing to more efficient combustion, diesel engines emit less CO, HC, and NOx (Saleh and Nelson, 1998). Particulate emissions from diesel vehicles are significantly higher than petrol vehicles. In Hong Kong, over 90 % of vehicular particulate emissions are
from diesel powered vehicles.

*Engine size (capacity)*  Engine capacity has been found to be an important parameter affecting pollutant emission and fuel consumption rates (Tong and Hung, 1998). Large engine capacity gives rises to higher emissions and fuel consumption.

*Vehicle size and weight*  The physical characteristics of a vehicle such as size and weight can affect emission and fuel consumption rates. More fuel is needed to generate enough power to move a large and heavy vehicle than a small and light vehicle, and thus pollutant emissions increase. It has been shown that fuel consumption increases systematically with increasing vehicle weight (Bleijenberg and Rutten, 1991).

*Exhaust after treatment*  Pollutant emission rates can be reduced by introducing exhaust after treatment devices such as catalytic converters and particulate traps. Catalytic converters remove CO, HC as well as NOx from the exhaust gas after it leaves the engine. Particulate traps are used for diesel vehicles to remove exhaust particles.

*Age and mileage*  Older vehicles generally produce higher emission levels and more fuel consumption. This is likely to be owing to several reasons such as gradual degradation of the engine and exhaust after treatment devices as well as bad vehicle maintenance with total mileage done.
<table>
<thead>
<tr>
<th>Factor</th>
<th>Examples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Engine type</td>
<td>Petrol, diesel, alternative fuels</td>
</tr>
<tr>
<td>Engine size (capacity)</td>
<td></td>
</tr>
<tr>
<td>Transmission</td>
<td>Automatic, manual</td>
</tr>
<tr>
<td>Exhaust after-treatment</td>
<td>Oxidation or three way catalyst, particulate trap, no controls</td>
</tr>
<tr>
<td>Maintenance level</td>
<td></td>
</tr>
<tr>
<td>Other characteristics</td>
<td>Aerodynamics/size/weight/age</td>
</tr>
</tbody>
</table>

Table 2.1  Technical factors affecting vehicle emissions and fuel consumption

2.2.2  Operational factors

A single vehicle will display wide variations in emissions depending on the way it is being used and driven. Much information relating to the effect of operational factors on emission and fuel consumption has been obtained from studies regarding emissions and fuel consumption modelling. Thus, the operational factors are decisive parameters.

*Average speed and speed variation*  Some studies suggested that the average speed over a trip is a dominant factor in estimating emissions and fuel consumption (Cernuschi, et. al., 1995). It has been the most common way of representing vehicle emissions and fuel consumption rates as a function of average speed. The typical relationship between average speed and emissions/fuel consumption is shown in Figure 2.3. In urban driving, vehicle speeds are generally lower than 65 km/h, emissions and fuel consumption are inversely proportional to average speed. High emission/fuel consumption levels are expected at low average speeds and then
emission/fuel consumption decreases as average speed increases. Sometimes the emissions or fuel consumption may attain a minimum level for certain average speeds, and then rise after that. The average speed is the most significant factor for CO, HC, particulate emissions as well as fuel consumption, but the effect on NOx is smaller.

![Graph showing the relationship between emission/fuel consumption and average speed.]

**Figure 2.3** General trend of average speed against emission/fuel consumption.

However, a number of researchers noted that there can be significantly different emission results for cycles with approximately the same average speed (e.g. Joumard et al., 1995). The way in which a particular average speed is achieved is also of importance in determining the emission and fuel consumption performance of the vehicle.

**Instantaneous speed and acceleration** The acceleration rate is a direct measurement of instantaneous speed variations (Joumard, et al., 1995). The operation of an engine necessary to attain a certain rate of acceleration depends on the speed. For example, a slow moving vehicle will accelerate at a considerably higher rate than a faster one and thus increase fuel consumption and emissions. In general, higher acceleration
rates result in higher emission/fuel consumption levels. The contribution of acceleration rate on vehicle emissions and fuel consumption should be significant at signal controlled junctions, where frequent stops and starts are likely to happen.

*Vehicle driving mode* The four standard vehicle driving modes are idling, accelerating, cruising and decelerating. Vehicle emissions and fuel consumption behave differently at different modes (Cernuschi, et. al., 1995). Transient modes (i.e. acceleration and deceleration) generally generate more pollution and fuel consumption than steady state driving modes (i.e. idling and cruising). Interrupted traffic flows, such as those caused by traffic signalisation, are combinations of these four driving modes. Matzoros and Van Vliet (1992a, 1992b) stated that emissions are higher near junctions than at mid-links.

2.2.3 *Cold start emissions*

The operational effects mentioned so far are all related to hot engines. Many studies suggested that fuel consumption emission rates are much higher for a short period after the vehicle has been started than when is fully warmed up. This is caused by the ineffectiveness of vehicle emission control devices (such as catalytic converter) and incomplete fuel combustion at startup (Singer, et. al., 1999).

2.2.4 *Evaporative emissions*

Hydrocarbon emissions occur as a result of evaporation from the fuel system, especially for petrol vehicles. Evaporative emissions occur as a result of the
volatility of the fuel and the variations in temperature. Cloke, et. al. (1998) stated that evaporative emissions are significant from hot engines after they are switched off.

2.2.5 Considerations in modelling at urban signal controlled junctions

Vehicle exhaust emissions and fuel consumption rates are dependent on a range of technical and operational factors. Clearly, it is not cost-effective, to take into account all factors at the same time. Therefore, it is important to identify those that are most related to modelling emissions and fuel consumption at urban signal controlled junctions.

Much of the research so far has concentrated on the effects of factors such as engine capacity, fuel type, speed and rate of acceleration. It is recognised that cold start and evaporative emissions can be significant under certain conditions. The cold start period and the amount of evaporative emissions are dependent on the ambient conditions and the period of parking, which are out of the scope of this study. Moreover, the cold start period is not well-defined in terms of the transition to hot emissions (Cloke, et. al., 1998). Therefore, emissions and fuel consumption considered in this study are from hot stabilised engines. Cold start and evaporative emissions are assumed to be insignificant.

To model hot engine vehicle emissions and fuel consumption at urban signal controlled junctions, operational factors are critical to the derivation of emission/fuel consumption estimation functions and technical factors are responsible for the
identification of different vehicle technology categories.

2.3 **Emission and Fuel Consumption Modelling Techniques**

The general principle in estimating emissions and fuel consumption from road traffic is the summation of the product of emission/fuel consumption factors and the traffic variables. This can be expressed as the following equation (Cloke, et. al., 1998):

\[ E_i = \sum_{j=1}^{n} \sum_{k=1}^{n} e_{i,j,k} \times T_{j,k} \]  \[ 2.1 \]

where:  
- \( E_i \) is the amount of pollutant \( i \) emitted  
- \( e \) is an emissions/fuel consumption factor  
- \( T \) is the amount of traffic  
- \( j \) identifies different types of vehicle  
- \( k \) identifies different types of vehicle operation.

There have been a variety of emission and fuel consumption models derived for different spatial and temporal requirements. These models can be divided into three basic groups:

1. emission factor models
2. average speed models
3. modal models.
2.3.1 Emission factor models

Emission factor models operate on the simplest level, use a single emission factor to represent a particular type of vehicle in a particular type of driving conditions (e.g. urban driving). The emission factors are calculated as a mean value of repeated measurement of total emissions over a given driving cycle and are usually expressed in terms of the mass of pollutant emitted per unit distance (e.g. g/vehicle.km).

![Diagram of Emission Modelling Process]

The emission models MOBILE (US EPA, 1994) and MVEI (CARB, 1996) that are currently used in the United States as well as the CHINA-MOBILE emission model developed in China (Hao, et. al. 2000) are of this type. The structures of these three models are basically the same (Figure 2.4) in that emission factors are multiplied by the traffic activity data to give the emission levels in terms of gram (g).

Baseline emission rates are derived from a laboratory based test procedure known as the Federal Test Procedure (FTP), which has been used to determine compliance of
vehicles with federal emission standards since 1972. The FTP driving cycle has been
criticised as being unrepresentative of high-speed driving and high acceleration rates
that are common features of today’s driving patterns. Several of the eleven other
driving cycles used to develop speed correction factors for adjustment of the
emission rates, are also not considered to be adequately representative of today’s
urban driving conditions (TRB, 1995).

These models are designed to provide emission inventory information on a large
spatial scale, such as national and regional levels, where there is little detail on traffic
flows and operation (e.g. Vehicle Miles Travelled). This approach has the merit of
easy and simple implementation, but the major disadvantages are that these models
are not sensitive to a vehicle’s modal changes such as idling, accelerating, cruising
and decelerating. It has been found that emissions of urban vehicle traffic depend
very much on the vehicle movement patterns governed by sophisticated traffic
control and management strategies. Therefore, this approach may not be suitable for
modelling emissions and fuel consumption at signal controlled junctions.

2.3.2 Average speed models

This type of model expresses average emission and fuel consumption rates for each
trip as a function of average speed. Emission and fuel consumption rates are
measured for a variety of trips with different average speeds. Usually, emission
testing is performed on a dynamometer in the laboratory using driving cycles. An
example of this type of model is COPERT (Computer Program to calculate
Emissions from Road Traffic), which is mainly applied to medium- and large-scale
emission estimates using average speed-dependent emission factors.

Bowyer, Akcelik and Biggs (1985) developed four emission and fuel consumption models. One is the Average Travel Speed Model of Fuel Consumption, which takes the following form:

\[ f_x = f_i / V_s + cK \]  

[2.2]

where \( f_x \) = fuel consumption per unit distance in mL/km, 
\( V_s \) = average travel speed in km/h 
\( f_i \) = idle fuel consumption in mL/h 
\( c \) = regression coefficient 
\( K \) = adjustment factor to allow for varying vehicle parameters

This approach is useful in estimating total emissions and fuel consumption of vehicles over a trip at a traffic network level (Cloke, et. al. 1998). However, only limited variations of vehicle operations are accommodated in these types of models, their application to the micro-scale may not be appropriate. The dominant parameter, average speed, statistically smoothes the effect of acceleration and deceleration (Barth, et. al., 1996). Two vehicle trips can have the same average speed but have different speed profiles consisting of drastically different modal characteristics (i.e. idling, accelerating, cruising and decelerating) and thus drastically different emissions and fuel consumption output (Joumard, et. al., 1995).
2.3.3 Modal models

Modal emission and fuel consumption models have been designed to provide an estimation technique at the microscopic level. Usually extensive vehicle testing is needed to measure vehicle operations, emissions and fuel consumption data at high time resolutions (typically second-by-second). The data are then analysed in terms of the vehicle's modal event so that instantaneous emissions and fuel consumption rates are estimated on a second-by-second basis.

*Speed and acceleration based*

A convenient method to characterise vehicle model events is to set up a speed/acceleration matrix (Zachariadis, et. al., 1997; Kishi, et. al., 1996; Hansen, et. al., 1995; Watsons, et. al., 1985). The speed/acceleration matrix gives the instantaneous emissions and fuel consumption rates for different combinations of instantaneous speed and acceleration. For each cell of speed and acceleration, the emission or fuel consumption rates are averaged to give a mean value.

Other researchers (Andre, et. al., 1997; Joumard, et. al., 1995) use the product of speed and acceleration (i.e. speed × acceleration) instead of the acceleration rate. The MODEM emission model is developed by this method (Joumard, et.al., 1995). Emissions and fuel consumption data are classified into different classes of speed and the product of (speed × acceleration). Instantaneous emissions and fuel consumption are then estimated by selecting values from the corresponding combination of speed and (speed × acceleration).
Cernuschi (1994) divided the data into five different acceleration classes, representative of high and low decelerating modes, cruising speed modes as well as high and low accelerating modes. For each class defined, best-fit lines were obtained by regression analysis on the emission-instantaneous speed plots. Emission and fuel consumption rates at idling were treated separately. This method in fact applies a specific case of the speed/acceleration map by restricting the acceleration ranges to only five classes. This reduces the data requirement in the construction of a speed/acceleration map.

The problem of this approach is the resolution of the speed/acceleration classes. Theoretically, the finer the resolution of the matrix the higher the accuracy. However, it is highly data intensive to construct a full and useful map as fine as 0.1 km/h resolution. Owing to time and manpower resources constraints, it is very difficult, if not impossible, to collect such huge amount of data. Kenworthy, et. al. (1983) stated that constructing acceleration/deceleration maps to 0.1 km/h is an unrealistic, if not impossible task.

_Emission map based on engine power and speed_

Another modal emission modelling method is to develop an emission and fuel consumption map based on engine power and speed (West, et. al., 1997). Instantaneous engine operational data such as engine speed and exhaust temperature are obtained on-road as a function of speed and acceleration. The engine conditions are then duplicated on the laboratory dynamometer vehicle testing and taking corresponding emissions and fuel consumption measurements. The data sets are then merged to provide emissions and fuel consumption against functions of speed and
acceleration. These maps serve as a table of emissions and fuel consumption as combinations of speed and acceleration. Again, the resolution of the lookup table is a problem. The emission mapping method can also be very time consuming in matching the engine conditions to emissions, fuel consumption and speed profiles (Barth, et. al., 1996).

**Physical power-demand modal modelling approach**

Barth and co-workers (2000, 1997) developed the Comprehensive Modal Emission Model (CMEM) which employed the physical power-demand modal modelling approach. In this approach, the emissions process is stratified into different components that correspond to physical phenomena associated with vehicle operation and emission production (Barth, et al., 1996). Each component is then modelled as an analytical representation consisting of 55 parameters that are characteristic of the process. Data from dynamometer tests of different vehicle types are used to calibrate the parameters.

This approach provides an explanation for the variations in emissions among different parameters and can potentially handle all the factors in the vehicle operating environment that affect emissions. However, it is highly data intensive. There are a large number of physical variables for various vehicle types to be determined. Too high degree of parameterisation may also complicate the modelling exercise. In CMEM, 24 vehicle categories are identified based on fuel and the emission control technology of the vehicles. Normally, vehicles in traffic models are classified into limited types in terms of the vehicle size. Thus, such a high resolution of vehicle classifications may be too complicated for interface with traffic models.
2.3.4 Fuel consumption models

The Australian Elemental Model is one of the best-known fuel consumption models. This model expresses fuel consumption as a function of the three principle elements of driving patterns: idling, cruising and stop-start manoeuvres. The elemental model can be expressed in different forms. A useful form of the model is (Akcelik and Bayley, 1982):

\[ \bar{f} = f_1 + f_2 \bar{d} + f_3 \bar{h} \]  

where \( \bar{f} \) = average fuel consumption per unit distance;
\( \bar{d} \) = stopped delay time per unit distance;
\( \bar{h} \) = average number of stops per unit distance;
\( f_1 \) = fuel consumption per unit distance while cruising;
\( f_2 \) = fuel consumption per unit time while idling;
\( f_3 \) = excess fuel consumption per stop.

The model estimates fuel consumption during idle and cruise. Excess fuel consumption per stop is the difference between the total fuel consumed during a stop-start manoeuvre and that when the distance taken during this manoeuvre is travelled at a cruising speed. The derivation of different functions describing the cruise, idling and stop-start parameters of the elemental \((f_1, f_2, f_3)\) will give different formulation of the elemental model. Akcelik and Bayley (1982) used a constant rate of idling fuel consumption and related the cruising and stop-start fuel consumption to the cruising speed.
Bowyer and co-workers (1985) developed a four mode elemental model in which the stop-start component was stratified into the acceleration and deceleration modes. In other words, fuel consumption is estimated for each of the four driving modes, namely idling, cruising, acceleration and deceleration. The fuel consumption functions for these driving modes are derived from another instantaneous fuel consumption model. The minimum items required for application of the four mode elemental model are total section distance, cruise speed, stopped time and average grade. The elemental model is designed for the estimation of fuel consumption at a short road short section level.

2.4 Traffic Modelling Techniques

Analysing the effects of traffic control measures on emissions and fuel consumption also requires the accurate estimate of traffic flow patterns to which emission rates can be applied. The problem involved in urban traffic signal road networks are not always easy to solve by deriving a highly accurate theory, because of the large scale and highly complicated structure of the system. Therefore, computer simulation and modelling do pay vital roles in compensating for this. Because of the high complexity of traffic systems and human behaviour, it is impossible to simulate all elements affecting the system at the same time. It is necessary to limit the scope of the problem in order to solve it. However, simulation techniques allow many more detailed models than theoretical analyses do, and permit cheaper, safer and more rapid experiments than are possible in field experiments.

In general, traffic modelling techniques can be classified into two categories, the
macroscopic and microscopic approaches. Macroscopic simulation models consider vehicle movements in some aggregated form (e.g. employing a fluid flow analogy or a statistical representation) while microscopic simulation models trace the movement of each individual vehicle through the study network (Al-Anazi, 1989).

There are usually two types of scanning techniques which are commonly used in traffic simulation:

1. **Time-scanning** is that the state of the simulated traffic is updated at equal intervals. It is assumed that the variables are at a steady state within the interval. Higher temporal resolution gives more detailed results but needs more computer-efficiency and time. This approach generally has the advantage of easy programming and direct interface with emission and fuel consumption models, which are normally time-based in nature.

2. **Event-scanning** is that the state of the simulated traffic is updated at the occurrence of the significant event. The model developed by Al-Anazi (1989) is an example of event-scanning simulation model. Events must be clearly defined and have the ability to change the system parameters. In an analogy with time-scanning method, this approach is more efficient in simulating a system which has some eventual periods and reduces computer time. However, it is more complex in terms of programming and interface with emissions and fuel consumption models. Therefore, models of this type will not be reviewed in the following sections.
A number of traffic simulation models are currently reported in the literature. These models are useful for predicting the impact of various management schemes or control measures in a study area before they are implemented. In the following sections in this chapter a review of the widely publicised models will be discussed.

2.4.1 Macroscopic models

The macroscopic approach models traffic streams as aggregated functions. They are generally deterministic in nature. They usually deal with traffic flow in terms of aggregate measures such as flows, mean space speed and density, and thus are more computer efficient in evaluating traffic behaviour on a large street network. Some of these models are discussed in the following sections.

2.4.1.1 SIDRA

SIDRA (Signalised and Unsignalised Intersection Design and Research Aid) is a junction-based program developed by Australian Road Research Board (ARRB) as an aid for capacity, timing and performance analysis of isolated junctions with up to eight approaches (Akcelik, 1994). The capacity and performance are analysed lane by lane (Akcelik, 1984) based on the analytical models as reported in the ARR Report No. 123 (1981).

The capacity model in SIDRA estimates saturation flow rates by basic saturation flow and adjustment factors for different influencing elements like traffic compositions (left, through and right turns, light and heavy vehicles), lane width,
gradient, turn radius and so on (Akcelik, 1993). The basic relationship for saturation flow estimation is

\[ S = (f_1f_2 \ldots f_n)S_b \]

where \( S \) = adjusted saturation flow;
\( S_b \) = basic saturation flow;
\( f_i \) = adjustment factor for traffic composition, lane width and so on.

The basic saturation flow rate, \( S_b \), is stratified into five environmental classes representing very good to very poor environment. The adjustment factors are estimated by different functions which can be calibrated for local use in different countries. For opposed turns, a gap-acceptance based method is used instead of adjustment factors. For shared lane, a free queue parameter is employed to model the blockage of two movements by each other when their effect green times differ. Because of the lane by lane capability, different lanes could have different sets of basic saturation flow and adjustment parameter values.

In addition to delay, SIDRA predicts queue length, number of stops (or stop rate), fuel consumption, pollutant emissions and operating cost (Akcelik, 1993). Fundamental to the estimation of delay, queue length and stop rate is the estimation of an average overflow queue length given as follows:

\[
N_o = \begin{cases} 
0.25QT_f x^n \left[ (x-1) + \sqrt{(x-1)^2 + \frac{m(x-x_o)}{QT_f}} \right] & \text{if } x > x_o \\
0 & \text{otherwise}
\end{cases}
\]
where \( N_o \) = average overflow queue in vehicles allowing for randomness and oversaturation effects;

\[
Q = \frac{sg}{c} \quad \text{(where} \ s = \text{saturation flow (veh/h)}, \ g/c = \text{ratio of effective green time to cycle time)}
\]

\[
= \text{capacity (veh/h)};
\]

\[
T_f = \text{flow period (hr)};
\]

\[
x = \text{degree of saturation}; \text{ and}
\]

\[
x_o = a + b \cdot sg \quad \text{(where} \ sg = \text{capacity per cycle}, \ s = \text{saturation flow}, \ g = \text{effect green time)}
\]

\[
= \text{the degree of saturation below which the overflow queue is zero}.
\]

SIDRA uses the concept of average overflow queue for predicting primary performance measures, namely average delay, queue length and stop rate. The average overflow queue models the overflow component of these performance measures. To allow for the effect of platoon arrivals on delays, progression factors are developed to multiply delays obtained for random arrivals. Progression factors are determined according to arrival type (random, platoon and so on) and signal type (fixed-time or actuated) specifications.

Secondary measures of performances such as fuel consumption, pollutant emissions and operating cost can also be calculated by the four-mode elemental model expressed in Section 2.3.4. Estimates of pollutant emissions and operating cost can be obtained instead of fuel consumption by specifying appropriate data.

SIDRA calculates green split based on the required green time ratio (ratio of the
required green time to the cycle time) instead of the flow ratio (ratio of flow to saturation flow) used in the conventional models by Webster (1958) and Miller (1968). This method distributes the total available green time to critical movements in proportion to their required green time ratios, which is equivalent to minimising the degree of saturation at junctions. It allows the use of unequal practical degrees of saturation for different movements at the junction, while the Webster's model assumes equal degrees of saturation. The critical movement is the one that has the largest required movement time.

2.4.1.2 PASSER II

Researchers at the Texas Transportation Institute (TTI) have developed the PASSER (Analysis and Signal system Evaluation Routine) model, which consists of three optimisation software programs that optimise traffic signal timings on single roadways or entire networks of roadways. The three programs work with three different traffic signal scenarios, PASSER II with single signalised roadways, PASSER III with diamond interchanges, and PASSER IV with single or multiple roadways and diamond interchanges.

The optimising principle of PASSER II is to maximise the bandwidth and determines phase sequences, cycle length and offsets for up to 20 isolated or co-ordinated signalised junctions (Skabardonis and May, 1985). It provides the best phasing sequences and offsets for maximal bandwidth along an arterial by minimising the sum of interferences to the bandwidth. The optimal cycle length is obtained by selection from repeated runs on the basis of the bandwidth efficiency. PASSER II
optimises splits for minimum delay at each junction by a modified Webster’s delay formula (1958) after the maximum bandwidth has been established. In offset optimisation, the objective of PASSER II is to find the offsets that maximise the weighted sum of the directional green bands on an arterial.

PASSER II does not explicitly model platoons of vehicles. However the effect of platoon dispersion is modelled by "stretching" the queue to estimate the portion of traffic that arrives outside of the downstream green vehicles (Mystkowski and Khan, 1999). Traffic performance measures are estimated using discrete, deterministic models. Traffic movements are handled differently in PASSER II-90 than in other model. It deals with only eight movements and does not evaluate right turns directly.

As other analytical models, PASSER II estimates the uniform and overflow delay separately. These two terms are then summed to provide an estimate of total delay. Total queue is estimated as the sum of the maximum queue length and average overflow queue. The average overflow queue is estimated from the overflow delay term. However, PASSER II models traffic for a single cycle, thus the queue lengths estimated represent the queue during an individual cycle, and queues do not build over time (Mystkowski and Khan, 1999).

2.4.1.3 TRANSYT

TRANSYT (Traffic Network Study Tool) has been found to be one of the most effective analysis tools for calculating settings for co-ordinated traffic signals for an urban road network (Vincent et. al., 1980). It consists of two main modules, the
traffic simulation model and the signal optimiser (Robertson, 1969). The TRANSYT traffic simulation model simulates the movement of traffic through a network and takes into account the effect of platoon dispersion. The model predicts the value of a performance index for the network, for any fixed time plan and set of average flows. The performance index is usually a weighted linear combination of estimated vehicular delay and stops on all the approaches and is used as a measure of the overall cost of traffic congestion. The signal optimiser adjusts the signal timings and checks, using the traffic model, to determine whether the adjustment reduces the performance index. Signal timings are successively improved by adopting only those adjustments which reduce the performance index. This technique is called a hill-climbing method.

TRANSYT makes the following assumptions about the traffic situation:

(i) All major junctions in the network have signals (or are controlled by a priority rule).

(ii) All the signals in the network have a common cycle time or a cycle time of half this value.

(iii) Traffic entering the network does so at a constant specified rate on each approach.

(iv) The proportion of traffic turning left or right at each signal remains constant throughout the cycle.

The road network is represented by nodes interconnected by links. Each node represents a signal controlled junction and each link represents each distinct
directional traffic stream leading to a node. A link may represent one or more traffic lanes, and traffic on one approach may be represented by one or more links. The decision to group traffic lanes into links depends on the circumstances.

Figure 2.5  Example of measured and predicted dispersion on a link (Vincent, et. al., 1980)
The common cycle time of the signals is divided into fifty equal units of time. All TRANSYT's calculations are made on the basis of the average values of the flow rates and vehicle queues which are expected to occur during each of these units of time. The average flow pattern of traffic past a point in the road is represented by a histogram. A typical example is shown in Figure 2.5.

In the TRANSYT traffic model (Robertson, 1969; Vincent, et. al., 1980), all calculations are accomplished by the manipulation of the above type of "histograms" and no representation of individual "vehicle" is made. Calculations of the behaviour of traffic within links are based on the manipulation of the following three types of flow pattern:

(i) IN pattern: the pattern of traffic that would arrive at the stop line at the end of the link if the traffic were not impeded by the signals at the stop line;

(ii) OUT pattern: the pattern of traffic leaving a link;

(iii) GO patterns: the pattern of traffic that would leave the stop line if there was enough traffic to saturate the green.

In a traffic signal network, the pattern of traffic entering a link will be modified during the journey along the link, owing to the different speeds of individual vehicles and thus platoons of vehicles will be partly dispersed. The prediction of platoon dispersion is obtained by the following recurrence relationship (Robertson, 1969):

\[ q'(k+t) = F \ q(k) \ p + (1-F) \ q'(k+t+1) \]  

[2.4]
where \( q'(k) \) is the derived flow in the \( k \)th time interval of the IN pattern;

\( q(k) \) is the derived flow in the \( k \)th time interval of the OUT pattern;

\( p \) is the proportion of the OUT flow entering this link;

\( t \) is 0.8 times the mean journey time over the distance for which the platoon dispersion is being calculated; and

\[
F = \frac{1}{1 + 0.35t}
\]

is a smoothing factor.

In the TRANSYT traffic model, the delay is divided into two components: the uniform and random-plus-oversaturation delays. The uniform delay represents the delay incurred when an identical pattern of traffic arrives during every cycle. It is obtained through the simulation of two cycles of the IN, OUT and GO patterns to obtain the queue formation patterns of all links. These are then used to calculate the uniform delay. The random-plus-oversaturation delay takes into account respectively the variations in traffic arrivals from cycle to cycle and the steady increase in queues on oversaturation links. To determine the random-plus-oversaturation delay, approximate delay formulae, adopting the co-ordinate transformation method (Kimber and Hollis, 1979), are employed to estimate their values. TRANSYT calculates the total rate at which vehicles are forced to stop on a link as the sum of uniform and random-plus-oversaturation stop rates. The uniform component for delay is obtained from the flow patterns and the random-plus-oversaturation component is calculated from simple equations. The weighted linear combination of the estimated delay and stops on all the links becomes the performance index in TRANSYT and is used as a measure of the overall cost of traffic congestion.
In addition to vehicle delay and stops, TRANSYT/8 employed the elemental model to provide an approximate estimate of fuel consumption in a network when a particular set for signal timings is in operation. This formulation of the elemental model estimates idling fuel consumption rate as constant. Fuel consumption at cruising and that due to stopping and starting are both estimated by the cruising speed (Vincent, et. al., 1980).

2.4.1.4 SATURN

SATURN (Simulation and Assignment of Traffic to Urban Road Networks, developed by Hall, et. al., 1980) is a macroscopic simulation model in which vehicle movements on each link are modelled as progressions of vehicle platoons. It is used for the analysis and evaluation of traffic management schemes over a relatively localised network. It is intended to cope with networks of roughly 5 to 100 traffic signals and priority junctions as well as roundabouts. It is noted that SATURN is basically a traffic assignment package and, as such, users are expected to supply the origin-destination (O-D) trip matrix and not the traffic flow patterns.

SATURN (Van Vliet and Hall, 1994) is composed of several modules that perform tasks such as network building, traffic assignments and traffic simulations (as such, it is more often, referred as mesoscopic model). These modules are stand-alone units with the main model, and are related to each other through input/output system files. The complete model is based on an iterative loop between the assignment and simulation phases. Thus, the simulation module determines flow-delay curves based on a given set of turning movements and feeds them to the assignment package. The
assignment, in turn, uses these curves to determine route choices and hence updated turning movements. These alterations continue until the turning movements reach reasonably stable values.

The objective of the assignment package in the model is to select for each element in the trip matrix minimum-time routes through the network, bearing in mind the relationship between travel time and flows. The equilibrium method is adopted in the model, in which a sequence of all-or-nothing assignments is combined.

The network being simulated is represented by nodes and links. There are two types of nodes, internal and external. Internal nodes are the junctions being simulated and must be specified in full details. External nodes represent the boundary junctions surrounding the simulation network. They are essentially only geometrical points without any physical properties and are only used to identify links entering and/or leaving the simulation network.

The main building block for the simulation in the model is the cyclic flow profile (CFP) which is the flow of traffic past a certain point as a function of time over a single cycle. The CFP's in SATURN are based on turning movements. Each turn from link $i$ to $j$ is associated with four CFP's as illustrated below:

(i) IN pattern: the flow profile at the upstream end of link $i$;
(ii) ARRIVE pattern: the profile at the downstream end of $i$;
(iii) ACCEPT pattern: the pattern of traffic which can actually make the turn;
(iv) OUT pattern: the flow at the upstream end of link $j$. 
The ARRIVE pattern is derived from the IN using platoon dispersion. The ACCEPT pattern is derived independently based essentially on capacities, signal timings and conflicting traffic. The OUT pattern is based on the ARRIVE and ACCEPT patterns and contributes to the total IN patterns of succeeding turns. In addition, there is a QUEUE profile, representing the average number of queued vehicles at any point in the cycle.

SATURN uses a 'suppressed flow' to keep track of over-saturation for over saturation modelling. In other words, within the assignment stage, the model uses a 'queue reduction factor' (QRF) calculated within the simulation model. Thus, a link with a QRF of 0.9 implies that only 90 percent of the total number of trips wishing to use that link will actually arrive during the time period simulated, and therefore the delays are calculated corresponding to 90 percent of the assigned flow (Van Vliet, 1982).

Similar to TRANSYT, delays at junctions are explicitly divided into two components in SATURN, uniform and random delay. Uniform delay is calculated from the queuing cyclical flow profile and random delay is calculated from the formula as used in TRANSYT. Another formulation of the elemental model is used to estimate the total fuel consumption (Van Vliet, 1982).

SATURN estimates vehicle emissions by an analytical model that consists of queuing and emission models and takes the four standard driving modes and their variable emission rates into account (Matzoros and Van Vliet, 1992a, 1992b). The
model calculates the percentage of the modelling time period that vehicles spend on each driving mode, based on the flow and capacity of the roads and the vehicle speeds and acceleration and deceleration rates. This information is then used by the emissions models, which, by taking into account the different emission rates of the driving modes, estimate the pollutant emission rates at every point along a road.

2.4.1.5 SCOOT

SCOOT (Split Cycle Offset Optimisation Technique) has proved to be an effective and efficient tool for managing traffic on signalised road networks (Department of the Environment, Transport and the Regions, 1999), and is currently installed in Hong Kong to manage traffic on Hong Kong Island (HKI). SCOOT is adaptive and responds automatically to traffic fluctuations and uses data from vehicle detectors and optimises traffic signal settings to reduce vehicle delays and stops (Hunt, et. al., 1981). The basic structure of the SCOOT method of traffic control is shown in Figure 2.6. It may be seen that the structure of SCOOT is similar to the TRANSYT method of calculating fixed time plans. TRANSYT is an "off-line" fixed time plan optimisation model while SCOOT is "on-line" and the prediction of delays and stops are recalculated every few seconds from the latest measurements of traffic behaviour.

A SCOOT network is divided into regions, each containing a number of nodes (which represent signal junctions). Nodes may be double cycled (i.e. operate at half of the regional cycle time). Region boundaries are located where links are long enough for lack of co-ordination not to matter.
SCOOT obtains information on traffic flows from detectors. As an adaptive system, SCOOT depends on good traffic data so that it can respond to changes in flow. Detectors are normally required on every link and are usually positioned at the upstream end of the approach link. Data from detectors are stored in link cyclic flow profiles (Robertson, 1974). These profiles contain information needed to decide how best to co-ordinate adjacent pairs of signals as well as information on the demand for green (Hunt, et. al., 1982).

![Image of a SCOOT-based Urban Traffic Control system](http://www.scoot-utc.com).

Figure 2.6 The flow of information in a SCOOT-based Urban Traffic Control system (http://www.scoot-utc.com).

For each link, the SCOOT traffic model predicts the current value of the queue at the stop-line (Figure 2.7). A typical cyclic flow profile is shown alongside the detector. The detected vehicle is assumed to travel at a fixed cruise speed to the stop-line. The
state of the signal is known and uses a preset saturation flow value, the length of the queue and the end of the queue is estimated. This information is used to provide congestion information for the signal optimisers (Hunt, et. al., 1892). SCOOT has three optimisation procedures by which it adjusts signal timings, the Split Optimiser, the Offset Optimiser, and the Cycle Time Optimiser. Each optimiser estimates the effect of a small incremental change in signal timings on the overall performance of the region's traffic signal network. A performance index is used, based on predictions of vehicle delays and stops on each link (Department of the Environment, Transport and the Regions, 1999). Weightings have been introduced to enable the user to favour specific links or routes.

Figure 2.7 Principles of the SCOOT traffic model (http://www.scoot-utc.com).
SCOOT has been updated continuously (Bretherton and Bowen, 1990; Bowen and Bretherton, 1996; Bretherton, et. al., 1998) and the most recent version 4.2 has been released in 1998 (http://www.scoot-utc.com). Many new features have been introduced to enhance the SCOOT model's accuracy and capability. These enhancements include, Bus Priority, ASTRID (Automatic SCOOT Traffic Information Database), INGRID (INteGRated Incident Detection) and estimate of CO, CO2, NOx, particulates and VOC (Volatile Organic Compounds) emissions from vehicles. The emission model is of the emission factor type.

2.4.2 Microscopic models

Microscopic traffic modelling is a process in which each individual vehicle in the system is traced. It is generally stochastic in nature that probability distributions of vehicle arrival, rates, speeds, gap acceptance and other parameters are considered. In application, it is useful for the design or assessment of very detailed, complex traffic control systems. Generally, it needs large computer storage. Consequently, it is usually used for studying traffic behaviour on small-scaled networks. Some of these models are described in the following sections.

2.4.2.1 SCATSIM

The SCATSIM network simulation model was developed by the Roads and Traffic Authority of New South Wales (NSW) as an aid to the SCATS (i.e. Sydney Coordinated Adaptive Traffic System) (Lowrie, 1982, 1992; Luk, 1982, 1984; Sims and Dobinson, 1979) model, which is installed on the Kowloon Peninsular (KLN) of
Hong Kong. SCATSIM is made up of two parts: (a) the road network and traffic movements, and (b) the traffic control techniques. It has been developed by incorporating the real SCATS software, modified only in its interface to the network simulation. Data from detectors are sent to the SCATS system set up to run alongside the simulation model. SCATS then analyses data received and returns the updated signal status to the network to control traffic for the next step (Nguyen, 1996).

Similar to SCOOT, SCATS is also an on-line adaptive traffic signal control system. Traffic data are collected by detectors, which are located in close proximity to the junction. The normal mode of co-ordination is the real time adjustment of the cycle, split and offset in response to detected variations in demand and capacity. The system is divided into a large number of comparatively small sub-systems varying from one to ten junctions. As traffic conditions demand, the sub-systems 'marry' with adjacent sub-systems to form a number of large systems or one large system. When a number of sub-systems are linked, the cycle time becomes that of the linked sub-system with the longest cycle time (Roads and Traffic Authority of NSW, 1997).

The simulation network is represented by a set of nodes (i.e., signal junctions) interconnected by links (i.e., traffic flow streams toward a junction). Traffic flows into and out of the network through traffic-generation sources and sinks called terminals. Areas downstream of the stop line belong to the next junction. Once a vehicle crosses the last stop line and enters the terminal, it is considered to have left the network (Nguyen, 1996). The simulation network of SCATSIM has the following limitation:
1. 16 junctions;
2. 16 terminals;
3. 5 approaches per junction;
4. 5 lanes per approach (including short turn bays);
5. 4 metre (fixed) car size; and
6. 6 stages (maximum) can be set at each junction.

Traffic is injected into the network by a random generator using exponential distribution. By entering different seed numbers, traffic will be generated differently around the given average flow volumes. This enables users to simulate one traffic network for different traffic arrivals while average flows are kept unchanged.

The traffic movements are determined by a car following law and a lane changing procedure (Fehon, et. al., 1986). The lane changing procedure is incorporated so that a vehicle being impeded by a slower one can change lanes, subject to gap acceptance criteria. The traffic flow dynamics of the vehicles are determined by the following car following model (Lieberman, et. al., 1972):

\[
a_{n+1} = \frac{(d_n - d_{n+1} - v_{n+1}(i) \cdot \Delta t - L_n) + (1/6) \cdot (2v_n^2 - 3v_{n+1}^2(i))}{v_{n+1}(i) + 3} [2.5]
\]

where 
\(a_{n+1}\) = acceleration of the following vehicle;
\(\Delta t\) = simulation time step;
\(v_{n+1}(i)\) = speed of the following vehicle at beginning of this time step;
\(v_n\) = speed of lead vehicle at end of this time step;
\[ L_n = \text{effective length of lead vehicle}; \]
\[ d_n = \text{distance of lead vehicle from upstream node at end of the time step}; \text{ and} \]
\[ d_{n+1} = \text{distance of following vehicle from upstream node at beginning of time step}. \]

The levels at which results may be aggregated are individual movement, approach, junction, subsystems, or total network. Time history of traffic count data of all lanes within the network during a simulation period is also available. This can be used for deriving traffic queue information.

Traffic delay is calculated as the difference between actual travel time and that at cruising speed. Vehicle stops are also counted. SCATSIM uses the elemental model of the following form to estimate fuel consumption (Nguyen, 1996):

\[ F = a \cdot T + b \cdot D + c \cdot S \quad [2.6] \]

where \( F \) = total fuel consumed (in litres);
\( T \) = total travel time (in seconds);
\( D \) = total delay time (in seconds); and
\( S \) = total number of vehicle stops.

CO, HC and NOx emission are calculated on the basis of traffic data (VMT and speed) and emission rates from environmental protection agencies in the US. The emission model is of the emission factor type.
NETSIM

NETSIM is a microscopic, stochastic simulation model of traffic operations on urban road networks. It is not an optimising tool, but rather a microscopic simulation model that handles each vehicle separately and keeps a historical record of all movements for summation at the end of each simulation time period (Dudeck, 1983). The vehicles are represented individually and their operational performance is determined uniquely every second.

The physical environment in NETSIM is represented as a network comprised of unidirectional links and nodes (Rathi and Santiago, 1990). Generally, the nodes of the network represent junctions, and links represent one-way urban streets. Vehicles enter the network at a uniform rate proportional to the input volume through the entry links and source nodes. Upon entering, a list of attributes concerning the characteristics of the vehicle and driver are randomly assigned to each vehicle. The program models automobiles, trucks, buses and carpool vehicles using the same logic and applies different acceleration, speed, vehicle length and so on to each class of vehicle to reflect its operating characteristics. Ten types of driver behaviour are identified in NETSIM which reflect the aggressiveness of different drivers.

The model keeps track of the time and position of each vehicle in the network. When a vehicle approaches a traffic signal, one of the following actions will occur. If the signal is red, the vehicle decelerates at a constant rate to stop. If the signal turns yellow, and if the vehicle's position is at a distance closer than the safe stopping distance from the stop line, the vehicle will proceed without stopping, otherwise, the
vehicles stops. If the signal is green, the vehicle will proceed without stopping. When the signal turns from red to green, the first three queued vehicles will experience a start-up delay time and the subsequent vehicles will leave the stop line at a constant rate.

As a vehicle is travelling downstream, it will react to lane obstruction. A leader moving towards an obstruction begins looking for a lane change opportunity at a distance \( D \) from the obstruction, where \( D = \max (40, v^2/2d) \). \( v \) and \( d \) are the approach speed and deceleration rate respectively. If the vehicle comes within five feet of the obstruction and an acceptable gap is still not available in the adjacent lane, the vehicle will stop behind the obstruction and continue to look for an acceptable gap (Wong, 1990).

NETSIM estimates vehicle emissions and fuel consumption using modal models. Emissions and fuel consumption tables are used to estimate instantaneous emissions and fuel consumption rates of individual vehicles (Rathi and Santiage, 1990).

2.4.2.3 MULTSIM

MULTSIM was developed by Gipps (1976). It is a microscopic model which simulates the progress of traffic in one direction through four signal controlled junctions on a carriageway of up to four lanes. The characteristics of each vehicle are stored as it travels along the simulated section of the roadway and its position and speed are updated once a second.
The basis of this approach is the hypothesis that flow patterns on the road will be realistically represented if the behaviour of individual drivers can be modelled with a reasonable degree of accuracy. Furthermore, by operating at the level of the individual vehicle it is possible to determine the variability of benefits between and within different classes of road users. In MULTSIM, the driver of each vehicle is provided with a set of goals, and released down the road subject to rules which govern his behaviour with respect to other vehicles and the driving environment (Gipps and Wilson, 1980).

The behaviour of the vehicle within its lane is determined by a car following model (Gipps, 1981) in which limits on acceleration and breaking are used to calculate a safe speed with respect to the preceding vehicle. The following relations are used for acceleration and braking respectively.

\[ v_n(t + \Delta t) = v_n(t) + \frac{2.5a_n\Delta t(1 - v_n(t)/V_n)}{\sqrt{0.025 + v_n(t)/V_n}} \quad [2.7] \]

where \( v_n(t + \Delta t) \) = speed of vehicle \( n \) at time \( t + \Delta t \);

\( v_n(t) \) = speed of vehicle \( n \) at time \( t \);

\( V_n \) = desired speed of driver \( n \);

\( a_n \) = maximum acceleration of vehicle \( n \);

\( \Delta t \) = time step between consecutive calculations of speed and position.

and, for braking
\[ v_n(t + \Delta t) = b_n \Delta t + \sqrt{b_n^2 (\Delta i)^2 - b_n [2[x_{n-1}(t) - s_{n-1} - x_n(t)] - v_n(t)\Delta t - \frac{v_{n-1}(t)^2}{\hat{b}}]} \]

[2.8]

where \( b_n(t) \) = the most severe braking that the driver of the vehicle \( n \) wishes to undertake \((b_n > 0)\);

\( x_n(t) \) = location of the front of vehicle \( n \) at time \( t \);

\( s_{n-1} \) = effective length of vehicle \( n - 1 \);

\( \hat{b} \) = estimate of \( b_{n-1} \) to be used by the driver of vehicle \( n \).

For any given circumstances, the speed of vehicle \( n \), is the minimum of Equations [2.7] and [2.8].

MULTSIM allows fast vehicles changing lanes to overtake slower vehicles or to avoid obstruction in the present lane. For turning vehicles, as they approach the junction, there is an increasing intention to change lanes in the desired direction only (Gipps and Wilson, 1980). Four types of vehicles have been defined in MULTSIM to represent the traffic composition. They include small motor cars, medium sized motor cars, bus and goods carrying trucks.

2.4.2.4 MITSIM

MITSIM (Microscopic Traffic SImulator) is one of the four components of a system developed for evaluating dynamic traffic management systems (Yang and Koutsopoulos, 1996). The objective of developing MITSIM is to simulate integrated
traffic networks supported by advanced traffic control and surveillance systems. This model is structured for testing and evaluating designs of Advanced Traffic Management Systems (ATMS) and Advanced Traveller Information Systems. Drivers in the network respond to the various traffic controls and guidance while at the same time interacting with one another. The movement of vehicles is recorded by the surveillance system then provides the traffic management module with the required data for generating control and routing strategies.

MITSIM represents road networks by nodes, links, segments, and lanes. A node is either a junction of several roadways or a source or sink where traffic flows enter or leave the simulated network. Links are directional roadways that connect nodes. Each link may consist of one or more segments, which are road sections with uniform geometric characteristics such as number of lanes. Each segment contains a number of lanes. The connections between upstream and downstream lanes are represented by a lane connection table.

MITSIM accepts as input time-dependent origin/destination trip (O-D) tables. Each trip table includes the data items that specify the time that the trip table becomes effective and a list of departure rates for various O-D pairs. Vehicles arrival times are generated from Poisson distribution. Vehicle and driver characteristics are then assigned to each vehicle after it enters the network. Parameters regarding vehicle performance are deterministic while driver behaviour parameters are randomly assigned. Its position and speed are determined based on the simulation step size, driver's desired speed, and position and speed of the leading vehicles. If there is no space available in the entrance link, vehicles are stored in a virtual queue and wait to
enter the network during subsequent time intervals.

A probabilistic route choice model is used to capture drivers' route choice decisions in the presence of real time traffic information provided by a route guidance system. The movement of a vehicle in the network is determined by its interactions with the vehicles ahead, response to traffic controls, desired speed, and lane-use preference. The simulator maintains a linked list of vehicles in each lane and moves individual vehicles according to the car following, lane changing and event responding models.

If the headway of the subject vehicle with the leading vehicle is larger than a pre-determined upper threshold, the vehicle travels at the driver's desired speed. If a vehicle has headway smaller than a pre-determined lower threshold, the vehicle uses an appropriate deceleration rate to avoid collision and extend its headway. If a vehicle has headway between the upper and lower threshold, the vehicle moves according to the Herman's general car following model (Herman, et. al., 1959):

\[ a_n = \alpha^\pm \frac{v_n^{\beta^\pm}}{g_n^{\gamma^\pm}} (v_{n-1} - v_n) \]  

[2.8]

where \( a_n \) is the calculated acceleration/deceleration rate, \( \alpha^\pm \), \( \beta^\pm \) and \( \gamma^\pm \) are model parameters related to driver behaviour. \( \alpha^+ \), \( \beta^+ \) and \( \gamma^+ \) are used for acceleration (\( v_n \leq v_{n-1} \)), and \( \alpha^- \), \( \beta^- \) and \( \gamma^- \) for decelerating (\( v_n > v_{n-1} \)) cases.

MITSIM models the lane changing behaviours based on the Gipps model (1986). For each vehicle, the Gipps model first checks the need for mandatory (necessary, such
as bypass lane blockage downstream) and discretionary (not necessary, change lane in order to increase speed or overtake slow vehicles) lane changing. If the vehicle needs to change lane, it selects the desired lane and waits for an acceptable gap to change lanes. The minimum acceptable gap for discretionary lane changes is generated from user defined distribution. For mandatory lane changes, the acceptable gaps may decrease as the vehicle approaches the downstream node (i.e. the drivers tend to accept smaller gaps as they get closer to the last location where the lane change has to take place).

2.4.2.5 AIMSUN

AIMSUN (Advanced Interactive Microscopic Simulator for Urban and Non-Urban Networks) is a Spanish microscopic simulator integrated into GETRAM (Generic Environment for Traffic Analysis and Modelling) and capable of reproducing the real traffic conditions on an urban network. It is mainly used for testing new traffic control systems and management policies. It provides a very detailed modelling of the traffic network since it deals with different types of vehicles and drivers travelling on a wide range of network geometry. Input data of AIMSUN falls into three types, network description, traffic control plans and traffic conditions.

AIMSUN models traffic network as a set sections (links) connected to one another through nodes (Montero, Codina, Barcelo J. and Barcelo, P., 1998; Barcelo, Ferrer, Barcia and Grau, 1998). A node is the intersection of two or more sections. The basic modelling structure is the Entity: sections are composed of section entities which correspond to lanes, and nodes are made up of node entities which connect
input and output entities and define the turning movement. Therefore, network can
be interpreted as a set of related entities. Vehicles move along the network through
entities according to driver behaviour models, which are a function of their state,
defined by the current and adjacent entities.

Traffic conditions may be input in two ways: (1) as the turning proportions at
junctions plus the input distribution of vehicles; or (2) as time-sliced OD matrices. In
the first case, vehicles are randomly generated into the network at the input section
following a user-selected statistical distribution, and they are distributed randomly
on the network according to the turning proportions defined for each junction on the
network. It means that vehicles do not know their complete path along the network,
but only their next turning movement. In the second case, vehicles are generated at
their specific origins and are allocated to specific routes from their origins to their
destinations. In this case explicit route are computed and assigned to each vehicle by
route choice models.

Vehicle movements along the network are updated according to three driver
behaviour models, car following, lane changing and gap acceptance. Drivers tend to
travel at their desired speed in each section but their behaviour is conditioned by
their state (i.e. preceding vehicle, adjacent vehicles, traffic signals and so on).

AIMSUN is capable of simulating Intelligent Transportation Systems (ITS) like
Advanced Traffic Management Systems (ATMS), Advanced Traveller Information
Systems (ATIS) and Vehicle Guidance Systems (Barcelo, Casas, Ferrer and Garcia,
1998; Barcelo, Ferrer and Martin, 1999; Barcelo, 2000). To model adaptive traffic
signal controls, a stage-based approach is applied to model traffic signal control, in which the cycle of the junction is divided into several stages, each one having a particular set of turns with right of way (Barcelo, Casas, Ferrer and Garcia, 1998). Through the modelling of detectors in the link entities, the simulated detection data are transferred to the traffic controller to decide which control actions have to be applied on the road network and sends the corresponding information to the simulation model to emulate the operations. Other ATMS like Variable Message Sign (VMS) are modelled in the same way.

AIMSUN has a user-friendly interface through which the user can define the and view the dynamic animation of the simulation experiment. In addition to animation, detailed statistical output like flows, speeds, travel times and so on, may be presented as printouts or plots. Environmental measurements, such as fuel consumption and pollution emissions are also provided.

2.4.2.6 PARAMICS

PARAMICS (Parallel Microscopic Simulation) is a suite of commercial software tools for microscopic traffic simulation to provide insight into large-scale congested networks and provide a highly useful tool for predictive network management and scenario evaluation (Duncan, 1996). Individual vehicles are modelled in detail for the duration of their entire trip, providing traffic flow information necessary for the analysis of congested road networks.

PARAMICS is sensitive to the definition of the road network layout and geometry.
User can define the road network by directly drawing on a base map overlay. A list of physical properties of the network can be altered like lane widths, lane arrangements including permitted turns and junction signal timings. Each junction is described by a set of locus points (Duncan, 1997). A vehicle entering a junction, must steer itself smoothly through a sequence of these control points. Each exit lane from a junction is described by a single point in the centre of the lane at the point at which it becomes straight. Additional points may be use to guide traffic around islands, or other physical constraints. Turning vehicles are constrained by the maximum angle it can turn.

Vehicles are randomly released onto the links through zones defined at the network boundary (Quadstone, 1999). Travel demand in PARAMICS is summarised by time-dependent vehicle zone to zone trip matrices. The simulated random release of vehicles onto the road network is constrained by the trip matrices and demand profiles. Three types of traffic assignment methods, all-or-nothing, stochastic and dynamic feedback, can be selected to model the vehicle routing behaviours.

Vehicles are modelled as Driver-Vehicle Unit (DVU) in PARAMICS (Mega Computing, 1997). The movement of individual DVU is governed by three interacting models representing vehicle following, gap acceptance and lane changing. Vehicle attributes (e.g. length, top speed, acceleration/deceleration capabilities) are randomly allocated using distributions. Each DVU in the PARAMICS simulation has a target headway to represent its aggressiveness. Under free flowing condition, DVU varies its speed so as to attain its target headway. Under car following condition, DVU reacts to the preceding vehicles in three ways refer to
as braking, cruising and accelerating. In conjunction with the car following model, the lane changing and gap acceptance models are employed to model the lane changing conditions, in that the accepted gap is based on the target headway.

PARAMICS is capable of modelling fixed-time and actuated signal controls. A supplementary programming module of PARAMICS allows user to code their own traffic signal control schemes. Thus, combining the simulation of detectors at individual lanes, adaptive traffic signal control can be modelled.

PARAMICS provides detailed output statistics like speed, travel time, delay and stops. Environmental assessment criteria (e.g. pollutant emissions and noise level) can also be estimated if appropriate data is provided. However, it should be noted that link and junction capacities are not explicitly output by PARAMICS. Their definitions and derivations are not relevant to the systems operations (Mega Computing, 1998).

2.5 Traffic Signal Control Systems

This section contains description of various type of traffic control systems. Traffic signal control systems may operate under various control methods include:

(a) fixed time signals: predetermined signal timings based on historic data;
(b) vehicle actuated signals: responsive to varying traffic conditions, with minimum and maximum timings set;
(c) co-ordinated traffic signals: several signal junctions linked in operation, to
minimise junction measures of effectiveness.

(d) traffic adaptive signal control: combination of (b) and (c) that co-ordinated signal timing plans are frequently adjusted with respect to dynamic traffic volume changes.

For fixed time traffic signal controls, optimal signal plans for each single junction are calculated based on historical traffic count data to minimise junction delay. Different fixed time plans for different days (weekdays or weekend) and different time of the day (am-, pm- or off-peak). For vehicle actuated signals, green times of each stage are varied in accordance with traffic demand. Demand information is recorded through detectors that are linked to the traffic signal controller. These two types of controls are designed for isolated junction.

The other two types of controls are now widely adopted to control urban signal networks, such as the TRANSYT and SCOOT systems. A large number of co-ordinated signal junctions are linked with and controlled by a central computer system. The signal timings under control are co-ordinated so as to minimise overall delays to traffic over the network. Measured flow and journey times through the network are used to calculate plans of optimum signal timings and offsets which suit different traffic patterns.

Off-line model has been developed to calculate optimum signal settings for a signal network. TRANSYT is probably the best known example. It can be used to compile a series of fixed time signal plans for different traffic conditions. However, preparing such signal plans requires traffic data to be collected and analysed for each situation.
This is time consuming and expensive and unless plans are updated regularly as traffic patterns change they become less and less efficient. Therefore, there is growing international interest in developing traffic adaptive signal control systems.

Recent urban traffic signal control systems are generally expected to have the capability to control junctions as either time-of-day (off-line) or adaptive (on-line) control. These systems are now referred to as one type of ATMS and they are usually linked with other ATMS facilities (e.g. VMS) to share real time information. There are several adaptive systems available namely, SCOOT, SCATS and RHODES. SCOOT and SCATS are widely accepted adaptive systems while RHODES is still under development. Three different system architectures are used in these models.

2.5.1 SCOOT Architecture

SCOOT is designed for operation using the traditional highly centralised traffic control system architecture. This architecture features a central minicomputer that communicates directly with each of the local signal controllers at a once-per-second rate. Real time traffic information are recorded by the detectors on each link and then transfer back to the central monitoring computer to perform optimisation calculations. In SCOOT, every red/green transition is optimised. Queue estimates are updated every four seconds and the split optimisation is performed a few seconds before every phase change. The offset optimisation is repeated once a cycle, by evaluating possible offset alterations of each junction. The selected split and offset alterations are then implemented immediately. Similarly, the cycle times of a group of junctions may also be altered.
2.5.2 **SCATS Architecture**

The SCATS systems can be run under four modes of operation:

1. **Masterlink** - This is the normal model of operation which provides integrated traffic responsive operation. There are two levels of control in this mode: strategic and tactical. The strategic control determines the best signal timings for the areas and sub-areas. The tactical control is concerned with the control of the individual junction.

2. **Flexilink Operation** - This is a cableless or synchronous operation. The cableless link operation is the normal fallback mode as it provides an effective linking system without the need for a master controller through an internal software cableless link program.

3. **Isolated Operation** - In this mode the controller is operating under independent vehicle actuation or a fixed-time control system.

4. **Flash Operation** - This is another manual function to override the normal automatic operation, which incorporates flashing yellow display for the major approaches and flashing red display for the minor approaches.

SCATS utilises a distributed intelligence, three-level, hierarchical system using microprocessors and minicomputers. The system architecture consists of a central monitoring minicomputer at the central centre, remote regional minicomputers and local traffic signal controllers.

Local controller at the traffic signal site processes strategic data collected from
traffic detectors, makes tactical decisions on signal operation, and assesses detector malfunction.

Each regional computer consists of minicomputers that autonomously control the junctions in their area. These computers are the heart of the SCATS system. They are usually installed at the centre of the groups of traffic signals to be controlled in order to reduce the cost of the communications. They implement the real-time operation of the signals by analysis of the detector information pre-processed by the local controllers.

The central monitoring computer allows access to the regional computers for traffic data collection, data input and monitoring. It also allows central control to monitor the system, subsystems, or individual junctions, alter control parameters, manually override adaptive functions.

2.5.3 **RHODES Architecture**

The RHODES system is developed by the University of Arizona (Mirchandani and Head, 2001). The system utilises a control architecture that

1. decomposes the traffic control problem into several sub-problems that are interconnected in an hierarchical fashion,
2. predicts traffic flows at appropriate resolution levels to enable pro-active control,
3. allows various optimisation modules for solving the hierarchical sub-problems, and
4. utilises a data structure and computer/communication approaches that allow for fast solution of the sub-problems, so that each decision can be downloaded in the field appropriately within the given rolling time horizon of the corresponding sub-problem.

At the highest level of RHODES is a dynamic network loading model that captures the slow-varying characteristics of traffic. These characteristics pertain to the network geometry and the typical route selection of travellers. Based on the slow-varying characteristics of the network traffic loads, estimates of the load on each particular link, in terms of vehicles per hour, can be calculated. The load estimates then allow RHODES to allocate green time for each different demand pattern and each phase. These decisions are made at the middle level of the hierarchy, referred to as network flow control. Traffic flow characteristics at this level are measured in terms of platoons of vehicles and their speeds. Given the approximate green times, the junction control at the third level selects the appropriate phase change epochs based on observed and predicted arrivals of individual vehicles at each junction. At each level of the hierarchy there is an estimation component and a control component. Methods of the level 2 and 3 have been developed while the level 1 control and predictions are still under development.

In current adaptive traffic signal systems, signal timings are optimised on the basis of the latest collected traffic data and implemented in the next time slice. However, this approach implicitly assumed that for the next time slice, the traffic in the network can be well characterised by the measured information. Thus signal plans produced by this approach may induce unnecessary delays and sometimes performed not as
good as fixed time controls (Wolshon and Taylor, 1999). In RHODES, the emphasis shifts from changing timing parameters in reacting to traffic conditions just observed to pro-active setting phase duration for predicted traffic conditions.

2.6 Approaches for Model in this Study

In view of the review, this section examines the fundamental traffic simulation and emissions/fuel consumption considerations for application to modelling at urban traffic signal junctions.

2.6.1 Emissions and fuel consumption

Conventional emission factor models, such as MOBILE and MVEI, which estimate emissions using aggregated traffic activity variables, are useful on regional and nation-wide applications where little details on traffic flows and operations are available. However, these models are not sensitive to vehicle model events, which occur frequently at signal controlled junctions. Average speed models and the elemental fuel consumption model is very useful in estimating total emissions and fuel consumption in a road network. However, the dominant parameter, average speed, smoothes the effect of acceleration and deceleration, which make significant contributions to emissions and fuel consumption.

Modal emission/fuel consumption models provide second-by-second estimates of emissions and fuel consumption rates and take into consideration the effects of instantaneous vehicle operating parameters, such as speed, accelerations and engine
conditions. While this approach is essentially structured sensitive to vehicle modal activities, none were developed based on the on-road emission data. In fact, even for actual speed driving cycles, the engine operating conditions do have significant differences from those of the on-road driving test (Rapone, et. al., 1995; St. Denis, et. al., 1994). Some factors are difficult to simulate on test beds (Foss, 1992). However, on-road emission data are limited and relatively few vehicles have been tested for each study (Tong, et. al., 2000; Cheung, et. al., 1999).

Usually, models are derived for a specific type of vehicle technology. In CEME, 24 vehicle technology categories are identified. It is recognised that different vehicle technology groups (or even within the groups) have different emission/fuel consumption behaviours. However, too detailed classification of vehicle categories may complicate the modelling exercise.

It appears that the modal approach, which takes into account the vehicle modal events, is appropriate for modelling vehicular emissions and fuel consumption at urban signal controlled junctions. However, vehicle operation data as well as tailpipe emissions and fuel consumption should be measured through on-road driving test of instrumented vehicles. The test vehicles should be carefully chosen to represent the typical traffic mix. Resolution of the vehicle technology categories should be comparable to that of the traffic simulation model.

2.6.2 Traffic simulations

Macroscopic traffic simulation models represent traffic flows as vehicle platoons
moving within links. They usually deal with aggregated measures such as flows, average speed and thus are more computer efficient. Hence, macroscopic models usually accompany other traffic behaviour analysis packages, like the signal optimisation tool in TRANSYT and SCOOT, assignment module in SATURN.

Microscopic models deal with each individual vehicle in the simulated network. Speed and location of each individual vehicle are updated for regular time steps. The movement of individual vehicles is governed by a number of sub-models, such as car-following logic, lane changing algorithms and turning regulations. This approach is computer storage demanding, thus this type of model is usually developed for studying traffic behaviour on small-scaled networks rather than performing signal optimisation and assignment analysis.

At the same time other modelling capabilities are introduced to cater for simulating ATMS like adaptive traffic signal operations. This is done by developing another traffic control model (resembles ITS traffic control centre) separately that collect detection data from the traffic simulation model to perform calculations. The resultant traffic control actions are then transferred back to the traffic model for implementation.

It seems that the microscopic traffic modelling approach is more suitable for simulating the vehicle modal events as it is dealing with individual vehicles. This approach needs large computer storage and is intended to simulate small-scale networks. The primary objective of this study is to simulate the effects of signal operations on vehicle emissions and fuel consumption, thus signal optimisation and
vehicle route choice algorithms are not considered in this study. However, this approach also allows the developed traffic model extending to incorporate the simulation of ATMS facilities.

Usually, vehicle arrival rates in microscopic simulation are randomly generated from probability distributions. In fact, the arrival patterns may not be completely random, especially for small-scale networks, because they may be affected by the junctions located at the upstream of the road section of interest. For many urban cities, such as Hong Kong, the majority of the junctions are signal controlled. Therefore, a more realistic vehicle arrival pattern can be achieved by considering the vehicle generation source nodes to be a signal controlled junction.
CHAPTER 3

EMPIRICAL INVESTIGATIONS OF URBAN DRIVING CHARACTERISTICS

3.1 Introduction

As discussed in Chapter 2 vehicle emissions and fuel consumption depend on vehicle speed and acceleration, which in turn depend on the driving conditions. Therefore, it is important to obtain a general understanding of the driving characteristics in Hong Kong. One of the approaches to characterise driving characteristics is to develop a standard driving cycle.

Driving cycles have been developed to provide a single speed-time profile that is representative of urban driving (Lyons, et al., 1986; Kenworthy, et al., 1983; Watson, et al., 1982; Kuhler and Karstens, 1978; Kent, et al., 1978; Kruse and Huls, 1973). Standard driving cycles have a wide range of uses. Vehicle manufacturers need these cycles to provide a long term basis for design, tooling and marketing (Watson, et al., 1982). Traffic engineers require driving cycles in the design of traffic control systems and simulation of traffic flows and delay. Environmentalists are concerned with the performance of the vehicle in terms of the pollutants generated, while negotiating specific driving patterns (Bullock, 1982). Furthermore, a speed-time trace can provide a convenient laboratory-based means to estimate fuel consumption and emissions of vehicles within the respective urban areas (Lyons, et al., 1986; Simanaitis, 1977).

Many driving cycles have been developed elsewhere under specific driving
characteristics. These characteristics clearly differ from one area to another, even within the same city. For example, use of the European test cycle to predict total exhaust emissions in Turkey did not produce accurate results (Ergeneman, et. al., 1997). In Hong Kong there is no existing driving cycle. The purpose of this investigation is to obtain a better understanding of the Hong Kong urban driving characteristics such as the idle proportions, average speed and acceleration in order to develop a standard driving cycle.

There are two distinct approaches to develop driving cycles. One is derived from the on-road driving data records such as the US 75 cycle (Kruse and Huls, 1973) and the Melbourne peak cycle (Watson, et al., 1982). The other are "modal" or "polygonal" driving cycles (Kuhler and Karstens, 1978), such as the Japanese cycle (Umino, 1991) and the ECE cycle, which is constructed from various representative constant acceleration and speed driving modes. The first category is experimental-based and appears to be reasonably representative of the real driving situations. The first approach is therefore adopted in this study.

This chapter begins by reviewing various mandatory driving cycles. The details of an on-road testing to collect speed-time data in the urban areas of Hong Kong is then described. An outline of the instrumentation and experimental setup of the test facilities as well as vehicle specifications are also included. The collected data are then analysed to obtain the essential parameters characterising the urban driving conditions in Hong Kong. Finally, a standard driving cycle is developed and compared to those driving cycles established elsewhere.
3.2 In-Use Driving Cycles

There is a number of driving cycles used elsewhere to represent different driving patterns. There are two major categories of driving cycles, legislative and non-legislative. Legislative cycles enable governments to control emissions from motor vehicles. Exhaust emissions from vehicles being examined, driven over the specific driving cycle must not exceed the statutory emission standard. The US 75 cycle, ECE cycle and Japan 10-15 mode cycles are all currently used in the US, Europe and Japan respectively to control vehicle emissions. These driving cycles are considered to be broadly representative of the driving conditions within their respective jurisdictions. These cycles, however, require constant updating. For example, the Japan 10-15 mode cycle replaced the previous 10-mode and 11-mode cycles since 1991. As the 10-mode and 11-mode cycles were developed 20 to 30 years ago, the introduction of the 10-15 mode cycle reflects the substantial changes in the traffic conditions such as the development of road networks. As Hong Kong has not developed such a driving cycle, all these three driving cycles have been referred to in its emissions control legislation.

Non-legislative cycles are developed for the estimation of exhaust emission and fuel consumption. The Sydney cycle (Kent, et. al., 1977), improved European cycle (Kuhler and Karstens, 1978), the Melbourne peak cycle and the Perth cycle (Kenworthy, et. al., 1983; Lyons, et. al., 1986) are some of the examples. The improved European cycle was developed for exhaust emission tests. The Sydney driving cycle was developed in the morning peak hours to estimate the emissions in this critical period. The Melbourne peak cycle, was developed based on a study of
Melbourne morning peak driving, aimed at providing a common basis for assessment of emission or fuel consumption prediction models (Watson, et. al., 1982). Because many fuel consumption data had been collected during the project, thus the Perth cycle was suggested to be used to evaluate and refine fuel consumption model (Kenworthy, et. al., 1983).

This investigation deals with the development of a non-legislative driving cycle. Although the synthesised driving cycle developed here is not for legislative purpose, it is of great interest to compare this cycle with the well-established legislative cycles elsewhere which are referred to in the local legislation.

3.3 Methodology in Developing Driving Cycles

Several methods are available for crystallising the large amount of on-road speed-time data to a cycle of reasonable duration so that the cycle matches the overall summary characteristics of the data. Kruse and Huls (1973) performed six runs and chose the run with the most representative speed-time profile based on the idle time, average speed, maximum speed and number of stops per trip. Representative profiles of a cycle of driving modes, i.e. idling, accelerating, cruising and decelerating, were selected from the chosen speed-time profile, to form a driving cycle.

Kent, Allen and Rule (1978) used the average speed, root mean square acceleration and percentage idle time to be the parameters in the synthesis of their driving cycle. The objective of their cycle was to estimate exhaust emissions, hence they chose the parameters that have an important bearing on emissions. A 10-minute cycle was
produced from randomly chosen segments that were bound by idling modes so that the resultant speed-time statistical parameters and predicted emissions matched those of the overall survey data.

Kuhler and Karstens (1978) developed their cycle by matching some mandatory driving cycles to test-run data. They compared these cycles with the test-run data based on ten parameters. These were average speed, average running speed, average acceleration, average deceleration, mean length of a driving period from start to stop, average number of acceleration-deceleration changes within one driving period and the proportions of the four operating modes, idle, acceleration, cruising and deceleration. The new driving cycle was developed by modifying the mandatory cycles that had the closest statistics of the ten parameters compared with the test-run data.

Watson, Milkins and Braunsteins (1982) employed a two-tier selection process based on some speed-time target parameters similar to those used by Kuhler and Karstens (1978). They were the mean speed, RMS speed and acceleration, PKE (positive acceleration kinetic energy per unit distance) and the relative amount of time in various speed ranges. These parameters were derived from the survey data according to the travel direction and the route types. Two trips from each route were selected at random and these trips were then subdivided into about 200 micro-trips. A random sequence of micro-trips was then chosen until the accumulative time of these micro-trips exceeded 15 minutes to form a cycle. Four cycles which most closely approximated the target parameters were selected. Final adjustments were made by swapping the micro-trips between the four cycles until a speed-time trace was
produced which matched the target characteristics.

Rather than synthesising the sample data, Kenworthy, et al., (1983) and Lyons, et al., (1986) reproduced the speed-time history of urban driving through a simulation procedure based on a "Knight's Tour" concept which relied on an understanding of the dynamics of urban driving.

With the limited equipment available in this study, the method utilised by Kuhler and Karstens (1978) is adopted. There are therefore nine assessment criteria in the analysis:

1. Average speed of the entire driving cycle, \( v_1 \);
2. Average running speed, \( v_2 \);
3. Average acceleration of all acceleration phases, \( a \);
4. Average deceleration of all deceleration phases, \( d \);
5. Mean length of a driving period, \( c \);
6. Time proportions of driving modes, i.e. idling \( P_i \), acceleration \( P_a \), cruising \( P_c \) and deceleration \( P_d \);
7. Average number of acceleration-deceleration changes (and vice versa) within one driving period, \( M \);
8. Root mean square acceleration, \( \text{RMS} \); and
9. Positive acceleration kinetic energy, \( \text{PKE} \).

The different driving modes are defined as follows:
(a) Idling mode: Zero speed.

(b) Acceleration mode: Portions having positive incremental speed changes of more than 0.1 m/s².

(c) Cruising mode: Portions having absolute incremental speed changes of less than or equal to 0.1 m/s².

(d) Deceleration mode: Portions having negative incremental speed changes of more than 0.1 m/s².

(e) Driving period: The segment of the speed-time trace bounded by idling modes at both ends (Idling mode is not included in the segment).

In developing the standard driving cycle for Hong Kong, the nine parameters are calculated from the survey data and also 20 short driving periods, each bound by idle times, are selected from the data set so that the values of these parameters can best fit those of the whole data sample.

3.4 Speed Data Collection

The following equipment was used in the collection of speed-time data. The test vehicle is a Toyota Hiace manual transmission van. The engine is a diesel engine with capacity of 2799cc. An infrared photoelectric sensor was used to measure the engine speed and the transmission shaft rotating speed. A Pentium micro-computer was used to collect and store the instantaneous data.

Speed-time data were collected using the small diesel van travelling many times through two selected routes in typical urban areas of Kowloon (KLN) and Hong
Kong Island (HKI). The roads in KLN are more spread out on the flat land while those in the HKI are bound on the northern shore of the Island, on one side by the hill and the other by Victoria Harbour. The routes were chosen to represent the two different urban driving environments in Hong Kong. Figure 3.1 shows the HKI route which passes through the central business areas. Air quality in these urban areas is of great concern and the government has installed several roadside air quality monitoring stations along the selected routes to monitor the traffic emissions. Figure 3.2 shows the KLN route which passes through the most crowded districts in Mong Kok, Tsim Sha Tsui and the less crowded district in Ma Tau Wai. Mong Kok and Tsim Sha Tsui are known to be the densest areas in KLN both during weekdays and holidays as there are many recreational and commercial activities in these areas.

![Diagram of HKI Route](image)

Figure 3.1  HKI Route

The data acquisition system is shown in Figure 3.3. It consists of an optical sensor pointing to the axle of the test vehicle. The infrared photoelectric sensor measures the rotation of the axle and sends an electrical pulse on each rotation to a pulse collector which would then pass to the pulse converter. The pulse converter would then convert the pulse from an analogue mode to a digital mode. Incorporated with a
PICO acquisition system, the speed data were collected into the microcomputer. The error and response time of the speed measurement were less than 2 percent and 0.01 second respectively. The resolution of the speed measurement was lower than 0.03 km/h.

![Diagram of KLN Route](image)

Figure 3.2 KLN Route

The data were collected at the peak period ranging from 8:00 a.m. to 11:00 a.m. in the months from September to December 1997 during calm and dry weather conditions. As stated before, the selected routes are located in the commercial areas
so that there is much traffic flowing towards these districts in the morning. Traffic congestion always occurs in these areas in the morning. Therefore, by choosing the morning peak hours to conduct surveys captures those driving conditions that have the largest impact on air pollution.

![Flow chart of the data acquisition system](image)

**Figure 3.3** Flow chart of the data acquisition system

3.5 **Results from Field Data**

The collected speed time data were plotted in graphs and inspected visually for any abnormal characteristics. The assessment parameters derived from the test runs are shown on Table 3.1. There were totally 17 test runs and 12 were eventually selected for further analysis. There are significant differences between runs 1 to 6 and runs 7 to 12. Test runs 1 to 6 were performed in KLN while runs 7 to 12 were on the HKI. As stated earlier, the background environments in the two districts are different, thus the driving patterns could have some differences. Table 3.2 compares the nine assessment criteria in each district, while Table 3.3 shows the values of the nine assessment parameters of other mandatory driving cycles.
Table 3.1 Mean values and overall mean values of the assessment criteria to individual runs.

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$v_1$ (km/h)</th>
<th>$v_2$ (km/h)</th>
<th>$a$ (m/s²)</th>
<th>$d$ (m/s²)</th>
<th>$c$ (s)</th>
<th>$P_r$ (%)</th>
<th>$P_a$ (%)</th>
<th>$P_c$ (%)</th>
<th>$P_d$ (%)</th>
<th>RMS (m/s²)</th>
<th>PKE (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Runs</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>11.64</td>
<td>18.68</td>
<td>0.636</td>
<td>0.591</td>
<td>43.21</td>
<td>37.59</td>
<td>26.19</td>
<td>7.87</td>
<td>28.28</td>
<td>6.6</td>
<td>0.807</td>
</tr>
<tr>
<td>2</td>
<td>13.41</td>
<td>21.66</td>
<td>0.560</td>
<td>0.555</td>
<td>43.77</td>
<td>38.05</td>
<td>25.94</td>
<td>9.81</td>
<td>26.20</td>
<td>6.1</td>
<td>0.716</td>
</tr>
<tr>
<td>3</td>
<td>11.99</td>
<td>19.50</td>
<td>0.531</td>
<td>0.586</td>
<td>46.81</td>
<td>38.46</td>
<td>26.58</td>
<td>11.00</td>
<td>23.95</td>
<td>5.6</td>
<td>0.665</td>
</tr>
<tr>
<td>4</td>
<td>12.76</td>
<td>19.88</td>
<td>0.524</td>
<td>0.583</td>
<td>40.16</td>
<td>35.73</td>
<td>30.08</td>
<td>7.08</td>
<td>27.07</td>
<td>4.1</td>
<td>0.600</td>
</tr>
<tr>
<td>5</td>
<td>13.02</td>
<td>20.94</td>
<td>0.502</td>
<td>0.562</td>
<td>42.07</td>
<td>37.77</td>
<td>29.08</td>
<td>7.16</td>
<td>25.99</td>
<td>4.0</td>
<td>0.587</td>
</tr>
<tr>
<td>6</td>
<td>12.89</td>
<td>20.15</td>
<td>0.493</td>
<td>0.550</td>
<td>42.86</td>
<td>36.02</td>
<td>29.59</td>
<td>7.84</td>
<td>26.55</td>
<td>4.2</td>
<td>0.574</td>
</tr>
<tr>
<td>7</td>
<td>21.04</td>
<td>26.78</td>
<td>0.641</td>
<td>0.661</td>
<td>60.75</td>
<td>33.87</td>
<td>32.91</td>
<td>7.76</td>
<td>32.49</td>
<td>8.1</td>
<td>0.716</td>
</tr>
<tr>
<td>8</td>
<td>16.03</td>
<td>23.22</td>
<td>0.565</td>
<td>0.655</td>
<td>45.74</td>
<td>30.89</td>
<td>32.05</td>
<td>9.40</td>
<td>27.67</td>
<td>4.6</td>
<td>0.700</td>
</tr>
<tr>
<td>9</td>
<td>17.36</td>
<td>23.75</td>
<td>0.619</td>
<td>0.627</td>
<td>59.46</td>
<td>26.83</td>
<td>32.91</td>
<td>7.76</td>
<td>32.49</td>
<td>8.1</td>
<td>0.716</td>
</tr>
<tr>
<td>10</td>
<td>16.14</td>
<td>22.64</td>
<td>0.508</td>
<td>0.581</td>
<td>52.27</td>
<td>28.64</td>
<td>32.83</td>
<td>9.99</td>
<td>28.54</td>
<td>5.4</td>
<td>0.588</td>
</tr>
<tr>
<td>11</td>
<td>17.07</td>
<td>22.15</td>
<td>0.525</td>
<td>0.583</td>
<td>51.99</td>
<td>22.85</td>
<td>33.82</td>
<td>12.82</td>
<td>30.51</td>
<td>6.7</td>
<td>0.717</td>
</tr>
<tr>
<td>12</td>
<td>21.08</td>
<td>27.41</td>
<td>0.531</td>
<td>0.565</td>
<td>65.93</td>
<td>22.99</td>
<td>34.63</td>
<td>9.85</td>
<td>32.54</td>
<td>6.7</td>
<td>0.609</td>
</tr>
<tr>
<td>Mean Value</td>
<td>15.37</td>
<td>22.23</td>
<td>0.553</td>
<td>0.592</td>
<td>49.64</td>
<td>31.43</td>
<td>30.63</td>
<td>9.38</td>
<td>28.55</td>
<td>6.0</td>
<td>0.686</td>
</tr>
</tbody>
</table>

Table 3.2 Mean values of the assessment criteria of grouped runs

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$v_1$ (km/h)</th>
<th>$v_2$ (km/h)</th>
<th>$a$ (m/s²)</th>
<th>$d$ (m/s²)</th>
<th>$c$ (s)</th>
<th>$P_r$ (%)</th>
<th>$P_a$ (%)</th>
<th>$P_c$ (%)</th>
<th>$P_d$ (%)</th>
<th>M (m/s²)</th>
<th>RMS (m/s²)</th>
<th>PKE (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLN</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(runs 1 to 6)</td>
<td>12.62</td>
<td>20.13</td>
<td>0.541</td>
<td>0.572</td>
<td>43.25</td>
<td>37.27</td>
<td>27.91</td>
<td>8.46</td>
<td>26.34</td>
<td>5.15</td>
<td>0.685</td>
<td>0.364</td>
</tr>
<tr>
<td>HKI</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(runs 7 to 12)</td>
<td>18.12</td>
<td>24.33</td>
<td>0.565</td>
<td>0.612</td>
<td>56.03</td>
<td>25.59</td>
<td>33.35</td>
<td>10.30</td>
<td>30.76</td>
<td>6.88</td>
<td>0.714</td>
<td>0.368</td>
</tr>
<tr>
<td>Mean (MV)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15.37</td>
<td>22.23</td>
<td>0.553</td>
<td>0.592</td>
<td>49.64</td>
<td>31.43</td>
<td>30.63</td>
<td>9.38</td>
<td>28.55</td>
<td>6.01</td>
<td>0.686</td>
<td>0.366</td>
</tr>
</tbody>
</table>

Table 3.3 Assessment criteria of the in used driving cycles

3.5.1 Stability of data

To assess the stability and reliability of the data, the concept of coefficient of variation is introduced. The coefficient of variation (C.V.) for a sample of values $Y_1$, 
$Y_3, \ldots, Y_n$ is defined by

$$C.V. = \frac{S}{\bar{Y}}$$ \hspace{1cm} [3.1]$$

where $S$ = Standard deviation of the sample

$\bar{Y}$ = Sample mean

This gives the standard deviation as a proportion of the mean, and it is an informative quantity. Standard deviation alone has little meaning unless it can be compared to something else. However, the C.V. values can reflect the amount of variation of the sample relative to the mean value. This is an ideal device for comparing the variation in two series of data that are measured in two different units (Ostle and Malone, 1988).

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$v_1$</th>
<th>$v_2$</th>
<th>$a$</th>
<th>$d$</th>
<th>$c$</th>
<th>$P_r$</th>
<th>$P_a$</th>
<th>$P_c$</th>
<th>$P_d$</th>
<th>$M$</th>
<th>RMS</th>
<th>PKE</th>
</tr>
</thead>
<tbody>
<tr>
<td>KLN</td>
<td>0.05</td>
<td>0.05</td>
<td>0.09</td>
<td>0.03</td>
<td>0.05</td>
<td>0.09</td>
<td>0.07</td>
<td>0.19</td>
<td>0.05</td>
<td>0.22</td>
<td>0.14</td>
<td>1.51</td>
</tr>
<tr>
<td>HKI</td>
<td>0.13</td>
<td>0.09</td>
<td>0.08</td>
<td>0.07</td>
<td>0.13</td>
<td>0.15</td>
<td>0.03</td>
<td>0.18</td>
<td>0.07</td>
<td>0.26</td>
<td>0.16</td>
<td>1.49</td>
</tr>
<tr>
<td>Mean (MV)</td>
<td>0.21</td>
<td>0.12</td>
<td>0.09</td>
<td>0.07</td>
<td>0.17</td>
<td>0.21</td>
<td>0.10</td>
<td>0.20</td>
<td>0.10</td>
<td>0.28</td>
<td>0.14</td>
<td>1.39</td>
</tr>
</tbody>
</table>

Table 3.4 Coefficient of variation (C.V.) of the test-runs

The C.V. values are shown in Table 3.4. The variations of the parameters between the test-runs are shown to be small in each of the districts, except the PKE. The variations between runs are found to be smaller in KLN than on the HKI. The C.V. values of $v_1$ and $v_2$ are less than 0.13 and less than 0.05 for the HKI and KLN runs respectively. The C.V. values for the average acceleration and deceleration are less than 0.1. The C.V. values of the proportion of different modes of operation are also
found to be less than 0.2 for both districts. The average length of driving periods and
the root mean square acceleration have C.V. values of less than 0.2. The C.V. value
of the average number of acceleration-deceleration changes within one driving
period $M$ is less than 0.3. The largest deviation among the nine assessment criteria is
the PKE, which has C.V. value as large as about 1.5. However, this variability is the
nature of on-road driving.

3.5.2 The driving characteristics in Hong Kong

The above results show characteristics of the driving pattern in the urban areas of
Hong Kong. There is a large idle proportion and an extremely small cruise
proportion. The discrepancies of the mean values drawn from the KLN runs and the
HKI runs reflect a significant difference of driving patterns in these two districts.

On the HKI, the average cycle speed $v_1$ and the average running speed $v_2$ are both
higher than those in KLN. The idle proportion for the HKI runs is significantly
smaller than that for KLN while the cruise proportion for HKI is larger. This can be
explained by the difference in the number of signalised intersections or junctions in
the two districts. About two thirds of the total number of traffic signals in the whole
territory of Hong Kong were installed in KLN. There are more than 500 signalised
intersections in KLN. The larger number of intersections tends to shorten the length
of roads between traffic signals and induces more stops to the vehicles. As a result
vehicles running in KLN are slowed down resulting in shorter cruising times, longer
driving periods, lower speeds, and increased proportions of idle, acceleration and
deceleration.
3.5.3 Comparison of driving data

In order to develop a driving cycle for Hong Kong, the test run data are first of all examined in the light of the widely adopted mandatory legislative cycles developed elsewhere (i.e. the ECE, US75 and Japanese 10-15 mode driving cycles). The comparative summary statistics employed by Kuhler and Karstens (1978) were plotted in Figure 3.4 to Figure 3.12.

For the average cycle speed $v_1$ (Figure 3.4), it appears that the ECE driving cycle corresponds closely to the combined mean value derived from all the test runs. However, those values from the other mandatory cycles are larger. The average speeds of these cycles are generally higher than 20 km/h but the average value of the current study is only 15.37 km/h.

![Average cycle speed $v_1$](image)

Figure 3.4 Average cycle speed $v_1$

The comparison for the average running speed $v_2$ (Figure 3.5) is almost the same as that of $v_1$. The only difference is that $v_2$ has a smaller variation than $v_1$ which can be explained by the large variation of the idle proportion (Figure 3.9). The coefficients
of variation of $v_1$ and $v_2$ are 0.21 and 0.12 respectively.

Figure 3.5  Average running speed $v_2$

For the average acceleration and deceleration (Figure 3.6 and Figure 3.7), the values from individual runs are generally smaller than those of the mandatory cycles. It is shown that the Japanese 10-15 mode driving cycle agrees well with the mean values of the Hong Kong cycle.

Figure 3.6  Average acceleration of all acceleration phases $a$
Figure 3.7  Average deceleration of all deceleration phases $d$

The mean length of driving periods (Figure 3.8) of the ECE driving cycle is close to the local mean value. Nevertheless, the other cycles are shown to have greater values than the local mean value. The US 75 cycle has a mean length of driving period as large as about 70 seconds while the mean value for Hong Kong is about 50 seconds.

Figure 3.8  Mean length of driving period $c$

Regarding the relative time proportions of different driving modes (Figure 3.9), the idle proportion of the ECE and Japanese 10-15 mode driving cycles are closer to the mean value of the Hong Kong cycle. However, the US 75 cycle has a small idle
proportion of about 20 percent while the mean value of the Hong Kong cycle is about 30 percent. The duration of acceleration and deceleration modes are more or less the same for all mandatory cycles with the exception of the ECE cycle. The proportions of acceleration and deceleration of the ECE cycle are as small as 18.5 percent while those of the local mean value are about 30 percent. The cruise proportion of the mean value for Hong Kong is significantly smaller than that for the mandatory cycles.

Figure 3.9 Time proportions of each operating mode

Concerning the average number of acceleration-deceleration changes within one driving period M (Figure 3.10), the US driving cycles agree very well with the mean value of Hong Kong. As M expresses irregularity of speed, the modal cycles (i.e. ECE cycle and Japanese cycle) are shown to have smaller values than those composed of real driving sequences (i.e. US 75 cycles and the Hong Kong mean value).
Figure 3.10 Average number of acceleration-deceleration changes (and vice versa) within one driving period ($M$)

The root mean square accelerations of the ECE and US 75 cycles are shown to be larger than that of the local value (Figure 3.11). In contrast, the Japan 10-15 mode cycle has a smaller value than the local value.

Figure 3.11 RMS acceleration ($RMS$)

For the positive acceleration kinetic energy (Figure 3.12), the mandatory cycles are generally larger than the value derived from the test runs. It is shown that the US 75 driving cycle has a value close to the derived value.
When comparing the Hong Kong assessment parameters to those of the mandatory driving cycles, it is found that none of the above mandatory legislative cycles could satisfactorily describe the Hong Kong data. This implies that the urban areas of Hong Kong have their own driving characteristics. A new driving cycle is therefore developed.

3.6 Development of the Driving Cycle

3.6.1 Development of the cycle

The most difficult task in developing a driving cycle is the condensation of the large amount of speed data into a cycle of reasonable duration. Some of the synthesis techniques have been described and discussed in earlier sections. Many of the methods (Kruse and Huls, 1973; Kent, et al, 1978; Watson, et al, 1982) try to randomly select parts of the speed-time segments from the test-run data so that the summary statistics meet the target statistics. Therefore, in synthesising the Hong
Kong's speed-time data, a similar random selection process has been developed. The method employed is briefly described below.

First of all, the mean values of the assessment criteria derived from the test runs were set to be the target summary statistics. The driving periods bound by idling times were identified for each test run. Twenty driving periods were then selected randomly to form a cycle. The assessment parameters for these twenty driving periods were then calculated. If the values were different from the mean values by less than 5 per cent, that cycle was accepted. Otherwise, another twenty driving periods had to be sampled again and the exercise repeated. Since the mean length of the driving periods is about 1 minute, a composition of 20 driving periods would result in a cycle of about 20 minutes.

The above procedures were applied to the test-runs in the two districts, KLN and HKI. It was found that a speed-time trace could be synthesised which closely matched summary statistics with the target. It shows that it is possible to generate a synthetic cycle by this method.

Clearly, the synthesised cycle obtained by this method is not unique. We can generate a number of these cycles and select the best one. Ten cycles were therefore generated. The assessment parameters of these ten cycles and the relative percentage difference with the local mean value are shown in Table 3.5 and Table 3.6 respectively.
Table 3.5 Assessment criteria of synthesised cycles

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$v_1$ (km/h)</th>
<th>$v_2$ (km/h)</th>
<th>$a$ (m/s^2)</th>
<th>$d$ (s)</th>
<th>$c$ (%)</th>
<th>$P_t$ (%)</th>
<th>$P_a$ (%)</th>
<th>$P_e$ (%)</th>
<th>$P_d$ (%)</th>
<th>$M$</th>
<th>RMS (m/s^2)</th>
<th>PKE (m/s^2)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MV</td>
<td>15.37</td>
<td>22.23</td>
<td>0.553</td>
<td>0.592</td>
<td>49.64</td>
<td>31.43</td>
<td>30.63</td>
<td>9.38</td>
<td>28.55</td>
<td>6.01</td>
<td>0.686</td>
<td>0.366</td>
</tr>
<tr>
<td>Syn1</td>
<td>15.90</td>
<td>22.01</td>
<td>0.544</td>
<td>0.591</td>
<td>50.71</td>
<td>30.96</td>
<td>31.28</td>
<td>9.27</td>
<td>28.49</td>
<td>5.80</td>
<td>0.696</td>
<td>0.377</td>
</tr>
<tr>
<td>Syn2</td>
<td>15.86</td>
<td>22.36</td>
<td>0.562</td>
<td>0.587</td>
<td>50.11</td>
<td>31.71</td>
<td>29.98</td>
<td>9.80</td>
<td>28.51</td>
<td>5.90</td>
<td>0.682</td>
<td>0.373</td>
</tr>
<tr>
<td>Syn3</td>
<td>15.48</td>
<td>21.66</td>
<td>0.551</td>
<td>0.585</td>
<td>50.79</td>
<td>31.44</td>
<td>30.87</td>
<td>9.05</td>
<td>28.64</td>
<td>5.90</td>
<td>0.666</td>
<td>0.371</td>
</tr>
<tr>
<td>Syn4</td>
<td>15.27</td>
<td>21.83</td>
<td>0.553</td>
<td>0.595</td>
<td>50.36</td>
<td>32.80</td>
<td>29.94</td>
<td>9.21</td>
<td>28.05</td>
<td>5.80</td>
<td>0.688</td>
<td>0.354</td>
</tr>
<tr>
<td>Syn5</td>
<td>15.03</td>
<td>21.28</td>
<td>0.564</td>
<td>0.588</td>
<td>47.53</td>
<td>31.68</td>
<td>30.26</td>
<td>9.15</td>
<td>28.92</td>
<td>5.80</td>
<td>0.668</td>
<td>0.371</td>
</tr>
<tr>
<td>Syn6</td>
<td>15.97</td>
<td>22.51</td>
<td>0.580</td>
<td>0.586</td>
<td>49.68</td>
<td>31.34</td>
<td>29.77</td>
<td>9.47</td>
<td>29.42</td>
<td>6.20</td>
<td>0.706</td>
<td>0.370</td>
</tr>
<tr>
<td>Syn7</td>
<td>15.79</td>
<td>22.52</td>
<td>0.555</td>
<td>0.590</td>
<td>50.39</td>
<td>32.48</td>
<td>30.07</td>
<td>9.10</td>
<td>28.22</td>
<td>6.00</td>
<td>0.711</td>
<td>0.349</td>
</tr>
<tr>
<td>Syn8</td>
<td>15.71</td>
<td>22.70</td>
<td>0.548</td>
<td>0.594</td>
<td>49.35</td>
<td>32.64</td>
<td>30.48</td>
<td>8.93</td>
<td>27.96</td>
<td>5.80</td>
<td>0.657</td>
<td>0.353</td>
</tr>
<tr>
<td>Syn9</td>
<td>15.52</td>
<td>21.40</td>
<td>0.570</td>
<td>0.598</td>
<td>49.00</td>
<td>30.53</td>
<td>30.87</td>
<td>9.22</td>
<td>29.39</td>
<td>5.80</td>
<td>0.676</td>
<td>0.382</td>
</tr>
<tr>
<td>Syn10</td>
<td>15.87</td>
<td>22.40</td>
<td>0.551</td>
<td>0.567</td>
<td>49.76</td>
<td>31.8</td>
<td>29.95</td>
<td>9.48</td>
<td>28.77</td>
<td>6.20</td>
<td>0.703</td>
<td>0.358</td>
</tr>
</tbody>
</table>

Table 3.6 Relative percentage difference with target assessment criteria

<table>
<thead>
<tr>
<th>Criterion</th>
<th>$v_1$</th>
<th>$v_2$</th>
<th>$a$</th>
<th>$d$</th>
<th>$c$</th>
<th>$P_t$</th>
<th>$P_a$</th>
<th>$P_e$</th>
<th>$P_d$</th>
<th>$M$</th>
<th>RMS</th>
<th>PKE</th>
<th>Error (E)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relative percentage difference with MV (%)</td>
<td>Syn1</td>
<td>3.45</td>
<td>0.99</td>
<td>1.63</td>
<td>0.17</td>
<td>2.16</td>
<td>1.50</td>
<td>2.12</td>
<td>1.17</td>
<td>0.21</td>
<td>3.49</td>
<td>1.46</td>
<td>3.01</td>
</tr>
<tr>
<td>Syn2</td>
<td>3.19</td>
<td>0.58</td>
<td>1.63</td>
<td>0.84</td>
<td>0.95</td>
<td>0.89</td>
<td>2.12</td>
<td>4.48</td>
<td>0.14</td>
<td>1.83</td>
<td>0.58</td>
<td>1.91</td>
<td>19.15</td>
</tr>
<tr>
<td>Syn3</td>
<td>0.72</td>
<td>2.56</td>
<td>0.36</td>
<td>1.18</td>
<td>2.32</td>
<td>0.03</td>
<td>0.78</td>
<td>3.52</td>
<td>0.32</td>
<td>1.83</td>
<td>2.92</td>
<td>1.37</td>
<td>17.90</td>
</tr>
<tr>
<td>Syn4</td>
<td>0.65</td>
<td>1.80</td>
<td>0.00</td>
<td>0.51</td>
<td>1.45</td>
<td>4.36</td>
<td>2.25</td>
<td>1.81</td>
<td>1.75</td>
<td>3.49</td>
<td>0.29</td>
<td>3.28</td>
<td>21.65</td>
</tr>
<tr>
<td>Syn5</td>
<td>2.21</td>
<td>1.99</td>
<td>0.68</td>
<td>4.25</td>
<td>0.80</td>
<td>1.21</td>
<td>2.45</td>
<td>1.30</td>
<td>3.49</td>
<td>2.62</td>
<td>1.37</td>
<td>26.64</td>
<td></td>
</tr>
<tr>
<td>Syn6</td>
<td>3.90</td>
<td>1.26</td>
<td>0.88</td>
<td>0.10</td>
<td>0.08</td>
<td>0.29</td>
<td>2.81</td>
<td>0.96</td>
<td>3.05</td>
<td>3.16</td>
<td>2.92</td>
<td>1.09</td>
<td>25.41</td>
</tr>
<tr>
<td>Syn7</td>
<td>2.73</td>
<td>1.30</td>
<td>0.36</td>
<td>0.34</td>
<td>1.51</td>
<td>3.34</td>
<td>1.83</td>
<td>2.99</td>
<td>1.16</td>
<td>0.17</td>
<td>3.64</td>
<td>4.64</td>
<td>24.01</td>
</tr>
<tr>
<td>Syn8</td>
<td>2.21</td>
<td>0.90</td>
<td>0.34</td>
<td>0.58</td>
<td>3.85</td>
<td>4.49</td>
<td>0.49</td>
<td>0.80</td>
<td>2.07</td>
<td>3.49</td>
<td>4.23</td>
<td>3.55</td>
<td>28.63</td>
</tr>
<tr>
<td>Syn9</td>
<td>0.98</td>
<td>3.73</td>
<td>3.07</td>
<td>1.01</td>
<td>1.29</td>
<td>2.86</td>
<td>0.78</td>
<td>1.71</td>
<td>2.94</td>
<td>3.49</td>
<td>1.46</td>
<td>4.37</td>
<td>27.71</td>
</tr>
<tr>
<td>Syn10</td>
<td>3.25</td>
<td>0.76</td>
<td>0.36</td>
<td>4.22</td>
<td>0.24</td>
<td>1.18</td>
<td>2.22</td>
<td>1.07</td>
<td>0.77</td>
<td>3.16</td>
<td>2.48</td>
<td>2.19</td>
<td>21.90</td>
</tr>
</tbody>
</table>

In order to choose the "best cycle" among the ten generated synthetic cycles, an error function is introduced as follows:

$$E = \sum_{j} e_j$$  \[3.2\]

where $e_j =$ relative percentage difference of the parameter $j$ with the target statistics

It is the total errors of each of the synthesised cycles, which are shown in Table 3.6.

It is shown that Syn3 has the minimum error. Thus Syn3 is chosen to be the "best
cycle" out of the ten. The resulting cycle is shown in Figure 3.13.

![Graph showing speed vs. time for Hong Kong driving cycle](image)

Figure 3.13 Synthesised driving cycle for Hong Kong

3.6.2 **Comparison with other cycles**

Table 3.7 compares some of the assessment parameters for various driving cycles, including the local mean value, the synthesised cycle for Hong Kong, the US 75 cycle, the Perth cycle, the Melbourne Peak cycle (MPC), the Sydney cycle and the Improved Europe cycle (IEC) proposed by Kuhler and Karstens (1978).

It is shown that the synthesised cycle for Hong Kong has significant difference from the other driving cycles. First of all, the average cycle speed, which is one of the most important parameters of the synthesised cycle, is far smaller than the others. The closest one is the IEC, which has an average cycle speed 13.44 km/h higher than the synthesised cycle. The synthesised cycle for Hong Kong has a relatively longer duration (1471 seconds) but a shorter trip length (6.33 km) than the other cycles. The extremely long idle proportion for the synthesised cycle is another impetus for the long duration and short trip length. The idle proportion is shown to be far greater
than the others. When attention is drawn to the average acceleration and
deceleration, the synthesised cycle exhibits smaller average acceleration and
deceleration rates than the others. Concerning the root mean square acceleration and
PKE, the other cycles are generally larger than the synthesised cycle.

<table>
<thead>
<tr>
<th></th>
<th>Length (km)</th>
<th>Duration (s)</th>
<th>Average cycle speed (km/h)</th>
<th>Average acceleration (m/s²)</th>
<th>Average deceleration (m/s²)</th>
<th>Idle proportion (%)</th>
<th>RM acceleration (m/s²)</th>
<th>PKE (m/s²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Syn. Cycle</td>
<td>6.33</td>
<td>1471</td>
<td>15.48</td>
<td>0.551</td>
<td>0.585</td>
<td>31.44</td>
<td>0.66</td>
<td>0.371</td>
</tr>
<tr>
<td>US 75</td>
<td>17.77</td>
<td>1876</td>
<td>34.1</td>
<td>0.61</td>
<td>0.71</td>
<td>18.0</td>
<td>0.75</td>
<td>0.380</td>
</tr>
<tr>
<td>Perth Cycle</td>
<td>14.2</td>
<td>1192</td>
<td>43.1</td>
<td>0.67</td>
<td>0.72</td>
<td>9.6</td>
<td>0.82</td>
<td>0.420</td>
</tr>
<tr>
<td>MPC</td>
<td>8.3</td>
<td>980</td>
<td>30.4</td>
<td>0.70</td>
<td>0.66</td>
<td>22.7</td>
<td>0.72</td>
<td>0.520</td>
</tr>
<tr>
<td>Sydney Cycle</td>
<td>5.9</td>
<td>637</td>
<td>33.6</td>
<td>0.78</td>
<td>0.76</td>
<td>18.2</td>
<td>0.79</td>
<td>0.520</td>
</tr>
<tr>
<td>IEC*</td>
<td>7.3</td>
<td>890</td>
<td>29.4</td>
<td>0.72</td>
<td>0.73</td>
<td>18.7</td>
<td>0.78</td>
<td>0.433</td>
</tr>
</tbody>
</table>

*Improved Europe Cycle proposed by Kuhler and Karsten (1978)

Table 3.7 Comparison of Synthesised cycle and other driving cycles

The above comparison reflects that driving in urban districts in Hong Kong
experiences longer idle times and lower average cycle speed. Hence, in general,
there will be higher exhaust emissions, especially for CO and HC, and higher fuel
consumption.

3.7 Concluding Remarks

In this chapter, nine commonly used assessment criteria parameters have been
employed to assess the driving characteristics in the urban areas of Hong Kong.
They are the average speed, average running speed, average acceleration and
deceleration rates, mean length of driving periods, the average number of
acceleration-deceleration changes (or vice versa) within one driving period, the
positive acceleration kinetic energy, root-mean-square acceleration and the time
proportions of the four vehicle operating modes (i.e. idling, accelerating, cruising and decelerating). The local values of these parameters were compared with those of the well-known driving cycles for Europe, Australia, Japan and USA. It was found that none of the driving cycles could satisfactorily resemble the Hong Kong driving characteristics. Therefore a standard driving cycle, which characterised the driving pattern in the urban areas of Hong Kong, was developed.

The driving cycle for Hong Kong indicated that driving in the urban areas of Hong Kong would experience the following characteristics:

1. Low average speed
2. Long idle times
3. Extremely small cruising times

In the next chapter, emphasis will be placed on the description of a series of on-road emission and fuel consumption testing, and the development of the ON-ROAD emission and fuel consumption prediction model.
CHAPTER 4

ON-ROAD EMISSION AND FUEL CONSUMPTION MODEL

4.1 Introduction

In this chapter, a series of on-road emission and fuel consumption testing as well as the development of the emission and fuel consumption model is described.

The on-road emission and fuel consumption testing procedures are outlined in detail. Discussions on the derived emission and fuel consumption factors and the effect of various variables (i.e. vehicle speed and driving modes) are also included. On the basis of the acquired data, the development of a mathematical model for estimation of instantaneous vehicle emissions and fuel consumption is described. The overall objective of the model is to reflect the impact of vehicle operating modes on tailpipe emissions and fuel consumption. The model developed is evaluated by comparing measured and predicted values.

4.2 Data Collection Methods

Conventionally, emission testings were performed by driving the vehicle engine through standard driving cycles in laboratory on chassis dynamometers. The merit of this method is simplicity but the test conditions are restrictive. These driving cycles may not represent the actual on-road driving conditions. A study found that fuel consumption and exhaust emission depended on whether they were measured at steady speed or on-road driving pattern (Joumard, 1995). It was found that emissions
measured on actual speed driving cycles were generally higher than those measured on the standard driving cycles. Even for actual speed driving cycles, the engine operating conditions do have significant differences with those of the actual on road driving tests (St. Denis, et. al., 1994; Rapone, et. al., 1995).

In fact, actual on road driving is more complex than driving cycle simulations. There are large variations in operating conditions during real life driving. Some factors are difficult to simulate on test beds (Foss, 1992; Cheung, et. al., 1999). Therefore on road emission and fuel consumption, as well as engine operating condition measurements, are necessary. However, emission data directly measured from the tailpipe of on road driving motor vehicles are limited and relatively few vehicles have been tested for each study (Cheung, et. al., 1999). St. Denis et. al. (1994) tested a petrol van in California. They found that the data obtained from on road test have significant differences to those obtained from a FTP driving cycle. Cicero-Fernandez et. al. (1997) examined the grade effect by a single test vehicle driving on hills. Both these studies have used a limited number of vehicles for their on-road testing. This limited the scope of their studies. Several other variables of interest for vehicle operating parameters could not be assessed.

In this research, emissions were measured directly from the tailpipe of four test vehicles under actual on road driving conditions. The test vehicles were chosen to represent typical traffic mix in the urban areas of Hong Kong, which enabled investigation of more variables of interest. Although only one vehicle from each vehicle category was tested, it is believed that the study would produce indicative results for actual on road vehicle emission behaviour of contemporary driving
patterns in urban areas, and the ways in which such behaviour differs from mandated certification procedures. The study can also produce supplementary results to laboratory tests.

4.3 On-Road Emission and Fuel Consumption Testing

In order to capture different on-road driving patterns in the urban areas, the test vehicles were driven in typical urban districts, namely MongKok and Central, located in KLN and on HKI respectively. The vehicle speed in these two districts seldom exceeds 50 km/h. Unlike the on-road testing for measuring vehicle speed in Chapter 3, there was no fixed route for emission testing in this experiment.

4.3.1 Test vehicle specification

Four vehicles with different types, sizes and weights were employed in the collection of instantaneous speed, emissions and fuel consumption data. The specifications of these test vehicles are shown in Table 4.1. The diesel van was the one described in Chapter 3 to perform vehicle speed measurement.

These four test vehicles were chosen to represent the typical traffic mix in Hong Kong. The Hong Kong Annual Traffic Census (1997) stated that among all the vehicles travelling in the urban areas of HKI during peak hours, 50.6% were passenger cars, 31.4% were light duty vans and diesel taxis, as well as 7.7% were buses. In the urban areas of KLN, the peak hour traffic mix was composed of 41.0% passenger cars, 27.4% light duty vans and diesel taxis as well as 6.5% buses.
Although buses occupy only a small proportion, they are a major source of vehicular particulate emissions.

<table>
<thead>
<tr>
<th>Gear mode</th>
<th>Passenger Car</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Double Decked Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle type</td>
<td>automatic transmission</td>
<td>Manual transmission</td>
<td>manual transmission</td>
<td>automatic transmission</td>
</tr>
<tr>
<td>Manufacturer</td>
<td>Sunny, 4-seats</td>
<td>Nissan</td>
<td>Urvan, 9-seats</td>
<td>Toyota</td>
</tr>
<tr>
<td>Model year</td>
<td>1997</td>
<td>1990</td>
<td>1990</td>
<td>Gardner</td>
</tr>
<tr>
<td>Weight (kg)</td>
<td>2040</td>
<td>2750</td>
<td>2800</td>
<td>10000</td>
</tr>
<tr>
<td>Max. power (kw)</td>
<td>81</td>
<td>64</td>
<td>60</td>
<td>150</td>
</tr>
<tr>
<td>Engine type</td>
<td>carburettor</td>
<td>injection</td>
<td>injection</td>
<td>injection</td>
</tr>
<tr>
<td>Bore x Stroke (mm²)</td>
<td>73.6 x 88.0</td>
<td>85 x 86</td>
<td>96 x 96</td>
<td>120.65 x 152.4</td>
</tr>
<tr>
<td>Engine capacity (L)</td>
<td>1.498</td>
<td>1.952</td>
<td>2.779</td>
<td>10.45</td>
</tr>
<tr>
<td>Cylinder number</td>
<td>4-cyl., OHC, in-line</td>
<td>4-cyl., in-line</td>
<td>4-cyl., DOHC, in-line</td>
<td>6-cyl., in-line</td>
</tr>
<tr>
<td>Fuel type</td>
<td>petrol</td>
<td>petrol</td>
<td>diesel</td>
<td>Diesel</td>
</tr>
<tr>
<td>Catalytic converter</td>
<td>with</td>
<td>without</td>
<td>without</td>
<td>Without</td>
</tr>
</tbody>
</table>

Table 4.1 Specifications of the test vehicles

4.3.2 Test routes

The test vehicles were driven by professional drivers. The passenger car, petrol van and diesel van were driven by the same driver and the double decker bus was driven by a professional bus driver. The main purpose of the investigation was to study the emission from and fuel consumption of motor vehicles travelling in the urban area of Hong Kong. The driving environments for the test vehicles were basically the same. The drivers were instructed to drive through the congested districts mentioned above. A single test runs was performed for the double decked bus while two test runs were performed for the other three test vehicles. The reason for not choosing a fixed route is that a fixed route may not necessarily reflect the whole picture of urban driving. However, changing routes for each test run allows capture of different driving conditions in the prescribed urban districts.
4.3.3 Experimental set-up

The arrangement of the on-board measurement system is outlined in Figure 4.1. The gas filter connected with the gas analyser is used to filter out water vapour and particulates in diesel vehicles. Otherwise, the gas analyser could easily be blocked by the particulate emissions.

![Diagram of on-board measurement system]

**Figure 4.1** Arrangement of the on-board measurement system

Engine speed and the transmission shaft rotational speed were measured as described in Chapter 3. An Econotest fuel flow meter was connected to the fuel supply pipe to measure the instantaneous fuel consumption. Instantaneous fuel consumption rate could then be obtained by simple calculations. The error and response times of the fuel flow meter were less than 1 ml/s and 0.1 second respectively.

Instantaneous concentrations of \( CO, CO_2, NO_x, HC \) and \( O_2 \) were measured by a
Flux-2000 five-gas analyser. In the gas analyser, the CO, CO₂ and HC measurements were recorded using the Non-Dispersive Infrared (NDIR) method while the O₂ and NOₓ measurements were taped using electrochemical transducers. The exhaust gas analyser was calibrated with standard gases before each of the test runs. The error and response times of the gas analyser were less than 2 percent and 0.5 second respectively for all the gas pollutants.

According to the HKEPD, diesel vehicles are responsible for an absolute majority of the vehicular particulate emissions, so particulate emission measurements in terms of smoke intensity were performed in particular for the diesel vehicles. Instantaneous smoke intensity from diesel vehicles was collected by a LUCAS Hartridge smoke meter. The analogue smoke signal in DC volt from the smoke meter was transmitted to the computer through the PICO data acquisition system. The smoke meter was calibrated before performing the test runs. The error and response times of the smoke meter were less than 2 percent and 0.1 second respectively.

The fuel consumption rate and gas emission concentrations were related to the speed measurement. However, there exists a time lag between the fuel meter, gas analyser and speed measurement. An experiment was conducted to determine the time lag under various engine speeds by the method of suddenly accelerating and one-cylinder-misfire. The time lag of the instrument had previously been calibrated and was taken to be 5 seconds in the data analysis.

The data were collected during the morning and off peak periods, ranged from 8:00 a.m. to 11:00 a.m. and from 2:00 p.m. to 5:00 p.m. respectively, in the months from
March to June 1998 during calm and dry weather conditions.

4.4 Data Handling Method

Data obtained for each test vehicle were grouped. Thus, there is a total of 4 sets of instantaneous speed, emissions and fuel consumption data by vehicle types, which are the light duty diesel van, the petrol passenger car, the light duty petrol van and the double decked public bus. The instantaneous pollutant concentrations collected are converted to instantaneous mass emission rates (g/s) by the following equations

Petrol vehicles:

\[
\text{CO}_{g/s} = \left( \dot{m}_{\text{air}} + \dot{m}_{\text{fuel}} \right) \times \frac{M_{\text{CO}}}{M_{\text{exhaust}}} \times \text{CO}_\text{ppm} \times 10^{-2} \quad [4.1]
\]

\[
\text{HC}_{g/s} = \left( \dot{m}_{\text{air}} + \dot{m}_{\text{fuel}} \right) \times \frac{M_{\text{HC}}}{M_{\text{exhaust}}} \times \text{HC}_\text{ppm} \times 10^{-6} \quad [4.2]
\]

\[
\text{NOx}_{g/s} = \left( \dot{m}_{\text{air}} + \dot{m}_{\text{fuel}} \right) \times \frac{M_{\text{NOx}}}{M_{\text{exhaust}}} \times \text{NOx}_\text{ppm} \times 10^{-6} \quad [4.3]
\]

where

\[
M_{\text{CO}} = \text{Molecular weight of CO} = 28.01
\]

\[
M_{\text{HC}} = \text{Molecular weight of the exhaust hydrocarbons (based on 1 C atom)}
= 12.011 + 1.008y + 15.999z
\]

\[
y = \text{H/C atomic ratio in the fuel (assuming the exhaust HC = fuel)}
\]

\[
z = \text{O/C atomic ratio in the fuel (assuming the exhaust HC = fuel)}
\]

\[
M_{\text{NOx}} = \text{Molecular weight of NOx}
= \frac{((14.007 + 15.999) + (14.0078 + 15.999 \times 2) \times 0.1)}{1.1} = 31.46
\]
\[ M_{\text{exhaust}} = \text{Molecular weight of the exhaust} \]

\[ = (13.88 \times HC_{\text{ppm}} \times 10^{-6}) + (28.01 \times CO_{\%} \times 10^{-2}) + (44.01 \times CO_{2\%} \times 10^{-2}) \]

\[ + (46.01 \times NOx_{\text{ppm}} \times 10^{-6}) + (32.00 \times O_{2\%} \times 10^{-2}) \]

\[ + (2.016 \times H_{2\%} \times 10^{-2}) + 18.01 \times (1-K) \]

\[ + \left[ 100 - \frac{HC_{\text{ppm}}}{10^4} - CO_{\%} - CO_{2\%} - \frac{NOx_{\text{ppm}}}{10^4} - O_{2\%} - (H_{2\%}) - 100 \times (1-K) \right] \times \frac{28.01}{100} \]

\[ K = [1 + 0.005 \times (CO_{\%} + CO_{2\%}) \times y - 0.01 \times H_{2\%}]^{-1} \]

\[ H_{2\%} = \frac{0.5 \times y \times CO_{\%} \times (CO_{\%} + CO_{2\%})}{CO_{\%} + 3 \times CO_{2\%}} \]

**Diesel vehicles:**

\[ CO_{g/s} = \frac{(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}) \times P_{\text{ambient}} \times M_{CO} \times CO_{\%} \times 10^{-2}}{T_{\text{ambient}} \times R_u} \]  \[ [4.4] \]

\[ HC_{g/s} = \frac{(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}) \times P_{\text{ambient}} \times M_{HC} \times HC_{\text{ppm}} \times 10^{-6}}{T_{\text{ambient}} \times R_u} \]  \[ [4.5] \]

\[ NOx_{g/s} = \frac{(\dot{m}_{\text{air}} + \dot{m}_{\text{fuel}}) \times P_{\text{ambient}} \times M_{NOx} \times NOx_{\text{ppm}} \times 10^{-6}}{T_{\text{ambient}} \times R_u} \]  \[ [4.6] \]

where

\[ M_{CO} = \text{Molecular weight of CO} = 28.01 \]

\[ M_{HC} = \text{Molecular weight of the exhaust hydrocarbons (based on 1 C atom)} \]

\[ = 12.011 + 1.008y + 15.999z \]

\[ y = \text{H/C atomic ratio in the fuel (assuming the exhaust HC = fuel)} \]

\[ z = \text{O/C atomic ratio in the fuel (assuming the exhaust HC = fuel)} \]

\[ M_{NOx} = \text{Molecular weight of NOx} \]

\[ = [(14.007 + 15.999) + (14.0078 + 15.999 \times 2) \times 0.1] / 1.1 = 31.46 \]
\[ P_{\text{ambient}} = \text{Ambient air pressure} \]
\[ T_{\text{ambient}} = \text{Ambient air temperature} = 300 \text{ K} \]
\[ R_u = \text{Universal gas constant} = 8314.2 \text{ J/mol-K} \]

The instantaneous emission rates of CO, HC and NO\textsubscript{x} of the vehicles in terms of gram per second were calculated by standard methods described in the SAE handbook (SAE, 1996, J1088). Equation 4.1 to Equation 4.3 are for petrol vehicles while Equation 4.4 to Equation 4.6 are for diesel vehicles. The mass concentrations of particulate emissions from diesel vehicles were obtained from the smoke intensity based on a conversion chart in the SAE handbook (SAE, 1996, J255). Accordingly, the mass emission rate of particulates can be calculated when the instantaneous engine speed and its swept volume are known. These data form the basis for emission and fuel consumption analysis of this study.

Vehicular emissions can be expressed in terms of gram of pollutants emitted per unit time, per unit distance travelled or per unit fuel consumed. Accordingly, three terms are defined to describe the vehicular emission and fuel consumption.

- Emission, Fuel Consumption Rate \([g/s]\)
- Emission, Fuel Consumption Factor \([g/km]\)
- Emission Index \([g/(kg\ fuel)]\)

4.5 **Empirical Results and Analysis**

It is a common practice to describe emissions and fuel consumption from motor
vehicles by an average value over a trip which is then parameterised in terms of the corresponding average speed. In fact, on-road driving is a random combination of the four standard driving modes. It is of great interest to characterise the emissions and fuel consumption behaviour at different driving modes. In this section, two approaches will be used to analyse the emissions and fuel consumption data, namely global and modal analysis.

4.5.1 Description of the data sample

Characteristics of the 4 sets of data for each test vehicle are shown in Table 4.2. It can be seen that the average speeds are generally higher than those of the Hong Kong driving cycle.

<table>
<thead>
<tr>
<th></th>
<th>Duration (s)</th>
<th>Average Speed (km/h)</th>
<th>Total Distance (km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>2613</td>
<td>19.47</td>
<td>14.13</td>
</tr>
<tr>
<td>Petrol Van</td>
<td>6500</td>
<td>23.85</td>
<td>43.06</td>
</tr>
<tr>
<td>Diesel Van</td>
<td>3133</td>
<td>24.91</td>
<td>21.68</td>
</tr>
<tr>
<td>Diesel Bus</td>
<td>1690</td>
<td>15.32</td>
<td>7.19</td>
</tr>
</tbody>
</table>

Table 4.2 Characteristics of test runs

The speed distributions for each vehicle during the test runs are shown in Figure 4.2. The bars are the proportions of each speed class while the lines represent the cumulative proportions. It can be seen that for over 90% of the time, the test vehicles are driving at speed lower than 50 km/h. It is a typical driving phenomenon in urban areas. The petrol van spent about 30% of the time on idling, which is the largest among the four test vehicles. However, very few data were recorded at the speed ranging from 0 km/h to 10 km/h. It indicates that the petrol van performed many
hard accelerations and decelerations during the test runs. The passenger car and the double decker bus spent most of the time driving at lower speed ranges. For over 90% of the time, the double decker bus was driving at a speed lower than 30 km/h. For the diesel van, the driving time spread through the speed range below 50 km/h with the largest proportion found in the speed range of 10 km/h to 15 km/h.

Figure 4.2 Speed distributions of test vehicles

4.5.2 Global analysis

4.5.2.1 Average emission and fuel consumption

In general, average vehicular emissions and fuel consumption over a trip were expressed in distance based (g/km) units or fuel based [g/(kg fuel)] units. Average emission, fuel consumption factors and indices of the vehicles were calculated by Equations 4.7 to 4.9. All the factors and indices were calculated over the whole data sample for each vehicle.
Average Emission Factor \([g/\text{km}]\) = \(\frac{3600 \times \sum e[\text{g/s}]}{\sum v[\text{km/h}]}\) \[4.7\]

Average Fuel Consumption Factor \([g/\text{km}]\) = \(\frac{3600 \times \sum f[\text{g/s}]}{\sum v[\text{km/h}]}\) \[4.8\]

Average Emission Index \([g/(\text{kg fuel})]\) = \(\frac{1000 \times \sum e[\text{g/s}]}{\sum f[\text{g/s}]}\) \[4.9\]

where \(e\) is the instantaneous emission rate of the subject gas pollutant; \(f\) is the instantaneous fuel consumption rate; \(v\) is the instantaneous vehicle speed.

<table>
<thead>
<tr>
<th></th>
<th>Passenger Car</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>CO</td>
<td>g/\text{km}</td>
<td>14.83</td>
<td>21.02</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td>g/(\text{kg fuel})</td>
<td>210.10</td>
<td>294.84</td>
<td>47.67</td>
</tr>
<tr>
<td>HC</td>
<td>g/\text{km}</td>
<td>0.99</td>
<td>2.79</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>g/(\text{kg fuel})</td>
<td>14.10</td>
<td>39.10</td>
<td>10.75</td>
</tr>
<tr>
<td>NO\textsubscript{x}</td>
<td>g/\text{km}</td>
<td>1.03</td>
<td>2.64</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>g/(\text{kg fuel})</td>
<td>14.62</td>
<td>37.00</td>
<td>15.39</td>
</tr>
<tr>
<td>Particulate</td>
<td>g/\text{km}</td>
<td>--</td>
<td>--</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>g/(\text{kg fuel})</td>
<td>--</td>
<td>--</td>
<td>1.30</td>
</tr>
<tr>
<td>Fuel</td>
<td>g/\text{km}</td>
<td>70.59</td>
<td>71.30</td>
<td>78.03</td>
</tr>
</tbody>
</table>

Table 4.3 Average emission factors and indices of each vehicle

The average emission, fuel consumption factors and indices of the test vehicles are shown in Table 4.3. The double decker bus is shown to have the largest emission factors and indices, probably because it is the oldest and has the largest size, engine capacity as well as the highest maximum power output. After the bus, the highest CO emissions are found in the petrol van, and followed by the petrol passenger car. The smaller size and engine capacity of the passenger car may contribute to
relatively low emission level, but the major factor should be the presence of a catalytic converter in the petrol passenger car. The catalytic converter can oxidise the majority of the hydrocarbons to carbon dioxides and water. However, the emissions and fuel consumption of the catalysed passenger car are still higher than expected, probably due to the low speed and irregularity of driving in Hong Kong (Tong, et. al., 1999), which restricted the optimal performance of the catalytic converter. Notably, the maximum power output of the catalysed passenger car is higher than that of the petrol van.

CO and HC emissions from the diesel van are lower than those from the petrol vehicles. NOx emissions from the petrol van, which does not have a catalytic converter, are higher than that of the diesel van. However, the petrol passenger car, which was equipped with a catalytic converter, emits less NOx than the diesel van. In general, diesel engines have fuel economy advantage over petrol engines, owing to efficient combustion and, as a result, diesel engines emit less CO, HC and NOx (Saleh and Nelson, 1998). However, when the engines were installed in vehicles and used practically, emissions and fuel consumption would be governed by the vehicle operating variables and the driving conditions, such as engine capacity, vehicle speed, pay load, road grades (i.e. uphill or downhill). It can be observed that the fuel consumption factor of the diesel van is larger than that of the petrol vehicles. This is probably because of the larger engine capacity of the diesel vehicle.

Table 4.4 shows the measured average emission factors of the four test vehicles and the fleet average emission factors for the corresponding type of vehicle in Hong Kong. The fleet average emission factors, which represent the average emission level
of each type of vehicles in Hong Kong, are provided by the HKEPD. However, the vehicle fleet used with HKEPD classifications is not the same as that shown in Table 4.4. The diesel and petrol vans were categorised by the HKEPD as a public light bus and a passenger van, respectively. It is understood that a significant proportion of passenger vans is in fact diesel vehicles.

<table>
<thead>
<tr>
<th></th>
<th>Passenger Ca</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>CO</strong></td>
<td>Measured factors (g/km)</td>
<td>14.8</td>
<td>21.02</td>
<td>3.72</td>
</tr>
<tr>
<td></td>
<td>HKEPD factors (g/km)</td>
<td>11.7</td>
<td>1.26</td>
<td>1.25</td>
</tr>
<tr>
<td><strong>HC</strong></td>
<td>Measured factors (g/km)</td>
<td>0.9</td>
<td>2.79</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>HKEPD factors (g/km)</td>
<td>0.9</td>
<td>0.71</td>
<td>0.69</td>
</tr>
<tr>
<td><strong>NOₓ</strong></td>
<td>Measured factors (g/km)</td>
<td>1.0</td>
<td>2.64</td>
<td>1.20</td>
</tr>
<tr>
<td></td>
<td>HKEPD factors (g/km)</td>
<td>1.6</td>
<td>2.31</td>
<td>2.21</td>
</tr>
<tr>
<td><strong>Particulate</strong></td>
<td>Measured factors (g/km)</td>
<td>-</td>
<td>--</td>
<td>0.10</td>
</tr>
<tr>
<td></td>
<td>HKEPD factors (g/km)</td>
<td>-</td>
<td>--</td>
<td>0.59</td>
</tr>
</tbody>
</table>

Table 4.4 Average emission factors compared with fleet average emission factors from HKEPD

The HKEPD fleet average emission factors for the passenger van were clearly not derived solely for petrol vans. Diesel-fuelled passenger vans could lower the fleet emission factors of CO, HC and NOₓ derived for all passenger vans. Thus, the measured average emission factors for the test petrol van are significantly smaller than those of the HKEPD fleet average emission factors for passenger vans. However, the deviations between the measured emission factors of the test diesel van and the HKEPD fleet emission factors for the public light bus are relatively smaller than those of the test petrol van, because the public light buses in Hong Kong are basically diesel-fuelled. Thus the derived fleet average emission factors are close to those derived for our diesel van.
The differences between the measured and fleet emission factors for the passenger car are smaller than those of the bus. For the passenger car, the measured emission factors are quite close to the HKEPD's fleet emission factors, especially for HC emissions which only differ by 6%. It indicated that the emission data of the passenger car could represent, to a certain extent, the average emission pattern of passenger cars in Hong Kong. However, the measured bus emission factors significantly deviate from the HKEPD's fleet emission factors. The measured emission factors overestimated CO, HC and NOₓ but underestimated particulate emissions. The large differences may be due to the age of the test bus. The fleet average emission factors from the HKEPD were derived to represent the average emission pattern of the buses in Hong Kong, which composed a small proportion of vehicles aged 10 years or higher. Therefore, the test bus, which is aged 10 years, should have higher emission factors than the HKEPD fleet average emission factor.

4.5.2.2 Influence of instantaneous speed

To investigate the influence of instantaneous speed on emissions and fuel consumption, records of instantaneous emissions and fuel consumption were grouped according to the instantaneous speed. Usually, instantaneous emission and fuel consumption will be expressed in terms of g/s rather than g/km and g/(kg fuel). However, it is of great interest to examine the trends of distance based and fuel based emissions as well as fuel consumption as vehicle speed changed. For each speed range, the average emission and fuel consumption rates, factors and indices were calculated by Equations 4.7 to 4.9 and plotted against the corresponding speed range. Figures 4.3 to 4.5 show the plots of the mean emissions and fuel consumption
in different units averaged for specific speed range. The curves were constructed in a 5 km/h resolution of instantaneous speed.

Figure 4.3 shows the emissions and fuel consumption factors (g/km) of each test vehicle. There is a very clear and distinct trend for the four test vehicles. It is shown that the emission factors of CO, HC, NOx and particulates, as well as the fuel consumption factors of the test vehicles, drop as the instantaneous speed increases. For the petrol van, when the instantaneous speed increased from (5-10] km/h to (15-20] km/h, the emissions factors decreased dramatically while the fuel consumption factor increased slightly and then dropped gradually after the speed exceeded 20 km/h. For the other three test vehicles, all emission and fuel consumption factors decreased as speed increased, especially for the double decker bus. For an instantaneous speed increase from (5-10] km/h to (10-15] km/h, the CO, HC, NOx and particulate emission factors of the double decker bus generally decreased more than 70%. The decreasing trend as instantaneous speed increased can be explained by the calculation method of the distance based emission factors (g/km). It can be observed from Equation 4.7 and Equation 4.8 that emission and fuel consumption rates (g/s) were divided by the vehicle speed to obtain the emission and fuel consumption factors (g/km). Therefore, the emission and fuel consumption factors (g/km) would be inversely proportional to the vehicle speed.
(a) Petrol Passenger Car

(b) Petrol Van

(c) Diesel Van
(d) Double Decked Bus

Figure 4.3 Emission and fuel consumption factors (g/km) against instantaneous vehicle speed.

(a) Petrol Passenger Car

(b) Petrol Van
Figure 4.4 Emission and fuel consumption rates (g/s) against instantaneous vehicle speed

Figure 4.4 shows the relationships between the instantaneous speed of the test vehicles and the emissions and fuel consumption rates (g/s). When the emission and fuel consumption are expressed in terms of g/s (i.e. emission and fuel consumption rates), the trends are reversed when compared with those expressed in terms of g/km (i.e. emission factors). In general, higher emission and fuel consumption rates are observed at higher vehicle speeds, this is because vehicles have to consume more fuel to generate enough power and maintain the engine operation at higher speeds.
For the petrol fuelled vehicles, the trend of CO and NO\textsubscript{x} emission rates as well as the fuel consumption rates is generally upward while the HC emission rates show an upward convex shape with a maximum in the 30-40 km/h region. The CO, HC and NO\textsubscript{x} emission rates as well as the fuel consumption rates of the diesel van increase as vehicle speed increases, while the particulate emission rates fluctuate over a small margin. For the double decker bus, the emission and fuel consumption rates tend to increase with an increase of vehicle speed. However, larger local fluctuations are observed at vehicle speeds higher than 40 km/h.

(a) Petrol Passenger Car

(b) Petrol Van
(c) Diesel Van

Figure 4.5 Emission and fuel consumption indices \([\text{g/(kg fuel)}]\) against instantaneous vehicle speed.

Unlike those of the emission rates and factors, emission indices shown in Figure 4.5, which are expressed in terms of \(\text{g/(kg fuel)}\), are less sensitive to instantaneous speed. It agrees with the results of other researchers (Singer and Harley, 1996; Singer, et al., 1999). The fuel based emission index \([\text{g/(kg fuel)}]\), to some extent, does indeed reflect the fuel combustion efficiency, which is governed by many factors such as vehicle characteristics and operating conditions as well as fuel type. Therefore, it is difficult to characterise fuel based emission indices \([\text{g/(kg fuel)}]\) with the vehicle speed only. However, some important points can still be extracted from Figure 4.5. It can be observed that diesel fuel is more efficient than petrol in terms of emitting less \(\text{CO, HC and NO}_x\). Except in terms of idling, the combustion efficiency of the diesel van is relatively stable at speeds lower than 45 km/h. The petrol van shows an increasing combustion efficiency as vehicle speed increases.

In brief, instantaneous vehicle speed has the greatest impact on emission and fuel consumption factors, followed by emission and fuel consumption rates. The fuel-
based emission indices, reflects that fuel combustion efficiency, vary much less than
distance-based and time-based emissions as instantaneous speed changed.

4.5.3 Modal analysis

The corresponding emissions and fuel consumption data for each vehicle were then
classified according to various driving modes. The four standard driving modes were
defined as described in Section 3.3. The instantaneous emission and fuel
consumption rates (g/s) for each driving mode were averaged to give the modal
emission and fuel consumption rates. Emission and fuel consumption factors (g/km)
and indices [g/(kg fuel)] for specific driving modes were calculated using Equation
4.7 to 4.9.

<table>
<thead>
<tr>
<th>Driving Mode</th>
<th>Modal Emission Rate (mg/s)</th>
<th></th>
<th></th>
<th>Particulate</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
<td>HC</td>
<td>NOx</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Passenger Car</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>9.54</td>
<td>0.69</td>
<td>0.62</td>
<td>--</td>
<td>62.62</td>
</tr>
<tr>
<td>Cruising</td>
<td>9.15</td>
<td>0.49</td>
<td>0.77</td>
<td>--</td>
<td>39.10</td>
</tr>
<tr>
<td>Deceleration</td>
<td>9.96</td>
<td>0.58</td>
<td>0.69</td>
<td>--</td>
<td>28.11</td>
</tr>
<tr>
<td>Idling</td>
<td>2.99</td>
<td>0.36</td>
<td>0.14</td>
<td>--</td>
<td>18.11</td>
</tr>
<tr>
<td>Petrol Van</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>15.14</td>
<td>1.85</td>
<td>1.96</td>
<td>--</td>
<td>67.29</td>
</tr>
<tr>
<td>Cruising</td>
<td>14.52</td>
<td>1.70</td>
<td>1.81</td>
<td>--</td>
<td>52.14</td>
</tr>
<tr>
<td>Deceleration</td>
<td>17.30</td>
<td>1.91</td>
<td>2.33</td>
<td>--</td>
<td>52.16</td>
</tr>
<tr>
<td>Idling</td>
<td>8.39</td>
<td>1.88</td>
<td>0.81</td>
<td>--</td>
<td>12.71</td>
</tr>
<tr>
<td>Diesel Van</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>2.71</td>
<td>0.65</td>
<td>0.91</td>
<td>0.08</td>
<td>62.02</td>
</tr>
<tr>
<td>Cruising</td>
<td>2.64</td>
<td>0.54</td>
<td>0.79</td>
<td>0.07</td>
<td>52.47</td>
</tr>
<tr>
<td>Deceleration</td>
<td>2.67</td>
<td>0.65</td>
<td>0.89</td>
<td>0.07</td>
<td>56.01</td>
</tr>
<tr>
<td>Idling</td>
<td>1.33</td>
<td>0.22</td>
<td>0.44</td>
<td>0.01</td>
<td>18.52</td>
</tr>
<tr>
<td>Double Deckered Bus</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>12.63</td>
<td>2.36</td>
<td>13.94</td>
<td>0.66</td>
<td>--</td>
</tr>
<tr>
<td>Cruising</td>
<td>8.16</td>
<td>1.36</td>
<td>10.62</td>
<td>0.17</td>
<td>--</td>
</tr>
<tr>
<td>Deceleration</td>
<td>10.92</td>
<td>1.96</td>
<td>11.65</td>
<td>0.31</td>
<td>--</td>
</tr>
<tr>
<td>Idling</td>
<td>7.50</td>
<td>1.15</td>
<td>4.04</td>
<td>0.05</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4.5 Modal emission and fuel consumption rates
The modal emission and fuel consumption rates (g/s), factors (g/km) and indices \([\text{g/(kg fuel)}]\) are shown in Table 4.5 to Table 4.7. Table 4.5 shows the modal emission and fuel consumption rates for the test vehicles. It can be seen that fuel consumption as well as CO, HC, NOx and particulate emission rates of the four test vehicles during the acceleration mode are comparatively higher than other driving modes. In the acceleration process, the engine needs more fuel to generate enough power to accelerate the vehicle, the higher the acceleration rate, the more fuel needed. Therefore, the fuel consumption and emissions increase. During deceleration, the engine does not necessarily generate power. However, the fuel flow rate cannot be stopped immediately when acceleration or cruising mode suddenly changed to deceleration mode. Excess fuel thus continues flowing at the early phase of deceleration, especially for hard acceleration/deceleration changes (Carlock, 1992). For the petrol passenger car, the fuel consumption rate during deceleration is lower than the cruising mode. The reason is that the average deceleration rate during all deceleration phases of the petrol passenger car is -0.436 m/s/s, which is smaller than those of the other three test vehicles.

In cruising mode, fuel is used to maintain the vehicle at a certain speed level so that emissions and fuel consumption are generally lower than in acceleration and deceleration modes. However, the difference in emissions during cruising and acceleration could be higher than observed. The cruising NOx emission rate of the passenger car is even higher than that during the acceleration. In the urban areas of Hong Kong, signal controlled intersections are very close to one another so that each individual cruising period is short, say less than 5 seconds, just like low acceleration or deceleration mode. As a result, emission factors during cruising are relatively
close to those of the acceleration and deceleration modes.

It is clear that idling emissions and fuel consumption rates are the lowest. A small amount of fuel is needed to maintain the operation of the engine, thus the idling emissions and fuel consumption rates are significantly lower than those of the other driving modes. However, differences of HC emission rates between idling modes and other driving modes are comparatively smaller than those of the fuel consumption as well as CO, NOₓ and particulate emissions. This may be caused by the evaporation of hydrocarbons in the unburned fuel.

<table>
<thead>
<tr>
<th>Driving Mode</th>
<th>Modal Emission Factors (g/km)</th>
<th>CO</th>
<th>HC</th>
<th>NOₓ</th>
<th>Particulate</th>
<th>Fuel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Passenger Car</td>
<td>Acceleration</td>
<td>14.41</td>
<td>1.04</td>
<td>0.94</td>
<td>--</td>
<td>94.58</td>
</tr>
<tr>
<td></td>
<td>Cruising</td>
<td>11.68</td>
<td>0.63</td>
<td>0.98</td>
<td>--</td>
<td>49.92</td>
</tr>
<tr>
<td></td>
<td>Deceleration</td>
<td>14.40</td>
<td>0.84</td>
<td>0.99</td>
<td>--</td>
<td>40.66</td>
</tr>
<tr>
<td>Petrol Van</td>
<td>Acceleration</td>
<td>17.38</td>
<td>2.13</td>
<td>2.25</td>
<td>--</td>
<td>77.28</td>
</tr>
<tr>
<td></td>
<td>Cruising</td>
<td>17.58</td>
<td>2.05</td>
<td>2.19</td>
<td>--</td>
<td>63.15</td>
</tr>
<tr>
<td></td>
<td>Deceleration</td>
<td>18.68</td>
<td>2.07</td>
<td>2.52</td>
<td>--</td>
<td>56.32</td>
</tr>
<tr>
<td>Diesel Van</td>
<td>Acceleration</td>
<td>3.48</td>
<td>0.83</td>
<td>1.17</td>
<td>0.11</td>
<td>79.77</td>
</tr>
<tr>
<td></td>
<td>Cruising</td>
<td>3.70</td>
<td>0.75</td>
<td>1.11</td>
<td>0.09</td>
<td>73.53</td>
</tr>
<tr>
<td></td>
<td>Deceleration</td>
<td>3.55</td>
<td>0.86</td>
<td>1.18</td>
<td>0.10</td>
<td>74.38</td>
</tr>
<tr>
<td>Bus</td>
<td>Acceleration</td>
<td>21.01</td>
<td>3.93</td>
<td>23.20</td>
<td>1.10</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Cruising</td>
<td>26.91</td>
<td>4.50</td>
<td>35.06</td>
<td>0.56</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>Deceleration</td>
<td>20.17</td>
<td>3.62</td>
<td>21.52</td>
<td>0.58</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4.6 Modal emission and fuel consumption factors

Table 4.6 shows distance-based modal emission factors. As it is distance-based, idling emission factors cannot be calculated. The comparisons of the modal emission and fuel consumption factors are almost the same with the modal emission and fuel consumption rates. However, the double decked bus has significantly larger cruising emission factors than those of the acceleration and deceleration modes. This is
because the average speed during cruising mode is 11 km/h while that of the acceleration and deceleration modes are 21 km/h and 20 km/h respectively. It has been demonstrated that average speed can explain up to 70% of the distance-based emissions (Alimoradian, 1986; Andre and Pronello, 1997; Cheung, et. al., 1999; Zhao, et. al., 1999), the lower the average speed, the higher the emissions. Therefore, combined the effect of short cruising periods described in previous paragraph, cruising emission factors of the double decker bus are larger than those of the acceleration and deceleration modes.

<table>
<thead>
<tr>
<th>Driving Mode</th>
<th>Modal Emission Index (g/(kg fuel))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>CO</td>
</tr>
<tr>
<td>Passenger Car</td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>152.37</td>
</tr>
<tr>
<td>Cruising</td>
<td>234.01</td>
</tr>
<tr>
<td>Deceleration</td>
<td>354.28</td>
</tr>
<tr>
<td>Idling</td>
<td>164.89</td>
</tr>
<tr>
<td>Petrol Van</td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>224.91</td>
</tr>
<tr>
<td>Cruising</td>
<td>278.43</td>
</tr>
<tr>
<td>Deceleration</td>
<td>331.62</td>
</tr>
<tr>
<td>Idling</td>
<td>660.31</td>
</tr>
<tr>
<td>Diesel Van</td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>43.68</td>
</tr>
<tr>
<td>Cruising</td>
<td>50.36</td>
</tr>
<tr>
<td>Deceleration</td>
<td>47.67</td>
</tr>
<tr>
<td>Idling</td>
<td>71.59</td>
</tr>
</tbody>
</table>

Table 4.7 Modal emission indices

Table 4.7 shows the fuel-based modal emission indices. The emission indices of the diesel van are significantly smaller than those of the petrol vehicles. As discussed in the previous sections, the diesel van is more fuel-efficient than the petrol vehicles. Therefore, the fuel-based emission indices should be smaller than those of the petrol vehicles. It can be observed that idling emission indices are higher than those of the acceleration and deceleration modes for the petrol van and diesel van. However, low
Idling emission indices are observed for the passenger car. This could be caused by the presence of the catalytic converter. During idling, the passenger car needs more fuel to maintain the operation of the engine as well as the catalytic converter and thus decreases the emission indices.

Meanwhile, the smallest emission indices were observed for the acceleration mode, which was different from the distance based and time based emissions. It meant that the highest fuel combustion efficiency occurred during the acceleration mode. The reason might be that the higher engine temperature during acceleration facilitates the fuel combustion process.

4.6 Emissions and Fuel Consumption Modelling

In this section, the ON-ROAD emissions and fuel consumption prediction model is described in detail. The emissions and fuel consumption data for each vehicle are analysed according to the four driving modes.

4.6.1 Idling emissions and fuel consumption

Usually, the idling emissions and fuel consumption are estimated by an idling emission and fuel consumption rates respectively. These emission rates are calculated as average values of instantaneous emission and fuel consumption rates at idling. The emission and fuel consumption prediction errors induced by this approach are generally the largest among various driving modes (Cernuschi, et.al., 1994). Therefore, it is necessary to derive an alternative method to improve the
prediction accuracy.

(a) Fuel consumption and CO emission

(b) HC and NOx emission

Figure 4.6 Idling emission and fuel consumption distributions of the petrol van
Figure 4.6 is a plot of instantaneous idling emissions and fuel consumption rates of the petrol van against idling time. It can be seen that the idling emission and fuel consumption rates are significantly correlated with the idling time. During the early phases of standstill, emission and fuel consumption rates are higher and then drop as the idling time increases. This is due to the fact that although the vehicle speed is zero at idling, the engine speed varies. In the early phases of standstill, the engine speed is high, it then drops and stabilises to the idling speed (Zhao, et.al., 1999). Accordingly, it seems that idling emission and fuel consumption can be estimated as a function of idling time. The best fit of the dependence of emission and fuel consumption on idling time resembles a negative exponential relationship of the form:

\[ E = F_i(t_i) = a \exp(-bt_i) \]  

[4.10]

where \( E \) is the instantaneous emission or fuel consumption rate, \( a \) and \( b \) are the regression coefficients and \( t_i \) is the idling time. From Equation 4.10, instantaneous emissions and fuel consumption rates decline as idle time (\( t_i \)) increases. This can probably explain the relationship between idling time and idling emissions as well as fuel consumption. It was found that the idling emission and fuel consumption distributions were very similar for the four test vehicles, thus only the results of the petrol van were shown. The general form of the relationships obtained is equally applicable to the other three test vehicles.
4.6.2 Non-idling emissions and fuel consumption

The next step is to assess the relationship of instantaneous emission, fuel consumption and speed for the other three driving modes. These can be found by classifying data for each driving mode into different speed classes with 2.0 km/h resolution. With this resolution, the sample data would widely spread within the speed class. Should the data point lie close to the centre point of the corresponding speed class, the data value would be considered as more informative (Alimoradian, 1986). It is desirable to give more weighting to the nearby points than to those more remote. Thus the emission and fuel consumption data of each speed class should be written in the form of a weighted average as shown below:

\[
f(x) = \frac{\sum_{j=1}^{N} w(x_j)e_j}{\sum_{j=1}^{N} w(x_j)} \quad [4.11]
\]

where \( x \) = distance between the data point and the centre point of the corresponding speed class

\( w(x) = \) weighting function = 1 - \( x \)

\( e_j = \) emission or fuel consumption rate of the data point located at \( x_j \).

The weighting function \( w(x) \) weighs the data points according to its distance from the centre point of the corresponding speed class. The weighting factor ranges from 0 to 1 for 2.0 km/h vehicle speed resolution. The nearer is the data point, the larger is the weighting. If the data point coincides with the centre point, the weight will be 1.
The weighted average CO, HC and NO\textsubscript{x} emission and fuel consumption rates in terms of (g/s) and (g/km) at each of the non-idling driving mode and speed classes of the test vehicles were calculated. As expected, the trends of emissions and fuel consumption as instantaneous speed changed for the four test vehicles at each of the non-idling driving modes were found to be very similar. Therefore, only the results for the petrol van were plotted in Figure 4.7 and Figure 4.8.

Figure 4.7 shows the emission and fuel consumption in terms of (g/s). It can be observed that the fuel consumption as well as CO and NO\textsubscript{x} emission rates in terms of (g/s) for the acceleration and deceleration modes generally increase as instantaneous speed increases. For cruising mode, the fuel consumption and CO emission rates tended to be stabilised after a certain instantaneous speed was reached. However, HC emissions for the three non-idling driving modes have an upward convex shape as instantaneous speed varied. The HC emissions approached the maximum at certain instantaneous speed and then dropped gradually as instantaneous speed increased. These results agreed with those obtained by Cernuschi (1994).
Figure 4.7 Weighted emission and fuel consumption in terms of (g/s) of the petrol van for the non-idling modes.
Figure 4.8 Weighted emission and fuel consumption in terms of (g/km) of the petrol van for the non-idling modes.

Comparing with the time-based (g/s) results, reversed tendencies were observed from Figure 4.8 when emissions and fuel consumption expressed in terms of (g/km). Distance-based emission and fuel consumption (g/km) decreased as instantaneous speed increased. The reason for this is that the time-based emission and fuel consumption were divided by the corresponding vehicle speed to obtain the distance-based emission and fuel consumption. Therefore, emission and fuel consumption should be inversely proportional to vehicle speed.
4.6.3 The mathematical model

The conceptual model is shown in Equation 4.12.

\[
E = \begin{cases} 
  F_i(t_i) & \text{in idling;} \\
  F_A(v) & \text{in accelerating;} \\
  F_c(v) & \text{in cruising;} \\
  F_D(v) & \text{in decelerating.}
\end{cases} \tag{4.12}
\]

where \( E \) is the instantaneous emission or fuel consumption rate. \( F_i(t_i) \) is the function of idle time in the form of Equation 4.10. \( F_A(v), F_c(v) \) and \( F_D(v) \) are piecewise interpolation functions of instantaneous speed at acceleration, cruising and deceleration respectively.

The collected emission and fuel consumption data were classified and weighted according to the procedures described in the previous section with instantaneous speed resolution of 2 km/h. The piecewise interpolation function of emission is a series of linear polynomial functions passing through the weighted emission for each speed class as shown in Figure 4.7. Instantaneous emission and fuel consumption can be calculated according to these functions by substituting the instantaneous speed records from a speed profile. Idling emission and fuel consumption can be estimated by the best-fit, derived by standard regression techniques, in the form of Equation 4.10.
4.7 Comparison of the Measured and Predicted Values of Emissions and Fuel Consumption

To test the developed emission model, the whole data set DS is divided into two parts, the model building set MBS and the validation set VS (Hjorth, 1994). MBS and VS are subsets of DS which is used to build and validate the model respectively.

Based on the MBS, a full set of emission and fuel consumption functions for all the vehicles and pollutants was derived as described in the previous section. The emission model described in Equation 4.12 was encoded in Turbo Pascal language to calculate the emissions and fuel consumption for the data in VS from a second by second record of speed. Each second, the rate of acceleration can be calculated from the speed profile. The appropriate instantaneous emission and fuel consumption rates can then be determined by the modal emission and fuel consumption functions from the instantaneous speed. The results were then compared with the observed emission and fuel consumption profiles.

4.7.1 The instantaneous results

Figure 4.9 is an example plot. It shows a comparison of the observed and predicted instantaneous emissions and fuel consumption in terms of (g/km) for the test set of the petrol van. Since distance-based emission and fuel consumption (g/km) cannot be calculated for the idling mode, idling was excluded from all predictions in terms of (g/km). The figures show good agreement between the observed and predicted emissions and fuel consumption.

123
<table>
<thead>
<tr>
<th></th>
<th>Passenger Car</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Fuel</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>0.6254</td>
<td>0.6254</td>
<td>0.4410</td>
<td>--</td>
</tr>
<tr>
<td>g/km</td>
<td>0.7318</td>
<td>0.8708</td>
<td>0.6362</td>
<td>--</td>
</tr>
<tr>
<td><strong>CO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>0.4778</td>
<td>0.5501</td>
<td>0.5557</td>
<td>0.6805</td>
</tr>
<tr>
<td>g/km</td>
<td>0.5285</td>
<td>0.8935</td>
<td>0.7285</td>
<td>0.8819</td>
</tr>
<tr>
<td><strong>HC</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>0.4438</td>
<td>0.5189</td>
<td>0.4180</td>
<td>0.6527</td>
</tr>
<tr>
<td>g/km</td>
<td>0.6398</td>
<td>0.5945</td>
<td>0.6822</td>
<td>0.6978</td>
</tr>
<tr>
<td><strong>NO\textsubscript{x}</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>0.5630</td>
<td>0.5508</td>
<td>0.3438</td>
<td>0.3808</td>
</tr>
<tr>
<td>g/km</td>
<td>0.6527</td>
<td>0.8804</td>
<td>0.6139</td>
<td>0.5241</td>
</tr>
<tr>
<td><strong>PM</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>--</td>
<td>--</td>
<td>0.4851</td>
<td>0.4930</td>
</tr>
<tr>
<td>g/km</td>
<td>--</td>
<td>--</td>
<td>0.6968</td>
<td>0.9274</td>
</tr>
</tbody>
</table>

Table 4.8  Correlation coefficients obtained by regression between measured and predicted values of instantaneous fuel consumption and emission.

The summary of the statistical analysis, using SPSS packages to compare the instantaneous observed and predicted values of fuel consumption and emissions, are given in Table 4.8. In this table, the correlation coefficients produced by linear regression between observed and predicted values are presented for both time-based and distance-based emission and fuel consumption. Better correlation coefficients were obtained for distance-based results, because the distance-based emission and fuel consumption have a more significant trend than those of the time-based (Tong, et.al., 2000).
(a) Fuel consumption

(b) CO emissions
Figure 4.9 Comparison of the observed and predicted instantaneous emission and fuel consumption in terms of (g/km) for the test set of the petrol van.
4.7.2 The trip based results

To evaluate the performance of the emission model over a trip, the total predicted emissions and fuel consumption throughout the test set were calculated. These values were then compared with the observed values. The average absolute percentage errors are shown in Table 4.9.

<table>
<thead>
<tr>
<th>Fuel</th>
<th>Average Absolute Percentage Error (%)</th>
<th>Passenger Car</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>g/s</td>
<td>2.57</td>
<td>13.50</td>
<td>9.09</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>g/km</td>
<td>2.72</td>
<td>3.19</td>
<td>5.77</td>
<td>--</td>
<td></td>
</tr>
<tr>
<td>CO</td>
<td>g/s</td>
<td>17.42</td>
<td>4.33</td>
<td>17.14</td>
<td>9.81</td>
</tr>
<tr>
<td></td>
<td>g/km</td>
<td>4.85</td>
<td>0.47</td>
<td>10.82</td>
<td>9.49</td>
</tr>
<tr>
<td>HC</td>
<td>g/s</td>
<td>7.93</td>
<td>7.48</td>
<td>14.16</td>
<td>18.67</td>
</tr>
<tr>
<td></td>
<td>g/km</td>
<td>4.90</td>
<td>0.65</td>
<td>10.51</td>
<td>7.61</td>
</tr>
<tr>
<td>NOx</td>
<td>g/s</td>
<td>1.78</td>
<td>2.01</td>
<td>6.47</td>
<td>9.95</td>
</tr>
<tr>
<td></td>
<td>g/km</td>
<td>3.80</td>
<td>1.73</td>
<td>2.29</td>
<td>3.99</td>
</tr>
<tr>
<td>PM</td>
<td>g/s</td>
<td>--</td>
<td>--</td>
<td>18.04</td>
<td>18.81</td>
</tr>
<tr>
<td></td>
<td>g/km</td>
<td>--</td>
<td>--</td>
<td>11.97</td>
<td>7.39</td>
</tr>
</tbody>
</table>

Table 4.9 Average absolute percentage error of the predicted total fuel consumption and emissions over a trip.

The highest accuracy obtained was the CO and HC emissions from the petrol van predicted by the distance-based emission rates, whereas the prediction error induced by the diesel van was found to be the largest. In general, NOx emissions prediction was found to have performed better for the four test vehicles, where the errors were smaller than 10%.
### Modal Evaluation

<table>
<thead>
<tr>
<th>Driving Mode</th>
<th>Correlation coefficients</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Fuel</td>
</tr>
<tr>
<td><strong>Passenger Car</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.5028</td>
</tr>
<tr>
<td></td>
<td>0.6730</td>
</tr>
<tr>
<td>Cruising</td>
<td>0.4493</td>
</tr>
<tr>
<td></td>
<td>0.8123</td>
</tr>
<tr>
<td>Deceleration</td>
<td>0.4342</td>
</tr>
<tr>
<td></td>
<td>0.8739</td>
</tr>
<tr>
<td>Idling</td>
<td>0.0714</td>
</tr>
<tr>
<td><strong>Petrol Van</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.3694</td>
</tr>
<tr>
<td></td>
<td>0.8857</td>
</tr>
<tr>
<td>Cruising</td>
<td>0.2912</td>
</tr>
<tr>
<td></td>
<td>0.8543</td>
</tr>
<tr>
<td>Deceleration</td>
<td>0.2964</td>
</tr>
<tr>
<td></td>
<td>0.8624</td>
</tr>
<tr>
<td>Idling</td>
<td>0.0873</td>
</tr>
<tr>
<td><strong>Diesel Van</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>0.4044</td>
</tr>
<tr>
<td></td>
<td>0.6321</td>
</tr>
<tr>
<td>Cruising</td>
<td>0.3609</td>
</tr>
<tr>
<td></td>
<td>0.6158</td>
</tr>
<tr>
<td>Deceleration</td>
<td>0.4155</td>
</tr>
<tr>
<td></td>
<td>0.6378</td>
</tr>
<tr>
<td>Idling</td>
<td>0.0873</td>
</tr>
<tr>
<td><strong>Bus</strong></td>
<td></td>
</tr>
<tr>
<td>Acceleration</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Cruising</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Deceleration</td>
<td>--</td>
</tr>
<tr>
<td></td>
<td>--</td>
</tr>
<tr>
<td>Idling</td>
<td>--</td>
</tr>
</tbody>
</table>

Table 4.10 Correlation coefficients obtained by regression between instantaneous measured and predicted values of fuel consumption and emission for each driving mode.

Table 4.10 shows the correlation coefficients produced by linear regression between observed and predicted emission and fuel consumption expressed in terms of (g/s) and (g/km) for each of the driving modes. For the double decked bus and the petrol
van, it was found that the prediction accuracy for the acceleration mode was generally higher. The correlation coefficients for cruising and decelerating modes were found to be similar to those for the acceleration mode.

For the diesel van, higher HC and NOX prediction accuracy were obtained for cruising mode. Whereas better correlation coefficient were observed for estimation of fuel consumption as well as CO and PM emissions during acceleration and deceleration modes. For the passenger car, the model generally performed better for cruising and decelerating modes than the acceleration mode.

The prediction errors are mainly induced by the idling mode. To compare the performance of the proposed negative exponential relationship with the average value method in predicting idling emission and fuel consumption, the prediction accuracy of these two approaches were calculated. Average absolute deviation between the observed and predicted idling emission and fuel consumption rates was computed to assess the performance of these two approaches as in Equation 4.13.

$$d_j = \frac{1}{n} \sum_{i} |o_i - e_i|$$  \hspace{1cm} [4.13]

where $d_j$ is the average absolute deviation; $o_i$ and $e_i$ are the observed and predicted instantaneous idling emission or fuel consumption rates; $n$ is the number of idling samples in the validation set. The percentage difference $D$ between $d_1$ (deviation obtained by the proposed method) and $d_2$ (deviation obtained by the average value method) were calculated as in Equation 4.14.
\[ D = \left( \frac{d_2 - d_1}{d_2} \right) \times 100 \] [4.14]

Therefore, a positive \( D \) implies the proposed method performs better than the average method or vice versa. The results are shown in Table 4.11. The proposed method clearly performed better than the average value method. It can be seen that there are only two negative values in Table 4.11, the fuel consumption and HC emission of the passenger car. However, they are smaller than 5%. Whereas, the proposed method generally reduced the error by 8% to 35%. In particular, significant improvements were observed for CO emissions for the three test vehicles. The largest improvement was found for predicting CO emission of the passenger car, where the error was reduced by 92%.

<table>
<thead>
<tr>
<th></th>
<th>Passenger Car</th>
<th>Petrol Van</th>
<th>Diesel Van</th>
<th>Bus</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel</td>
<td>( d_1 ) (g)</td>
<td>0.0694</td>
<td>0.0432</td>
<td>0.1931</td>
</tr>
<tr>
<td></td>
<td>( d_2 ) (g)</td>
<td>0.0669</td>
<td>0.0473</td>
<td>0.2358</td>
</tr>
<tr>
<td></td>
<td>( D ) (%)</td>
<td>(-3.70)</td>
<td>(8.69)</td>
<td>(18.08)</td>
</tr>
<tr>
<td>CO</td>
<td>( d_1 ) (g)</td>
<td>0.0153</td>
<td>0.0352</td>
<td>0.0077</td>
</tr>
<tr>
<td></td>
<td>( d_2 ) (g)</td>
<td>0.1928</td>
<td>0.0436</td>
<td>0.0085</td>
</tr>
<tr>
<td></td>
<td>( D ) (%)</td>
<td>(92.06)</td>
<td>(19.27)</td>
<td>(9.32)</td>
</tr>
<tr>
<td>HC</td>
<td>( d_1 ) (g)</td>
<td>0.00239</td>
<td>0.00468</td>
<td>0.0022</td>
</tr>
<tr>
<td></td>
<td>( d_2 ) (g)</td>
<td>0.00228</td>
<td>0.00710</td>
<td>0.0025</td>
</tr>
<tr>
<td></td>
<td>( D ) (%)</td>
<td>(-4.82)</td>
<td>(34.08)</td>
<td>(11.86)</td>
</tr>
<tr>
<td>NO(_x)</td>
<td>( d_1 ) (g)</td>
<td>0.000893</td>
<td>0.00606</td>
<td>0.0015</td>
</tr>
<tr>
<td></td>
<td>( d_2 ) (g)</td>
<td>0.001045</td>
<td>0.00725</td>
<td>0.0017</td>
</tr>
<tr>
<td></td>
<td>( D ) (%)</td>
<td>(14.55)</td>
<td>(16.41)</td>
<td>(12.15)</td>
</tr>
<tr>
<td>PM</td>
<td>( d_1 ) (g)</td>
<td>--</td>
<td>--</td>
<td>0.00012</td>
</tr>
<tr>
<td></td>
<td>( d_2 ) (g)</td>
<td>--</td>
<td>--</td>
<td>0.00013</td>
</tr>
<tr>
<td></td>
<td>( D ) (%)</td>
<td>--</td>
<td>(8.61)</td>
<td>(10.00)</td>
</tr>
</tbody>
</table>

Table 4.11 Comparison of average absolute error of the proposed negative exponential relationship with the average value method in predicting idling emission and fuel consumption.
4.8 Concluding Remarks

The ON-ROAD modal emissions and fuel consumption model developed for vehicles travelling in the urban areas has been described. Generally good agreement was achieved between the modelling and measurement results for the four test vehicles.

Owing to budget limitation, only four test vehicles have been employed to calibrate the model developed thus, in its present form, the model cannot be generalised to the whole vehicle fleet in Hong Kong. However, the results obtained indicate that an on-road driving emission measurement is feasible. The form of the model developed is potentially applicable to microscopic traffic simulation that deals with individual "vehicle". When the model is fully developed by taking into account of other factors, the limited number of input variables of the model make it possible to be readily incorporated in a microscopic traffic simulation model to predict tailpipe emissions and fuel consumption. To achieve more definitive results, more instrumented vehicles can be tested under different conditions and then sub-models for each composite vehicle types can be derived.

In general, tailpipe emissions and fuel consumption are affected by a number of factors discussed in Chapter 2. From the traffic model interface perspective, the number of input variables for the emission prediction is critical. For example, many traffic simulation models categorised vehicles into a few types based on limited factors like vehicle size and model year. They may not characterise vehicles in such detail as different emission control technologies or whether the air-conditioning
system is running or not. Therefore, the recommended approach for modelling vehicle fleet is to calibrate sub-models for each composite vehicle type. Too detailed characterisation of vehicle categories would not have great interest to transportation application
CHAPTER 5

DEVELOPMENT OF THE SIMULATION MODEL

5.1 Introduction

In this chapter the development of the TRaffic Emission and Fuel consumption Simulator (TREFSIM) is described. The modelling process of the TREFSIM model involved the selection of a set of input elements and development of the logic that controls the generation and movement of vehicles through the urban signal network being simulated. This chapter begins by describing the overall design of the TREFSIM model. An investigation of some studies that have direct bearing on the modelling process of TREFSIM will then be presented along with the final decisions for selection of elements. Full descriptions of the main elements including network representation, vehicle generations, vehicle movements, traffic signal operations as well as calculation of the model outputs are also presented in this chapter.

5.2 Model Overview

The main structure of TREFSIM consists of a loop over a set of modules being scanned at specific time steps. The simulation logic is summarised in Figure 5.1.

The simulation starts with loading the simulation parameters, road network, and scenario definition. An iterative procedure is then initiated with a pre-specified step size. The tasks performed within each iteration include:
1. The update of the state of traffic signals for each junction.

2. The generation of vehicle arrival headway: Two methods are used to generate vehicle into the network, Neural Network Model (NNM) Generation and Distribution Generation. If the distribution method is chosen, vehicle arrival headway is generated according to statistical distributions. If the NNM method is selected, vehicle arrival headway is generated according to the operation of the signal junction located at the boundary of the simulated area.

3. The loading of vehicles into the network.

4. The update of vehicles' acceleration rates and checking of whether they need to change lane and whether the gaps are acceptable for the desired lane change.

5. The advancement of vehicles to its new positions and the update of their speeds. At the end of a lane, a vehicle is either removed from the network (if it arrives at the boundary of the simulation area) or handed to the downstream lane.

6. The calculation of vehicle emission and fuel consumption rates by the ONROAD Emission Model and other measures of effectiveness (MOEs), such as vehicle delay and journey time.

The TREFSIM model uses the time-based approach in processing the vehicle movements. The car following, lane changing, emission and fuel consumption as well as signal responding functions are invoked for each vehicle at every 1 second interval. All calculations at the update phase for time step $t+1$ are based on information at time step $t$. After all vehicles in the network have been scanned, speeds and positions of the vehicles as well as the signal states at time step $t+1$ are
updated based on the information calculated in the update phase.

Figure 5.1 Flowchart of the TREFSIM model
5.3 Network Representation

In TREFSIM, road networks are represented by nodes, links and lanes, as defined in the following paragraphs.

5.3.1 Nodes

A node can be a signal controlled junction of several roadways, a source or sink. Source and sink are nodes where traffic flows enter and leave the simulated network, respectively. Each node is identified by its type (junction, source or sink), and a unique identification number (Id).

All inbound nodes should be signal controlled junctions. These nodes should have a name and a set of signal timing data, which are described later in this chapter. Boundary nodes are categorised into sources and sinks. Inbound nodes can be connected to any number of links, while boundary nodes can only be connected to 1 link.

5.3.2 Links

Links are directional roadways that connect nodes. Each link may consist of one or more lanes and is characterised by an identification number, start node, end node and the lanes it consists of. Each link can have up to 6 lanes.
5.3.3 Lanes

The TREFSIM model represents the network in such fine detail as each individual lane. Each lane contains the following attributes:

- **Id**: A unique identification number
- **LinkId**: Id of the link that the subject lane belongs to
- **L.Lane**: The lane to the left along the direction of the subject lane
- **R.Lane**: The lane to the right along the direction of the subject lane
- **Length**: Length of the lane
- **SpdLimit**: Speed limit of the lane
- **LaneUsePro**: Lane use proportion, the percentage of the link's total volume carried by the lane
- **TurnPro**: Proportion of turning vehicles
- **L.Reg**: Turning regulation to L.Lane
- **R.Reg**: Turning regulation to R.Lane
- **Manoeuvre**: Turning direction of the lane
- **LaneEnd**: Indicate whether the lane is connected to upstream and/or downstream nodes or not

In general, the length of the lanes should be equal to the length of the corresponding link. For lanes with lengths equal to the corresponding link, LaneEnd is equal to 2. To represent short lanes connecting to the upstream node only, 0 is assigned to LaneEnd. For short lane connecting to the downstream node only, LaneEnd should be 1. L.Reg and R.Reg specify whether vehicles are allowed or not to switch
respectively to the *L.Lane* and *R.Lane* from the subject lane.

5.3.4 **Movements**

Movements are used to represent the connections between upstream and downstream lanes. Each separate queue leading to a junction and characterised by its direction and right of way provision is called a movement. For queues that have more than one movement direction (i.e. mixed lane such as mixed left and through movement), two separate movements have to be defined.

5.4 **Signal Operations**

All inbound nodes are modelled as signal controlled junctions. The signal sequence in Hong Kong is red, red/amber, green, amber and then red. There are two alternative concepts used in describing the signal control at junctions, the stage and phase controls (TPDM, 1994). Stage control concerns sequential steps in which the junction control is varied. The other concept, phase control, refers to the periods of time allocated to each traffic stream. In this study, the stage control method is employed to represent traffic signal operations. Figure 5.2 shows the stage sequences of the Chatham Road South/ Austin Road junction in Hong Kong. It shows the traffic movements permitted in each stage control step. Superimposed on this figure are the designations of each phase if the junction is under phase control.

Figure 5.3 shows a time diagram for the same junction in which the period for which each phase has a green signal is indicated.
A stage is usually determined from the start of red/amber period or red period (if all red period is employed) and always ends at the start of the following stage. They are arranged to follow one another in a predetermined order. A complete series of stages during which all traffic movements are served in turn is known as a cycle. The cycle time is the sum of the stage times.
In the TREFSIM model, each inbound node is associated with a set of signal timing data:

- **CycleTime**: The total time for a signal to complete one cycle
- **RefNode**: Id of the node that the subject node referred to in a co-ordinated signal system
- **RefStage**: The stage of the **RefNode** that the subject node referred to in a co-ordinated signal system
- **Offset**: The time difference between the start of the first stage at the subject signal junction as related to the **RefStage** of the **RefNode**
- **Stage**: A sequence of ordered stages defined for this node

Each stage should have the following attributes:

- **Id**: Stage Id (i.e. A, B, C, etc.)
- **StageSplit**: Proportion of the cycle time assigned to the corresponding stage
- **AllRed**: Length of the all red period
- **Movement**: The set of movements permitted in the corresponding stage

5.5 **Vehicle Arrival Headways**

In many microscopic traffic simulation models like NETSIM, vehicle arrival headways are randomly generated from probability distributions. Numerous attempts have been made by researchers to fit some of the well known statistical distributions to observed data and the negative exponential distribution has been one of the most commonly used headway distributions. In fact, the arrival patterns may not be completely random because they may be affected by the junctions located at the
upstream end of the road section of interest (Griffiths and Hunt, 1991). In order to
account for this fact, alternative distributions have been proposed by other
researchers (Cowan, 1975; Tolle, 1976; Leutzbach, 1988), for example, Erlang
distribution, displaced (shifted) negative exponential distribution as well as log-
normal distribution. Most investigators seem to agree that no single distribution will
adequately describe the headway distribution. Troutbeck (1986) employed the
Cowan's dichotomised M3 headway model which assumed that there is a proportion
of vehicles which are restrained to follow other vehicles at a minimum headway and
that the remaining vehicle (free vehicles) have headways greater than the minimum
headway. Griffiths and Hunt (1991) suggested that the double displaced negative
exponential distribution provided a good fit to the observed headways of vehicles
discharging from signal controlled junctions. It is stated that the distribution can
reflect the well-known platoon effect with the associated preponderance of short
headways. For many urban cities, such as Hong Kong, the majority of the junctions
are signal controlled. Therefore, it is feasible to assume the sources are impeded by
signal controlled junctions.

Headways generated from statistical distributions are independent from one another.
In fact, the discharge headway of queued vehicles at urban signal controlled
junctions are dependent on a number of factors. Therefore, it is important to use an
alternative approach to incorporate these effects by considering the sources as a
signal controlled junction (Tong and Hung, 2000).

For oversaturated cycles, vehicle headway can be modelled as the discharge
headway of each vehicle queued at the signal controlled sources, waiting to enter the
network. For saturated portions of unsaturated cycles, the same method as that of the oversaturated cycles can be applied. These are done by the neural network modelling technique. For unsaturated portions, headway could be randomly generated from the above mentioned headway distributions.

5.5.1 Neural network discharge headway model (NNDHM)

The NNDHM model was developed to estimate the discharge headway of each queued vehicle at signal controlled junctions. The neural network approach was employed in the model development.

5.5.1.1 Definition of discharge headway

In general, discharge headway at signalised junctions is defined as the difference of passage times between two consecutive vehicles over a stop line or any predetermined reference line in the junction. However, the exact definition of discharge headway varied from one study to another (Teply and Jones, 1991) to suit different conditions of studies. As such, it is necessary to define it for this study.

The vehicle discharge headway can be defined as the difference of passage time between the front or rear bumper of successive vehicles over the stop line. If the front bumper is used, the headway of the subject vehicle depends mainly on the characteristics of the preceding vehicle. The larger the preceding vehicle, the longer the headway of the subject vehicle. Therefore, a passenger car following a bus will have longer headway than that of a bus following a passenger car. It gives
misleading result because a passenger car should understandably have a smaller headway than a bus. Whereas, if the rear bumper is used, the measured headway depends essentially on the length and characteristics of the subject vehicle. Larger vehicles probably result in longer headways. Therefore, in this study, the vehicle discharge headway is defined as the difference of passage time between the rear bumper of successive vehicles over the stop line.

For the first queued vehicle, the definition of headway has to be modified as there is no preceding vehicle. The definition can have a number of variations. Variations are not only due to the selection between front and rear bumper of the vehicle but also the use of which signal indication for the start counting of the headway. Different places may have slightly different signal display sequences. In Hong Kong, the cyclic sequence is "red", "red/amber", "green" and "amber". To be consistent with the vehicle discharge headway definition discussed in the previous paragraph, the rear bumper of the first vehicle is counted. It is observed that some drivers start moving their cars before the signal turns green. In order to take this effect into account, the discharge headway of the first vehicle is defined as the time elapse between the start of red/amber period and the time at which the rear bumper of the first vehicle passes the stop line.

5.5.1.2 Influencing factors on discharge headway

Greenshields et. al. (1947) carried out one of the earliest studies to investigate the discharge headway at junctions. They found the average vehicle discharge headway for different queue positions. The average discharge headway decreased from the
first queued vehicle to the fifth and then remained relatively constant until the last
vehicle in the queue. Large vehicles such as trucks and buses were found to require
more time to get through the junction and also cause the following vehicles to have a
longer headway.

Carstens (1971) studied the starting delay and discharge headways of different types
of vehicles at signalised junctions. A decreasing trend of discharge headway with
respect to the queue position was detected. Passenger car equivalents to straight
through trucks and right-turn vehicles were derived. It was found that straight
through passenger cars have the smallest discharge headway.

Lu (1984) analysed the protected and unprotected left-turn vehicles. He revealed that
left-turn vehicles had lower discharge headway values than findings in other studies.
It was found that the smaller the vehicles, the smaller the discharge headways. The
size of the leading vehicles was also found to have great impact on the discharge
headway. The trend of changes in the average discharging headway for protected
left-turn vehicles by queue position was found to be consistent with the results of
similar studies.

Lee and Chen (1986) examined the sensitivity of six factors affecting the discharge
headway of the straight through movement of passenger cars. It was found that the
approach speed limits and queue length influenced significantly the discharge
headway.

Moussavi (1990) studied the discharge headway of passenger cars making straight
through movements, by queue position. He proposed a set of average discharge headway values that could be used in the capacity analysis and calculation of signal timing of at-grade junctions. It was found that the first vehicle in a queue required the longest time to clear the junction and that the clearance time decreased from the first vehicle to the fourth. After that the discharge headway was more or less constant. This was defined as the minimum discharge headway.

Parker (1996) investigated the effect of heavy vehicles on the discharge headways of the following vehicles. It was found that the size of leading and following vehicles had important bearings on discharge headway. Compared to other heavier vehicles, passenger cars were found to induce a smaller headway to the following vehicles.

Akcelik, Besley and Roper (1999) conducted a comprehensive study on discharge headway at signal stop line. The study had been carried out for about 9 years, which composed of extensive traffic surveys as well as analytical analysis of the fundamental relationships and characteristics of traffic queue discharged at the signal stop line. The time since the start of green was used as an important variable, instead of the traditional approach (queue position), relating vehicle discharge headway, flow rate and speed. The study suggested that discharge headway has an exponential relationship with the minimum discharge headway, time since the start of green and average start response time. It was also found that through and right-turn vehicles differ significantly.

In brief, these studies revealed that the queue position, vehicle size and movement types (i.e. straight through, left turning or right turning) of the leading and following
vehicles were the most important elements affecting the discharge headway.

5.5.1.3 **Mandatory discharge headway models**

There are two basic types of discharge headway prediction models. Briggs (1977) proposed a deterministic model to predict the average discharge headway at a signalised junction based on a key assumption that queued vehicles accelerate at a constant rate. For simplicity, queued vehicles were assumed to have an average vehicle length and the distance between stopped vehicles was assumed to be constant. The first vehicle was supposed to start right at the stop line. The reaction time of each vehicle was also assumed to be the same. Based on these assumptions, the passage time of queued vehicles and thus the discharge headway were derived using Newtonian mechanical equations. The model has the following form.

\[
 h_n = \begin{cases} 
 T + \sqrt{\frac{2Dn}{A}} - \sqrt{\frac{2D(n-1)}{A}} & \text{if } nD < D_{\text{max}} \\
 T + \frac{D}{V_q} & \text{otherwise} 
\end{cases}
\]  

[5.1]

where  

\( h_n \) = headway of the \( n \)th queued vehicle  

\( n \) = queue position  

\( D \) = distance between vehicles in a stopped queue  

\( V_q \) = desired speed of queued traffic  

\( D_{\text{max}} \) = distance travelled to reach speed \( V_q \)  

\( T \) = driver starting response time, and  

\( A \) = constant acceleration of queued vehicles
It can be seen that the model equation has two parts. For the first few vehicles, having speed smaller than the desired speed of queued traffic, the discharge headway was proposed to be a function of acceleration and queue position. After vehicles reached the desired speed, headways became dependent on driver response time and the desired speed. Thus, this model predicts that the average headway becomes relatively constant after the desired speed has been reached.

The model was calibrated with data from five previous studies conducted in the United States and Germany. The model demonstrated the trend of decreasing average discharge headways with queue position.

Bonneson (1992) developed a model of discharge headway based on driver reaction time as well as vehicle speed and acceleration. The model comprises a driver acceleration model, a stop line speed model, a discharge headway model and finally a minimum discharge headway model. Unlike the Briggs's model, this model was derived based on the assumption of non-constant acceleration. On the basis of a mandatory acceleration model, which was developed by other researchers, the speed-time and distance-time relations were derived using simple integral calculus. It was further assumed that the driver reaction times were the same for each vehicle, and that there was an additional response time for the first vehicle. Using these relations and assumptions, the passage time of queued vehicles and thus the discharge headway was derived as the following form.

\[ h_n = \tau N_1 + T + \frac{D}{V_{\text{max}}} + \frac{V_{s(tn)} - V_{s(tn-1)}}{A_{\text{max}}} \tag{5.2} \]
where \( h_n \) = headway of the \( n \)th queued vehicle
\( T \) = driver starting response time
\( \tau \) = additional response time of the first queued driver
\( N_1 \) = 1 if \( n = 1 \) or 0 if \( n > 1 \)
\( D \) = distance between vehicles in a stopped queue
\( V_{sl(n)} \) = stop line speed of the \( n \)th queued vehicle (i.e. the vehicle speed at passing the stop line)
\( V_{max} \) = maximum speed corresponding to zero acceleration, and
\( A_{max} \) = maximum acceleration.

The proposed discharge headway model is dependent on the driver accelerations, stop line speed, queue position and driver reaction time. It can be seen from the structure of Equation 5.2 that minimum discharge headway is not reached until the queue reaches its desired speed \( (V_{max}) \). At this point, the difference in the stop line speed of successive vehicles becomes zero and the minimum discharge headway will be dependent on driver reaction time and the desired speed of the queued traffic. The stop line speed is estimated with another model, as shown in Equation 5.3.

\[
V_{sl(n)} = V_{max} \left(1 - e^{-nk}\right) \tag{5.3}
\]

where \( V_{sl(n)} \) = stop line speed of the \( n \)th queued vehicle,
\( V_{max} \) = maximum speed corresponding to zero acceleration,
\( k \) = \( \frac{\beta}{V_{max}} \), and
\( \beta \) = empirical calibration constant.
The stop line speed model was developed by substituting the queue position \( n \) for time \( t \) in the speed-time relation obtained from the acceleration model. These models were calibrated using field data and were proposed to be used in the prediction of average discharge headway by queue position.

Akcelik, Besley and Roper (1999) developed a set of models and comprehensive fundamental relationships for queue discharge behaviour at traffic signal. This set of models employed the exponential form of the Bonneson's discharge speed model. Instead of the queue position, the time since the start of the displayed green period had been used to model queue discharge speed, flow rate and headway. The models are shown as follows:

\[
\begin{align*}
v_s &= v_n (1 - e^{-m_s(t-t_r)}) \\
q_s &= q_n (1 - e^{-m_q(t-t_r)}) \\
h_s &= h_n / (1 - e^{-m_h(t-t_r)})
\end{align*}
\]

where \( t \) = time since the start of the displayed green period
\( t_r \) = average start response time (constant)
\( v_s, q_s, h_s \) = queue discharge speed, flow and headway at time \( t \), respectively
\( v_n, q_n \) = maximum queue discharge speed and flow rate
\( h_n \) = minimum queue discharge headway
\( m_v, m_q \) = parameter in the queue discharge speed and flow rate model, respectively

These models improved the traditional method of conducting capacity and
performance analysis at signal junctions. Traditional queue discharge model for traffic signal uses a constant saturation flow rate and associated start loss and end gain times. However, this set of queue discharge models represents queue discharge behaviour of traffic directly without the need to resort to various simplifying assumptions needed to derive saturation flows and effective green time.

The model performance was affected by lack of data at very low speeds and low flow rates. This is a result of the difficulty in measuring speed and headway for the first few vehicles in the queue at the start of the green period. Although the queue discharge models were generally satisfactory, there were several cases where the predicted headway and flow rate values for low speeds were entirely satisfactory. This was particularly observed for those with low values of maximum queue discharge speed, which applied to most turning lanes.

The three headway models estimated the discharge headway in terms of average values by queue position. They tended to prescribe the functional form of the headway model and therefore may be somewhat restrictive in capturing the true effect of the explanatory variables. It is clear from reviewing the work of previous researchers that the relationships between the discharge headway and various influencing factors are so complex that the form may not be specified easily. The equations proposed in the models were developed under various assumptions such as constant acceleration, average reaction time and average vehicle length. These assumptions may be suitable for average headway models, but clearly they are not applicable for the estimation of discharge headways for individual vehicles owing to the irregularity of traffic conditions and vehicle characteristics.
5.5.1.4 Neural network

The basic elements of a neural network are artificial neurons (or nodes) which are arranged in a layered structure. The nodes are interconnected through links. Each link is associated with a weight. Each node, will probably receive many inputs from other nodes, applies an activation function to its input to determine its output signal (Smith, 1993). The hyperbolic tangent function (Equation 5.7), which is one of the typical activation functions, is chosen in this study.

\[ f(a) = \tanh(a) = \frac{e^a - e^{-a}}{e^a + e^{-a}} \]  

[5.7]

A typical fully connected 3-layered neural net is shown in Figure 5.4. The first layer is the input layer that contains the nets' input units \( X_i \). The inputs are linked to the nodes in the hidden layer \( Y_j \) with associated weight \( w_{ij} \). The nodes in the hidden layer are also connected to the output nodes \( Z_k \) with associated weight \( v_{jk} \). The output units (\( Z_k \)) and the hidden units (\( Y_j \)) also may have bias units. The bias unit is a weight on a connection that has its input value always equal to 1. The bias weights of the output and hidden units are denoted as \( v_{0k} \) and \( w_{0j} \) respectively. The inclusion of such a term is largely a matter of experience (Freeman and Skapura, 1991). The neural net can be trained through the adjustment of weights by input training patterns, so that it learns the underlying structure of the problem, and generates correct output for the corresponding input.
Figure 5.4 A typical fully connected 3-layered neural net

A number of training algorithms are currently available and the backpropagation rule, which is one of the most widely utilised training algorithms to deal with prediction problems, is chosen in this study. The principle of this rule is to minimise the total output error with respect to the weights (Smith, 1993). In each epoch the network adjusts the weights in the direction that reduces the error. The training rules are as follows:

Step 1: Select a learning rate $\alpha$ and initialise the weight vectors $w$ and $v$ using random numbers.

Step 2: Present the input data and compute the layers' output by Equations 5.5 and 5.6.

$$y_j = f(w_{0j} + \sum_{i=1}^{s} x_i w_{ij}) \quad [5.8]$$

$$z_k = f(v_{0k} + \sum_{j=1}^{m} y_j v_{jk}) \quad [5.9]$$

where $s$, $m$ are the number of input and hidden units respectively.
Step 3: Compute the weight correction terms of the output and hidden units by Equations 5.7 and 5.8.

\[ \Delta v_{jk} = \alpha (t_k - z_k) f'(v_{ok} + \sum_{j=1}^{m} y_j v_{jk}) y_j \]  \hspace{1cm} [5.10]

\[ \Delta w_{ij} = \alpha f'(w_{ij} + \sum_{i=1}^{l} x_i w_{ij}) \sum_{k=1}^{q} \left( (t_k - z_k) f'(v_{ok} + \sum_{j=1}^{m} y_j v_{jk}) y_j \right) x_{ij} \]  \hspace{1cm} [5.11]

where \( q \) is the number of output units and \( \alpha \) is the learning rate which governing the learning speed of the net.

Step 4: If all the input data patterns are trained, go to Step 5, otherwise, go to Step 2.

Step 5: Sum all the weight correction terms and then add correspondingly to the old weights.

Step 6: Repeat Steps 2 to 5 until a sufficiently small output error has been obtained.

Each iteration from Steps 2 to 6 is called an epoch. Usually many epochs are required before training is completed. The training algorithm has been proved to be convergent (Gurney, 1997), provided that a relationship is present between the input and target.

In order to speed up the training process, the "adaptive learning law" is used. The concept is simple (Smith, 1993). Let there be a different learning rate \( \alpha \) for each weight in the network. Apply the following rule to each weight separately: if the direction in which the error decreases at this weight change step is the same as the direction in which it has been decreasing in the previous step, make \( \alpha \) larger; if the direction in which the error currently decreases is the opposite of the recent direction, make \( \alpha \) smaller.
5.5.1.5 The model

The modelling technique proposed in this discharge headway model is based on the main factors affecting discharge headway as discussed in previous sections. To estimate the vehicle discharge headway of individual queued vehicles, a 3-layered neural net with 1 output unit is used. The one and only one output unit is the discharge headway. It has been proved that a 3-layered neural network is capable of universal approximation in a precise and satisfactory sense (Hornik et. al., 1989).

5.5.1.5.1 Selection of input variables

Since there are no systematic methods for selecting variables for neural network models (Smith, 1993), considerations of variable selection are based on the literature review and judgement. In general, vehicle discharge headway depends on a list of potential explanatory variables such as the geometrical and vehicle variables. Some of these variables have been discussed in previous sections. While it is impossible to include all the potential variables, some have to be excluded from the model. Variables that have been selected must be easily measured on site since a considerable amount of data has to be collected to develop the model. Based on this objective, eight variables have been chosen to be the input variables for estimation of the discharge headway of individual queued vehicles. They are shown in Table 5.1.

The rationale of choosing these variables is explained as follows. First of all, the geometrical variables are well researched to have significant effect on the discharge headway. On the average basis the discharge headway decreases with lane width
(X_1). It was also found from field data, that the discharge headway of the kerb-side lane is significantly larger than that of the offside lane. The discrepancies may arise from interruption by pedestrians. It is of great interest to include this effect (i.e. X_2) in the model. The lanes were numbered from the kerb side (i.e. lane position 1 is the kerb-side lane) and then consecutively outwards.

<table>
<thead>
<tr>
<th>Variables</th>
<th>Definition</th>
<th>Ranges</th>
</tr>
</thead>
<tbody>
<tr>
<td>X_1</td>
<td>Lane width (meters)</td>
<td>No specific range</td>
</tr>
<tr>
<td>X_2</td>
<td>Lane positions</td>
<td>1 – 5</td>
</tr>
<tr>
<td>X_3</td>
<td>Vehicle type of the subject vehicle</td>
<td>1 – 4</td>
</tr>
<tr>
<td>X_4</td>
<td>Queue position of the subject vehicle</td>
<td>1 – queue length</td>
</tr>
<tr>
<td>X_5</td>
<td>Turning radius of the subject vehicle</td>
<td>0 for ahead movements; No specific range for turning movement</td>
</tr>
<tr>
<td>X_6</td>
<td>Discharge headway of the preceding vehicle</td>
<td>No specific range</td>
</tr>
<tr>
<td>X_7</td>
<td>Vehicle type of the preceding vehicle</td>
<td>0 – 4; (0 for the first queued vehicle)</td>
</tr>
<tr>
<td>X_8</td>
<td>Turning radius of the preceding vehicle</td>
<td>0 – 4; (0 for the first queued vehicle)</td>
</tr>
</tbody>
</table>

Table 5.1 Definition of input variables

The queue position of the subject vehicle X_3 is an indispensable variable in the estimation of the discharge headway. Previous research revealed that the first few vehicles do need more time to pass through the junction and the queue position does have important bearings on the discharge headway.

It is well researched that the vehicle discharge headway differs between various vehicle types. Correction factors on the headway for large vehicles were first derived by Carstens (1971) and further developed by Tsao and Chu (1995). This made X_4 necessary to be incorporated in the model. In the present study, vehicles are categorised into 4 types, namely
Type I  Passenger cars and taxis;
Type II  Vans and small goods vehicles;
Type III Medium and heavy goods vehicles; and
Type IV  Buses and coaches.

As the proportion of motorcycles is very small in Hong Kong and they do not usually queue up like other vehicles, they are not included in the model.

Logically, turning vehicles should have longer discharge headways. Under the safety constraints, turning vehicles should travel at lower speeds and induce longer headways than straight through vehicles. The left-turning and right-turning vehicles have shown respectively by Lu (1984) and Carstens (1971) that they do have different headways. Akcelik (1981) and Taylor, Bonsall and Young (2000) also suggest that turning vehicles have longer headways. Under different driving system (left- or right-hand), the effect of the turning movements has different impacts on headways. Instead of a turning movement, the turning radius is more suitable to describe the effect of turning. These necessitate the presence of $X_5$.

Characteristics of the preceding vehicle do have important bearings on the discharge headway of the following vehicle. Heavy vehicles, probably pass through the junction at lower speeds, making the following vehicle follow at a lower speed and result in a longer discharge headway. Greenshields et. al. (1947) showed that large vehicles not only require more time to enter the junction but also causes other following vehicles to have a large headway. Therefore, characteristics of the preceding vehicle (i.e. the discharge headway $X_6$, vehicle type $X_7$ and movement
type $X_6$) have to be included in the model. For the first vehicle, no vehicle is followed so $X_7$ and $X_8$ will be equal to the 0 while $X_6$ will be equal to the starting reaction time of the first vehicle. Starting reaction time of the first vehicle was defined as the time interval between the signal change to go and the movement of the first queued vehicle (Greenshields et. al., 1947). However, it is observed that some vehicles started to move at the red/amber period. Therefore, the definition was modified to the time interval between the signal turns red/amber and the movement of the first queued vehicle.

There are other important factors, such as the approach speed which was considered as a significant influencing factor (Lee and Chen, 1986). However, vehicle speeds in urban areas are restricted. In the urban areas of Hong Kong, the speed limit is 50 km/h. In the signalised urban network the approaching speed is around 20 km/h with very little variation. Since the present model is designed for urban junctions, the approach speed may have less significant impacts on the discharge headway. Should the model be extended to non-urban areas, this factor may have to be further investigated.

Driver reaction time was also found to be an important variable, which can take into account the random human behaviours. Johansson and Rumer (1971) reported that the median reaction time was 0.66 seconds and the range was between 0.3 and 2.0 seconds in alerted situations. However, there are difficulties in recording the reaction time of all the following vehicles with the equipment available. If counting is performed manually, data accuracy is expected to be low. Under these constraints, the driver reaction time of each of the following vehicle is discarded. However,
reaction time of the first queued vehicle was recorded and taken into account in developing the model.

The length of the green period may also have an impact on discharge headway. In case of very short green periods, say less than 10 seconds, drivers may be more aggressive to get through the junction as fast as possible so that slightly shortened discharge headway may result. However, our recorded green periods are well over 10 seconds. They range from 30 seconds to 60 seconds. The effect of a very short green period on the headway is expected to be small and has not been explored.

5.5.1.5.2 NNDHM model structure

The structure of the NNDHM model is shown in Figure 5.5. The procedure starts by feeding the model with the geometrical variables as well as the characteristics of the first vehicle, and then calculates its discharge headway. For the following vehicles, headways are obtained based on the nine variables described in the previous section. These includes the lane width, lane position, vehicle type, turning radius and discharge headway of the preceding vehicle, queue position, vehicle type and turning radius of the subject vehicle. The procedures are repeated until the end of the queue.

During the training stage, the model weights are adjusted with respect to the training data set. The AAPE of the validation set is used to check whether the model is over-fitted or not. All data in both sets are collected on site. For each epoch, the model prediction errors (i.e. AAPE) are calculated for both the training and validation data set after weight adjustments. When calculating the error on the validation sample,
input data only needs to be fed forward through the neural network and calculates the error for each data sample. It is not necessary to feed back the error information because weight adjustments are based on the training data set only.

Figure 5.5 The structure of the NNDHM model

At the validation stage, only the test data will be used. It can be seen from the model structure that the headway obtained in the preceding step is in turn used as input data to calculate the headway of the following vehicles. Therefore, unlike the training stage, the calculated headway in the preceding step of the model will be used instead
of the actual discharge headway measured on site as input data at the validation stage. In other words, when the model has been trained, the calculated headway is used practically as an input data. These modelled headways are then compared with the headways in the test data set and the AAPE is computed.

In brief, a new discharge headway model NNDHM has been developed and unlike other previous headway models, this model does not need to pre-specify or presume the explicit form of the relationship among the dependent and independent variables. Those input variables have been carefully selected. They are representative and can be measured easily with the available equipment. Once the NNDHM model is trained with sufficient data, it can be applied to estimate the discharge headway of individual queued vehicles at signal controlled sources.

5.6 Vehicle Generations

Vehicles are generated from the sources by the following scheme. Each source can be selected to generate vehicle arrivals by either the distribution or the NNDHM method. If the distribution method is selected, the mean traffic flow rate of the connected link and the proportions of the four types of vehicle have to be specified. Vehicle arrival headway will be generated by the double displaced negative exponential distribution (DDNED).

\[
f(h) = \begin{cases} 
0 & h < d \\
\phi \lambda_1 e^{\lambda_1(h-d)} + (1-\phi)\lambda_2 e^{\lambda_2(h-d)} & h \geq d 
\end{cases} \quad [5.12]
\]
where $\phi = \text{weight factor in } [0.5, 0)$

\[ \phi = b_0 + b_1 \text{ (flow)} + b_2 \text{ (flow)}^2 \tag{5.13} \]

$d = \text{displacement parameter}$

\[ d = c_0 + c_1 \text{ (flow)} \tag{5.14} \]

$\lambda_1, \lambda_2 = \text{constants associated with the traffic flow}$

The DDNED was chosen from those discussed in previous sections. It was chosen because it was developed for estimating vehicle headway influenced by the output pattern of vehicle discharges from an upstream signal controlled junction (Griffiths and Hunt, 1991). With the specified mean traffic flow rate the values of $\phi$ and $d$ are then estimated from Equations 5.13 and 5.14 respectively. The standard deviation, $s$, of headways is estimated from the following equation

\[ \left[ s^2 - (1 + \phi)(\bar{x} - d)^2 / (1 - \phi) \right] / \lambda_1^2 + 4\phi(1 - \phi)(\bar{x} - d)\lambda_1 - 2\phi/(1 - \phi) = 0 \tag{5.15} \]

where $\bar{x} = (1 / \text{flow})$

\[ = d + \phi / \lambda_1 + (1 - \phi) / \lambda_2 \tag{5.16} \]

Finally, the four parameters can be determined by Equation 5.13 to Equation 5.16.

For generating vehicle arrival times by the NNDHM method, the corresponding source should associate with a set of signal timing data and stage sequence of those lanes (call NNLanes) in which vehicles will queue up to enter the network. Each NNLanes should have the following attributes:
Id                  A unique identification number
SourceId            Id of the source the NNLane belongs to
Length               Length of the NNLane
Width                Width of the NNLane
L.Pos                Lane position as defined in Section 5.5.1.5.1
Flow                 Mean traffic flow
T.Radius             Turning radius from the NNLane to the network
T.Pro                Proportion of vehicles will turn into the network (for mixed lanes)
VehPro               Proportions of different vehicle types carried by the NNLane

Vehicles are generated to the NNLanes according to the DDNED. Vehicle arrival headway for the link connected to the source is given by the estimated discharge headway for those NNLanes that have right of way. If there is a queue in the NNLane, headway is estimated by the NNDHM model, otherwise, it is generated according to the DDNED.

5.7 Vehicle/Driver Attributes

In the current traffic simulation model, individual vehicles and drivers are assigned a set of permanent attributes which remain constant throughout the simulation run, and a set of temporary attributes which are updated periodically.

Permanent Attributes:

Id                  Vehicle identification number assigned sequentially to each vehicle
Arr.Time            Arrival time of the vehicle to the system
**BRT**  Vehicle brake reaction time  
**Length**  Length of the vehicle  
**SD**  Safety distance (i.e. the distance with the leading vehicle in a queue)  
**DesSpd**  Desired Speed  
**MaxDec**  Maximum deceleration rate  
**C.Gap**  Critical gap

Temporary Attributes:

**CurPos**  Current position of the vehicle  
**UpdPos**  Updated position of the vehicle  
**CurSpd**  Current speed of the vehicle  
**UpdSpd**  Updated speed of the vehicle  
**CurLane**  The current lane of the vehicle  
**DesLane**  Desired lane of lane changing vehicle  
**TurnInd**  Turning indicator, indicated the intended turning direction of the vehicle  
**ChangeType**  The change type (i.e. 0 – non changing; 1 – essential changing, 2 – non-essential changing)  
**Lcf**  Lane changing factor  
**SpdAdj**  Speed adjustment indicator, indicated the direction (down- or upward) of speed adjustment for lane changing vehicles to adopt the traffic conditions

5.7.1 **Brake reaction time**

Brake reaction time has long been the object of study in the fields of physiology and
psychology. It was first measured under simulated conditions in the laboratories and later from field driver responses (Drew, 1968; Johansson and Rumar, 1971; Hooper and McGee, 1983; Olson and Cleveland, 1984). The time measured in these field driver response experiments is the sum of the time to perceive the need for braking and the time to move the foot from the accelerator to the brake pedal. Drew (1968) conducted an experiment consisting of 1000 men and women drivers. The mean reaction time for men was 0.57 and for women was 0.62 second.

Johansson and Rumar (1971) measured the brake reaction times of 321 drivers under an anticipated condition and a much smaller sample of 5 drivers under surprise conditions. It was reported that the median brake reaction time was 0.66 second and the range was between 0.3 to 2.0 seconds in alerted situations. The result of this study stated that on 10 percent of the occasions, mean brake reaction time was estimated to be 1.5 seconds.

Olson and Cleveland (1984) have conducted a study to investigate perception-response time for young (age 40 or less) and older (age of 60 or more) drivers under surprised and alerted conditions. Under alerted conditions the 20th and 90th percentile values for both young and old drivers were in the range of 0.42 to 0.70 second. Under surprised conditions the 20th and 90th percentile values were (0.57, 0.95) and (0.63, 1.00) for young and older drivers respectively.

The results from the study by Johansson and Rumar (1971) have been used by WEAVISIM, a simulation model for freeway weaving sections (Mohsen, 1987), and CARSIM, a car following model for traffic simulation (Benekohal and Treiterer,
1988), to generate the brake reaction times. In this traffic simulation model, vehicle brake reaction times are generated stochastically from a gamma distribution based on the results of the Johansson and Rumar study. The mean and variance of the gamma distribution are 0.745, and 0.073 seconds, respectively. To prevent the generation of unreasonable brake reaction times, the generated values are truncated at 0.25 and 1.50 seconds.

5.7.2 Length

Vehicle length is assigned deterministically based on vehicle type defined in Section 5.5.1.5.1: 3.96 meters for Type I vehicles, 4.5 meters for Type II vehicles, 9.75 meters for Type III vehicles, and 12.2 meters for Type IV vehicles. Vehicle type is assigned by comparing a uniform random number with the cumulative distribution for the four types of vehicles.

5.7.3 Safety distance

Mohsen (1987) modelled the safety distance as a function that is inversely proportional to the driver's maximum speed in the range of 1.5 to 4.5 meters. In the current traffic simulation model, the safety distance is generated from truncated normal distribution with mean and variance of 3.05 and 0.5 meters, respectively. The generated values are truncated at 1.5 and 4.5 meters.
5.7.4 Desired speed

Speed distribution is influenced by various factors such as traffic volumes, density, vehicle conditions as well as the restraints of speed and regulations. At the system entry point where the conditions are such that drivers can select whatever speed they desire (i.e. a free flowing condition). There is always a wide range of speeds at which the various individuals operate their vehicles.

Numerous researchers have used normal distribution to represent speeds (Pignataro, 1973; Breiman et. al., 1977). Some researchers, however, have found speed distributions to be quite skewed when a fit of normal distribution is attempted, and therefore, have suggested other distributions for speed, such as Erlang distribution (Ashworth, 1976) and log-normal distribution. Some investigators have suggested the use of truncated normal distributions to represent speeds (Rathi, 1983; Benekohal and Treiterer, 1988). NETSIM (Wong, 1990) models the speed distribution by introducing 10 distinct driver types. The speeds of these drivers are represented by the percentage of the mean free flowing speed, which varied from 75 to 127 percent.

In the TREQSIM model, desired speeds are sampled from truncated normal distribution. The mean and standard deviations for the distribution are the corresponding lane's speed limit and 1, respectively. The generated values are truncated at 75 and 127 percent of the lane's speed limit.
5.7.5 Minimum stopping distance

According to the Transportation and Traffic Engineering Handbook (1982), the minimum stopping distance MSD should be proportional to the vehicle speed.

\[
MSD = \frac{v^2}{255} (f \pm g) \tag{5.17}
\]

where \( v \) = vehicle speed

\( f \) = coefficient of friction, tire to pavement

\( g \) = gradient

The Transportation and Traffic Engineering Handbook (1982) contains skidding friction coefficients for various pavement and tire conditions. Using a mean value of 0.58 of the friction coefficient and zero grade, Equation 5.17 is reduced to:

\[
MSD = \frac{v^2}{147.9} \tag{5.18}
\]

5.7.6 Acceleration/Deceleration capabilities

Acceleration/deceleration rates are influenced by speed as well as by vehicle type. Several attempts have been made to investigate the acceleration/deceleration capabilities of different vehicle types at various speeds. Buhr (1968) assumes constant values for both acceleration and deceleration rates. Those values are provided as input information and are held constant throughout the simulation.
process. Some others (Rathi, 1983) assume a discrete or step function relationship between acceleration/deceleration rates and speed. Some use mathematical formulation of acceleration/deceleration rates as a continuous function of operating speed.

In the TREFSIM model, the maximum rate of acceleration is expressed as an inverse linear function of speed for different vehicle types. This was done by regression analysis of the data present in the Traffic Engineering Handbook (1982). Figure 5.6 illustrates the relationship between maximum rates of acceleration and speed for the different vehicle types. The normal acceleration and deceleration rates are, in contrast, obtained from a discrete step function relationship developed from information given in the Transportation and Traffic Engineering Handbook (1982). They are shown in Table 5.2.

![Graph showing relationship between maximum rates of acceleration and speed](image)

Figure 5.6 Relationship between maximum rates of acceleration and speed

From the laws of dynamics, using the constant deceleration model, the stopping
distance with deceleration rate \( d \) is given by \( \frac{v^2}{2d} \). Therefore, the maximum deceleration rate \( (d^{\text{Max}}) \) can be derived by equating \( \frac{v^2}{2d} \) with Equation 5.18:

\[
\frac{v^2}{147.9} = \frac{v^2}{2d} \implies d^{\text{Max}} = 35.42 \text{ m/s/s}
\]  

[5.19]

This value is imbedded in the TREFSIM model as the maximum deceleration rate.

<table>
<thead>
<tr>
<th>Speed Change</th>
<th>Accelerations</th>
<th>Decelerations</th>
</tr>
</thead>
<tbody>
<tr>
<td>km/h</td>
<td>km/h/s</td>
<td>km/h/s</td>
</tr>
<tr>
<td>0-24</td>
<td>5.3</td>
<td>8.5</td>
</tr>
<tr>
<td>0-48</td>
<td>5.3</td>
<td>7.3</td>
</tr>
<tr>
<td>48-64</td>
<td>5.3</td>
<td>5.3</td>
</tr>
<tr>
<td>64-80</td>
<td>4.2</td>
<td>5.3</td>
</tr>
<tr>
<td>80-97</td>
<td>3.2</td>
<td>5.3</td>
</tr>
<tr>
<td>97-113</td>
<td>2.1</td>
<td>5.3</td>
</tr>
</tbody>
</table>

Table 5.2  Normal acceleration and deceleration

5.7.7  The critical gap

The critical gap is defined as the time headway between two successive vehicles in a traffic stream of a conflicting movement that is accepted by drivers in a subject movement that must cross or merge with it (HCM, 1985). It depends on a number of factors such as vehicle speed. It has been represented by log-normal (Troutbeck, 1992) and hyper-Erlang (Brilon, 1995) distributions. Among these two distributions, the log-normal distribution has been used more extensively (Velan and Van Aerde, 1996). Thus, in the current traffic simulation mode, the critical gap for each vehicle
is generated from a log-normal distribution with mean and variance of 5.0 and 0.5 respectively (Velan and Van Aerde, 1996).

5.8 Vehicle Movements

The movement of a vehicle in the network is determined by its interactions with the vehicles ahead, responses to traffic controls and desired speed. These interactions are manifested in lane change decisions as well as acceleration and deceleration rate applied at any given time. The simulator maintained a linked list of vehicles in each lane and moves individual vehicles according to the car following, lane changing and other event responding models described in this section. The car following model computes the speed of a vehicle at the next time step in terms of its relationship with the leading vehicles; the lane changing model represents the behaviour of switching lanes; and the event responding model captures drivers' responses to traffic signals.

Having obtained the speed at the next time step, the updated position is then determined using the following equations:

\[ x_{n}^{t+1} = x_{n}^t + v_{n}^t + (0.5)\alpha_{n}^t \]  \hspace{1cm} [5.20]

where \( v_{n}^t \) = speed of vehicle \( n \) at time \( t \)

\( x_{n}^t \) = distance of vehicle \( n \) from the stop line at time \( t \)
5.8.1 Vehicle loading

Vehicles are generated and introduced into the system by the method stated in Section 5.6. The vehicles are randomly generated on different available lanes based on lane use proportion. Upon entering, the vehicles are randomly designated as through, left, or right turning based on the turning proportion of the lane. Other vehicle/driver attributes are also generated to the vehicle as described in Section 5.7. The initial position is assigned to be at the upstream end of the lane and the speed is governed by the car following model. If there is no space available in the entrance lane, vehicles are discarded if it is generated by the DDNED method while if it is generated by the NNDHM method, vehicles are stored in the NNLane as a queue and wait to enter the network during subsequent time intervals.

5.8.2 Car following model

The car following model calculates a vehicle's updated speed at the next time step in terms of its relationship with the leading vehicle. It has been the subject of numerous modelling efforts in the past (Chander et. al. 1958; Gazis et. al., 1961; Gipps, 1980; Benekohal and Treiterer, 1988). Detailed reviews of the mandatory car following model are available elsewhere (Tong and Hung, 1999; Brackstone and McDonald, 1999).

The most frequently used form of a traditional car following model is the generalised form of Gazis, Herman and Rothery (1961).
\[ a'_n = \beta'_n [v'_{n-1} - v'^{-1}], \quad n = 2, 3, \ldots, N \]  

[5.21]

where \( \beta'_n \) is the sensitivity of vehicle \( n \) and is given by

\[ \beta'_n = \frac{\alpha [v'_n]^m}{[x'_{n-1} - x'^{-1}]^l}, \quad n = 2, 3, \ldots, N \]  

[5.22]

where \( \tau \) is the reaction time, \( \alpha \) is a (positive) coefficient of proportionality and \( m \) and \( l \) are non-negative constants, not necessarily integers. The complexity of the model depends on the selection of \( m \) and \( l \). Gazis et. al. (1961) pointed out that the simple form in Equation 5.21 should not be extrapolated to the range of low traffic concentration where interactions between vehicles disappear statistically. This type of model makes no allowance for the effect of the inter-vehicle spacing independent of the relative speed (Addison and Low, 1996; Low and Addison, 1998).

Theoretically, vehicles governed by the traditional type of car following model can travel arbitrarily close together provided their speeds are identical. This is very dangerous that collision may be occurred if the following vehicle is travelling at a high speed and an extremely short distance headway with the preceding vehicle.

Another approach in developing car following models is setting restrictions on the speed or acceleration of the subject vehicle. The restrictions are imposed in terms of safe driving. It assumes that the driver will possibly travel as fast as possible when all the safety constraints are satisfied. Examples of this type of model are those models developed by Lieberman (1972), Gipps (1976, 1980) as well as Benekohal and Treiterer (1988).
The current car following logic is based on the distance and relative speed between the leading and the following vehicles. Depending on the magnitude of this headway, a vehicle is classified into free flowing or car following.

5.8.2.1 Free flowing

If the distance between the leading and following vehicles is larger than the normal stopping distance, the following vehicle is considered to be in a free flowing state and that there is no interaction with the leading vehicle. In this case, the vehicle speed is governed by the following equation:

\[
\begin{align*}
v_{n+1}' &= \begin{cases} 
v_{n}' + a_{n}^{\text{Max}} & \text{if } v_{n}' < v_{n}^{\text{desire}} \\
0 & \text{if } v_{n}' = v_{n}^{\text{desire}} \\
v_{n}' + d_{n}^{\text{Normal}} & \text{if } v_{n}' > v_{n}^{\text{desire}} 
\end{cases} 
\end{align*}
\]

[5.23]

where \( a_{n}^{\text{Max}} \) = maximum acceleration rate of vehicle \( n \)

\( d_{n}^{\text{Normal}} \) = normal deceleration rate of vehicle \( n \)

\( v_{n}^{\text{desire}} \) = desired speed of vehicle \( n \)

If the vehicle's current speed is lower than its desired speed, it accelerates at the maximum acceleration rate to achieve its desired speed as quickly as possible. If the current speed is higher than the maximum speed, the vehicle decelerates with the normal deceleration rate in order to slow down.
5.8.2.2 Car following

If the distance between the leading and following vehicles is smaller than the normal stopping distance, the following vehicle is considered to be at the car following state that the following vehicle is interacting with the leading vehicle. It is assumed that driver of the following vehicle will attempt to drive as fast as the physical capability and safety constraints are satisfied.

![Diagram of car following model development](image)

**Figure 5.7** Illustration of the car following model development

Suppose that two successive vehicles are disposed as shown in Figure 5.7 and during \((t, t+1)\) the speeds of the leading and following vehicles change uniformly from \(v_{n-1}'\) to \(v_{n-1}''\) and \(v_n'\) to \(v_n''\) respectively, then we have
\[ D_{n-1/n}^t + \frac{1}{2}(v_{n-1}^t + v_{n-1}^{t+1}) = D_{n-1/n}^{t+1} + \frac{1}{2}(v_n^t + v_n^{t+1}) \]  

where \( D_{n-1/n}^t \) = distance between rear bumpers of vehicle \( n-1 \) and \( n \) at time \( t \)

If the leading vehicle \( (n-1) \) commences maximum braking, it will stop after a further \(-\frac{(v_{n-1}^{t+1})^2}{2d_{n-1}^{Max}}\) meters (where \( d_{n-1}^{Max} \) is the maximum deceleration rate). After a delay due to driver reaction time, \( BRT \), the following vehicle \( (n) \) also commences maximum deceleration and stops after travelling \( BRT \cdot v_n^{t+1} - \frac{(v_n^{t+1})^2}{2d_{n-1}^{Max}} \) meters.

For safe driving, the following vehicle should stop behind the leading vehicle at least equal to the safety distance \( SD \). Thus, the following inequality must hold:

\[ BRT \cdot v_n^{t+1} - \frac{(v_n^{t+1})^2}{2d_{n}^{Max}} \leq D_{n-1/n}^{t} - SD \]

\[
+ \frac{1}{2}(v_{n-1}^t + v_{n-1}^{t+1}) - \frac{1}{2}(v_n^t + v_n^{t+1}) - \frac{(v_{n-1}^{t+1})^2}{2d_{n-1}^{Max}}
\]

Solve Equation 5.25 for \( v_n^{t+1} \), we have

\[ v_n^{t+1} \leq \frac{B + \sqrt{B^2 - 4C}}{2} \]

where \( B = d_n^{Max}[2BRT + 1] \)

\[ C = d_n^{Max}[2(D_{n-1/n}^t - SD) + v_{n-1}^t + v_{n-1}^{t+1} - v_n^t - (v_{n-1}^{t+1})^2 \left( \frac{d_{n}^{Max}}{d_{n-1}^{Max}} \right)] \]
Additional constraints are imposed on $v_{n+1}^{t+1}$ by the requirements that it must not exceed the desired speed of the following vehicle and beyond its physical capabilities (maximum acceleration $a_{n,\text{Max}}^\text{Max}$). Thus, under the following condition, the speed of the following vehicle at $t+1$ should be given by

$$v_{n+1}^{t+1} = \min\left\{ \frac{-B + \sqrt{B^2 - 4C}}{2}; v_n^{\text{desire}}, v_n' + a_{n,\text{Max}}^\text{Max} \right\} \tag{5.27}$$

The speed obtained from Equation 5.27 is inhibited by the following conditions:

1. It cannot be less than the speed obtained by applying the maximum deceleration rate ($d_{n,\text{Max}}^\text{Max}$) on the vehicle's current speed. If it is, the speed obtained by applying $d_{n,\text{Max}}^\text{Max}$ will be used.

2. It cannot exceed the speed obtained by applying the maximum acceleration rate ($\alpha_{n,\text{Max}}^\text{Max}$) on the vehicle's current speed.

3. It cannot exceed the vehicle's desired speed ($v_n^{\text{desire}}$).

5.8.3 **Responses to traffic signal**

*Queue formation*

Vehicles react to traffic signal when the distance is less than or equal to the normal stopping distance. If a vehicle finds that the signal is red as it approaches the junction, it will adopt the deceleration rate given by:
\[ d_a = -\frac{v_a^2}{2x_a} \]  

[5.28]

At the next time step, the vehicle will scan the status of the signal again. If the signal is still red, it will continue to decelerate according to Equation 5.28 until it stops to form a queue. But if the signal turns green, the vehicle will start accelerating from that moment onward according to the car following logic. If a vehicle arrives when the signal is green, but the queue has not started moving completely, it will join the queue and will start moving when all the downstream vehicles have started moving.

*Queue dissipation*

When the signal turns green, the queue established during the previous red period starts dissipating. Every vehicle in the queue experiences a start-up delay, which is the reaction time of each individual driver. This reaction time \((RT_i)\) of the first queued vehicle is generated by the extreme value distribution. Development of this reaction time distribution will be described later in the next chapter. The first vehicle moves \(RT_1\) seconds after the signal turns red/amber. Every subsequent vehicle, \(i\), moves \(RT_i\) seconds after the vehicle ahead of it moves. For the fourth and subsequent vehicles, the start up delay time is assigned to be 1 second while \(RT_2\) and \(RT_3\) are calculated by the method of interpolation and is given by:

\[ RT_i = RT_1 - \frac{(i-1)}{3} (RT_4 - RT_1) \]  

[5.29]

Every vehicle in the queue accelerates according to its starting acceleration rate. The vehicle keeps scanning the status of the signal until it clears the approach and enters
the junction. If the signal turns red before a vehicle clears the approach, the vehicle will again start decelerating to form a secondary queue. If the vehicle is less than braking distance away from the junction, it will ignore the signal and continue to travel through the junction.

5.8.4 Right turning logic

In Hong Kong, vehicles are driven on the left, so right turning control may be of whether permitted or protected type. When the signal is red, irrespective of whether permitted or protected right turn control is specified, the right turn vehicles form a queue and wait until the signal turns green again. A difference exists in protected and permitted right turns behaviour only when the signal is green. In the TREFSIM model, only protected right turning type is considered. When the signal is green, vehicles proceed along the approach based on the car following logic and clear the junction.

5.8.5 Left turning logic

When the vehicle comes within normal stopping distance of the junction, it will scan the signal status. If the signal is green, the vehicle will decelerate so that its speed is equal to the left turning speed when it reaches the junction, and it will travel through the junction at this left turning speed.

Left turning speed is related to the turning radius. Limiting speeds corresponding to various turning radii are given in Table 5.3. The left turning speed assigned to each
driver is taken from the normal distribution with a mean equal to 0.85 times the limiting speed and a standard deviation of 1.6 km/h. If the speed is less than the left turning speed, it will accelerate, provided it fulfils the car following logic, to the left turning speed and travel through the junction at this speed.

<table>
<thead>
<tr>
<th>Turning Radius (m)</th>
<th>Limiting Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.10</td>
<td>15.75</td>
</tr>
<tr>
<td>9.15</td>
<td>19.31</td>
</tr>
<tr>
<td>12.20</td>
<td>22.20</td>
</tr>
<tr>
<td>15.25</td>
<td>24.92</td>
</tr>
<tr>
<td>18.30</td>
<td>27.19</td>
</tr>
<tr>
<td>21.35</td>
<td>29.44</td>
</tr>
<tr>
<td>61.00</td>
<td>49.72</td>
</tr>
<tr>
<td>91.50</td>
<td>60.98</td>
</tr>
</tbody>
</table>

Table 5.3  Limiting speed for different turning radii

5.8.6  Speed adjustment

This part operates in relation to the lane changing model to speed up or slow down vehicles in order to make the lane changing possible. Vehicles flagged for downward (upward) speed adjustment, the normal deceleration (acceleration) rate will be applied.

5.9  Lane Changing Model

The lane changing model is based on Gipps (1986) and Mohsen (1987). The model classifies lane changes into two types, essential and non-essential. Essential lane changing that is necessary for the subject vehicle to get to its destination. It occurs when drivers have to change lanes in order to access the lane necessary for an
intended turn. Vehicles will not be prohibited to reach their destination without performing non-essential lane changing. Vehicles perform this type of lane changing to overtake slow or heavy vehicles.

Essential lane changing vehicles attempt to change lanes once they enter the lane until they arrive at the nearest target lane. The nearest target lane is the lane with the same direction of the vehicle’s intended turn and that the least number of lane changing is required to get to it from the current lane. Non-essential lane changing is desired if a vehicle catches up to a slower vehicle in the same lane, and wishes to change lanes to maintain its speed. However, not all vehicles change lanes in this way. The motivation for this type of lane changing is generated uniformly according to the proportion of lane changing vehicles.

Vehicles cannot change lanes under the following situations:

1. If the vehicle entered the junction.
2. If distance from the vehicle to the stop line plus the vehicle length is shorter than 20 meters or a pre-specified marker.

The lane changing logic in the TREFSIM model consists of the following steps:

1. Check if a change is necessary and identify the type of lane changing.
2. Select a desired lane.
3. For essential lane changing vehicles, compute the lane changing factor (LCF).
4. Perform the initial gap acceptance check to establish whether or not the
change is currently possible. If yes go to Step 5, otherwise go to Step 6.

5. Perform the final gap acceptance check at the next time step for any drastic changes in the system status on which the initial gap acceptance check relied.

6. Perform speed adjustment (upward/downward) in order to improve its position with respect to the available gap.

5.9.1 Selection of desired lane

The desired lane should be immediately adjacent to the current lane. When selecting the desired lane, the vehicle first locates the nearest target lane and the desired lane is the adjacent lane in the direction of the nearest target lane.

5.9.2 Lane changing factor (LCF)

The primary motivation behind development of this factor was the fact that as vehicles move closer to the final location from which the lane change has to take place, they become more willing to accept higher risks. The LCF developed in this study is similar to that derived by Mohsen (1987). He assumed the LCF to have an exponential form of:

\[ \text{LCF}(x) = A + e^{Bx} \]  \[5.30\]

where \( x \) = the distance from the last location where the lane change has to take place

\( A, B = \) constants
Figure 5.8 shows the general form of LCF. The LCF can be thought of as the intensity of lane changing. As \( x \) decreases, the intensity of lane changing desire increases. Therefore, the LCF should have its maximum value \((1 + lcf_0)\) near the last location where the lane change has to take place. Consequently the following two boundary conditions are set:

\[
\begin{align*}
\text{LCF}(L) &= 1 \\
\text{LCF}(0) &= lcf_0
\end{align*}
\]  

[5.31]

where \( L \) is the length from the upstream end of the lane and the last location where the lane change has to take place. Substituting the boundary conditions into Equation 5.31,

\[
\begin{align*}
\text{LCF}(L) &= A + e^B L = 1 \\
\text{LCF}(0) &= A + 1 = 1 + lcf_0
\end{align*}
\]  

[5.32]

Solving Equations 5.32, then

\[
\begin{align*}
A &= lcf_0 \\
B &= \frac{1}{L} \ln(1 - lcf_0)
\end{align*}
\]  

[5.33]

\[
\text{LCF} = lcf_0 + e^{\frac{L}{L} \ln(1 - lcf_0)}
\]  

[5.34]
In fact, $1 + \text{lf}_o$ is the range of the LCF (i.e. $\text{LCF} \in [1, \; 1 + \text{lf}_o]$). The $\text{lf}_o$ can also be interpreted as the aggressiveness of the driver. The larger the $\text{lf}_o$, the smaller the gap the driver will accept. It is assumed that the $\text{lf}_o$ is normally distributed between 0 and 1 with mean and variance of 0.5 and 1, respectively. Thus, LCF varies between 1 and 2 (i.e. $\text{LCF} \in [1, \; 2]$).

![Diagram showing the relationship between LCF and gap acceptance](image)

Distance from the last location where lane changing has to take place

**Figure 5.8** General form of the lane changing factor (LCF)

### 5.9.3 Initial gap acceptance check

Once a driver has decided to change lanes, he examines the lead and lag gaps in the desired lane to determine whether the desired change can be executed safely. The criteria for checking the lead and lag gaps in this gap acceptance model is based on
Mohsen (1987). All the comparisons are based on the information of the current time step.

*Lead gap criterion:*

If the speed of the changer is less than the speed of the leader and the distance between them is at least 3 meters, the lead gap is acceptable.

*Lag gap criterion:*

If the speed of the lane changing vehicle is greater than that of the follower and the distance between them is more than 5 meters, the lag gap is acceptable.

*Critical gap criterion:*

For non-essential lane changing, if the available gap (distance between the potential lead and follower) is greater than the changer's critical gap, the available gap is acceptable. For essential lane changing, a Lane Changing Factor (LCF) will be applied to the available gap and if it exceeds the changer's critical gap, the available gap is acceptable.

For non-essential lane changing, if all the three criteria are satisfied, the lane changing is considered to be safe and is initiated in the current time scan. If not satisfied, the non-essential lane changing attempt is aborted.

If the vehicle is making an essential lane change, and if the criteria are satisfied, this check is then considered successful. If it is unsuccessful, the lane changing attempt is aborted and at each successive interval these criteria will be carried out until the
vehicle is successfully moved to the desired lane.

5.9.4 Final gap acceptance check

The check will be carried out for lane changing vehicles at the next time step after they have successfully passed the initial gap acceptance check. This check is performed primarily to detect any drastic changes in position and speed of the potential leader and follower of the changer. It is done by performing the same set of comparisons described in the initial gap acceptance check based on the information at the current time step. If the current positions of the leader and follower still guarantee the safe manoeuvring of the lane changing vehicle, the changing process is considered complete and the vehicle will be moved to its desired lane. In case of a failure in the final gap acceptance check, an initial check will be initiated during the next time step.

5.9.5 Speed adjustment

If during the last lane changing attempt the lead gap check has failed, the changer will flag for downward speed adjustment in order to improve its position with respect to the available gap. If the lag gap was not successful during the last lane changing attempt, the changer will flag for upward speed adjustment.

It is noted that speed adjustments are not directly applied in the lane changing algorithm. As discussed earlier, these adjustments are made in the car following algorithm.
5.10 Model Outputs

Model outputs includes measures of effectiveness such as delay, journey time, average speed, emissions and fuel consumption for each vehicle.

5.10.1 Delay

Reilly et. al. (1976) revealed that no standard set of terms describing delays and stops on approaches to signalised junctions has been presented and accepted by traffic researchers. They stated that most of the work failed to present, in concise terms, definitions of the terms used. Therefore, the development of a logical and precisely defined set of terms is important. The following is a brief review of terminology which has been used in past studies. Another set of comprehensive delay definitions and discussion can be found in Taylor, Bonsall and Young (2000).

1. Total Delay - the total delay due to the signalised junction and includes deceleration delay, stopped delay and acceleration delay. (i.e. the difference between the travel time of a vehicle traversing a junction approach and the travel time of an unimpeded vehicle moving at the free flow speed.)

2. Travel Time Delay - similar to total delay except that the base speed for unimpeded flow has usually been described as the average speed of approaching traffic.

3. Approach Delay - the difference between the time used by any vehicle to
travel a fixed distance from a pre-specified point upstream of a junction to
the junction stop line and the free-flow time associated with that distance.

4. *Time in Queue Delay* - the difference between time a vehicle joins a queue,
which comes to a stop, and the time that the vehicle clears the junction.

5. *Stopped Time Delay* - the time a vehicle is stopped at a junction.

6. *Proportion of Vehicles Stopped* - the number of vehicles having to stop on
the approach to a signalised junction divided by the total number of vehicles
passing through the approach in a given time period.

![Diagram of delay events](image)

Figure 5.9 Definition of various type of delay events

Figure 5.9 shows a plot of distance versus time for the progress of one vehicle and
illustrates different types of delay. Before Point 1, the vehicle is moving at a uniform
speed. From Point 1 to Point 2, the vehicle decelerates until it stops at Point 2 to join
the standing queue before the signalised junction. The vehicle remains stopped between Points 2 and 3, waiting for the signal changes from red to green. Between Points 3 and 5, the vehicle accelerates until it reaches a uniform speed at Point 5.

In Figure 5.9, the total delay $d_t$, approach delay $d_{ap}$, time in queue delay $d_{tiq}$, and stopped delay $d_s$ are given by

$$d_t = (t_5 - t_1) - \frac{L_5 - L_1}{v_f}$$  \[5.35\]

$$d_{ap} = (t_4 - t_1) - \frac{L_4 - L_1}{v_f}$$  \[5.36\]

$$d_s = t_3 - t_2$$  \[5.37\]

$$d_{tiq} = t_4 - t_2$$  \[5.38\]

where $v_f =$ free flow speed. Most researchers (Reilly, et. al., 1976) have agreed that the best indicator of junction performance is approach delay but it may be quite difficult to obtain directly in the field. In contrast, stopped time delay and time in queue delay are easier to measure in the field but they only give part of the approach delay. Therefore, approach delay is considered to be the most indicative delay measure and is used in the TREFSIM model.

5.10.2 Journey time

Journey time $T$ is the total time from the moment a vehicle is generated and introduced into the system until the vehicle clears the junction.
5.10.3 Average speed

Average speed $\bar{v}$ is estimated based on the total distance travelled and the journey time. Total distance travelled $S$ is the distance travelled on the approach and in the junction area. Average speed is given by:

$$\bar{v} = \frac{S}{T}$$  \[5.39]\n
5.10.4 Emissions and fuel consumption

Instantaneous vehicle emissions and fuel consumption are estimated by the ONROAD emissions and fuel consumption model described in Chapter 4. Emissions and fuel consumption of Type I to IV vehicles are estimated by the emission functions derived from the passenger car, petrol van, diesel van and bus respectively.

5.11 Concluding Remarks

In this chapter, the TREFSIM model was described. The model includes a new vehicle generation method, Neural Network Discharge Headway Model (NNDHM), at the network boundary nodes. This model account for the arrival headway affected by the upstream signal junctions.

The car following logic and lane changing algorithm are developed based on mandatory models. It is believed that the car following logic can reasonably model the movements of individual vehicles. When vehicle encounters obstructions, say red
signal indication, it will decelerate to form a queue. The introduction of a reaction time in the car following logic can model the green wave observed for queue discharging at traffic signal when the green signal is displayed.

The lane changing algorithm can account for several observed behaviours as well. Firstly, both essential and non-essential lane changings are considered. Non-essential lane changing algorithm models aggressive driver/vehicle overtaking slower vehicles in front of it. The LCF factor describes essential lane changing vehicle taking higher risk to change lane as it approaches the stop line. The phenomenon that turning vehicle blocking the through lane due to the storage turning lane is full can also be simulated.

Model outputs include the vehicle approach delay, journey time, average speed as well as emissions and fuel consumption. In the next chapter, the newly developed NNDHM model will be trained, validated and tested against field data.
CHAPTER 6

NNDHM MODEL CALIBRATION, VALIDATION AND SENSITIVITY ANALYSIS

6.1 Introduction

In this chapter, the calibration, validation and sensitivity analysis of the neural network discharge headway (NNDHM) model are described. Included are neural network model training, comparison of the model results with field data as well as results from other headway models. Finally, sensitivity analyses of different model parameters are performed.

6.2 Data Collection

Discharge headway data were collected at 26 lane-based sites. The characteristics of the selected sites are shown in Table 6.1.

The selection of these measurement sites were based on the following criteria:

1. Different geometrical characteristics available
2. Significant heavy vehicle proportions
3. Significant turning vehicle proportions for mixed lanes
4. No parking
5. Insignificant disturbances from bus stops
<table>
<thead>
<tr>
<th>Site No.</th>
<th>Movement Type</th>
<th>Lane Width (m)</th>
<th>Turning Radius (m)</th>
<th>Turning Proportion (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>S</td>
<td>2.62</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>2</td>
<td>SL</td>
<td>2.72</td>
<td>17.50</td>
<td>0.53</td>
</tr>
<tr>
<td>3</td>
<td>SL</td>
<td>3.31</td>
<td>10.75</td>
<td>0.56</td>
</tr>
<tr>
<td>4</td>
<td>S</td>
<td>3.59</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>5</td>
<td>S</td>
<td>3.70</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>6</td>
<td>R</td>
<td>3.40</td>
<td>29.00</td>
<td>1.00</td>
</tr>
<tr>
<td>7</td>
<td>R</td>
<td>3.27</td>
<td>25.00</td>
<td>1.00</td>
</tr>
<tr>
<td>8</td>
<td>S</td>
<td>3.26</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>9</td>
<td>S</td>
<td>3.20</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>10</td>
<td>R</td>
<td>3.32</td>
<td>33.75</td>
<td>1.00</td>
</tr>
<tr>
<td>11</td>
<td>R</td>
<td>3.20</td>
<td>30.25</td>
<td>1.00</td>
</tr>
<tr>
<td>12</td>
<td>SL</td>
<td>4.75</td>
<td>11.00</td>
<td>0.65</td>
</tr>
<tr>
<td>13</td>
<td>S</td>
<td>4.50</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>14</td>
<td>L</td>
<td>3.50</td>
<td>9.50</td>
<td>1.00</td>
</tr>
<tr>
<td>15</td>
<td>S</td>
<td>3.35</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>16</td>
<td>S</td>
<td>3.25</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>17</td>
<td>SL</td>
<td>2.75</td>
<td>7.50</td>
<td>0.13</td>
</tr>
<tr>
<td>18</td>
<td>SR</td>
<td>2.75</td>
<td>13.00</td>
<td>0.58</td>
</tr>
<tr>
<td>19</td>
<td>R</td>
<td>3.38</td>
<td>22.50</td>
<td>1.00</td>
</tr>
<tr>
<td>20</td>
<td>S</td>
<td>3.37</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>21</td>
<td>S</td>
<td>3.96</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>22</td>
<td>S</td>
<td>3.22</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>23</td>
<td>S</td>
<td>3.46</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>24</td>
<td>S</td>
<td>3.63</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>25</td>
<td>S</td>
<td>3.18</td>
<td></td>
<td>0.00</td>
</tr>
<tr>
<td>26</td>
<td>S</td>
<td>3.18</td>
<td></td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 6.1 Site Characteristics

In this study, opposed turning movements were excluded. The turning radii were measured from the site map while the lane widths of each lane were measured directly on site. Because the proportion of motorcycles in Hong Kong is small and the queuing behaviour is different from (i.e. one by one) that of other vehicles, all signal cycles with motorcycles were removed from the study. Vehicles that did not start from queue were also eliminated. If the platoon was impeded by pedestrians and cross traffic, it was excluded. In other words, only platoons of unimpeded
vehicles starting from a queue at discharge were considered valid cases for the study. The starting reaction time of the first queued vehicle, discharge headway, vehicle types were directly recorded on site by a portable microcomputer. A Visual Basic program was written to record the start of red/amber and the time at which the queued vehicles passed the stop line. The time at which the first queued vehicle starts moving was recorded to calculate the starting reaction time. Passage times of successive queued vehicles were recorded by pressing predefined keys from keyboard. Different keys represented different types of vehicles. The data were then stored in the microcomputer directly. During the data collection periods, the surveyor stood beside the stop line of the selected approach to collect data. This data collection methodology has the advantage of saving time and effort. The accuracy of the measured discharge headways was assured because of the accuracy of the computer clock and with less human error involved in recording the data. Data input error was avoided as the measured headways were stored directly in the computer. Surveys were conducted at the peak periods (8:00 to 9:00 and 17:00 to 18:00) on weekdays in November of 1999. A total of 1642 signal cycles and 17061 vehicle discharge headways were recorded.

6.2.1 Data characteristics

The average discharge headway, standard deviations and sample sizes of Type I to Type IV vehicles are 1.96 (0.69, 10112), 2.24 (0.72, 3686), 2.74 (0.78, 1352), 3.79 (0.94, 1862) seconds respectively. Larger vehicles have larger headway. The number of vehicles in the queues varied from 1 to 20. In general, queues with more than 20 vehicles were rare occurrences at urban signal controlled intersections in Hong
Kong. The average discharge headway for the first eighteen headways were compared with values reported in previous studies. The comparison is shown in graphical form in Figure 6.1.

![Graph showing comparison of departure headway pattern from various studies](image)

**Figure 6.1** Comparison of departure headway pattern from various studies

The average headway from this study is consistent with previous work (Greenshields, 1947; Gerlough and Wanger, 1967; Carstens, 1971; Lee and Chen, 1984; Moussavi and Tarawneh, 1990). All the discharge headways from various studies appear to follow a similar pattern, that is, discharge headway decreases with respect to the queue position. The average discharge headways derived for all data in this study are almost the average of other studies. The reasons contributing to this pattern have been addressed by many researchers elsewhere. The discrepancies of the discharge headway of the first vehicle are the result of the differences in definition in various studies (Lee and Chen, 1984; Teply et. al., 1991).
6.2.2 Starting reaction time distribution

The starting reaction times of the first queued vehicle were grouped by vehicle type and sampling distributions were then fitted. The distribution fitting software BestFit was employed to fit the sampling distribution (Jankauskas and McLafferty, 1995). The software estimates the parameters of more than 20 bell-shaped continuous distributions (includes normal distribution, exponential distribution and so on) that optimise the goodness-of-fit using the Levenberg-Marquardt method. The first guess of parameters is made by maximum-likelihood estimators. The commonly used chi-square statistic is used as the goodness-of-fit test. This test measures the deviations between the sample distribution function and the hypothetical distribution function. The one with the lowest deviation is considered to be the best fit. All functions are compared and ranked.

Using the BestFit software, it was found that the Type I Extreme Value Distribution obtained the best fits for all four groups. The distribution function is as follows:

\[
F(x) = \exp \left\{ - \exp \left( - \frac{x - a}{b} \right) \right\}
\]  

[6.1]

where \(a\) and \(b\) (> 0) are parameters. \(a\) is the sample mean and \(b\) is the multiple of the sample standard deviation. The comparison between the observed and fitted distributions of the starting reaction time of a passenger car (Figure 6.2) shows that the observed distribution is close to the fitted distribution. Those comparison graphs for the van, truck and bus are not shown because they are similar to this. The
distribution parameters for each group are shown in Table 6.2. The average reaction time is basically proportional to the vehicle size and the dispersion increases for larger vehicles.

![Graph showing comparison of observed and fitted starting reaction time distribution for Type I vehicle](image)

Figure 6.2 Comparison of observed and fitted starting reaction time distribution for Type I vehicle

<table>
<thead>
<tr>
<th></th>
<th>Type I</th>
<th>Type II</th>
<th>Type III</th>
<th>Type IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample Size</td>
<td>969</td>
<td>325</td>
<td>125</td>
<td>223</td>
</tr>
<tr>
<td>Parameter 1 ((a))</td>
<td>1.32</td>
<td>1.48</td>
<td>1.55</td>
<td>1.53</td>
</tr>
<tr>
<td>Parameter 2 ((b))</td>
<td>0.66</td>
<td>0.65</td>
<td>0.73</td>
<td>0.82</td>
</tr>
</tbody>
</table>

Table 6.2 Starting reaction time distribution parameters for each vehicle type

6.3 Training of the NNDHM model

In order to validate the trained neural network, the data set has to be divided into three subsets, namely the training, validation and test sets. The training set is used to
train to network while the validation set is to check whether the network is over-fitted or not. Should the network be over-fitted, the validation set will lead to large prediction errors. This method of assessing the neural network is called the cross validation method (Smith, 1993).

Several types of prediction errors are available to assess the performance of the neural network such as the mean squared error and average absolute percentage error. In the present study, the average absolute percentage error (AAPE) is used to evaluate the model performance, which is shown as follows:

\[
\text{AAPE} = \frac{1}{t} \left( \sum_{i=1}^{t} \left| \frac{O_i - E_i}{O_i} \right| \right) \times 100\% \tag{6.2}
\]

where \( O_i \) = target output value

\( E_i \) = model output value

\( t \) = number of testing data set

The test set is used to measure the model performance expected from the trained network, when it is put into service.

There are a number of software packages available to perform backpropagation algorithms and the MATLAB software was chosen to run on a personal computer. The MATLAB software has a neural network toolbox that can perform the backpropagation algorithm with adaptive learning rate (Demuth and Beale, 1994). The data collected were divided into three sets, the training, validation and test set.
Each set contained data obtained from each site. The characteristics of the three data sets are shown in Table 6.3.

<table>
<thead>
<tr>
<th></th>
<th>Sample Size</th>
<th>Mean Headway (s)</th>
<th>Standard Deviation</th>
<th>Minimum Headway (s)</th>
<th>Maximum Headway (s)</th>
<th>Range (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Training</td>
<td>6888</td>
<td>2.39</td>
<td>0.86</td>
<td>0.60</td>
<td>10.0</td>
<td>9.40</td>
</tr>
<tr>
<td>Validation</td>
<td>5108</td>
<td>2.34</td>
<td>0.58</td>
<td>0.24</td>
<td>7.90</td>
<td>7.66</td>
</tr>
<tr>
<td>Test</td>
<td>4980</td>
<td>2.45</td>
<td>0.86</td>
<td>0.80</td>
<td>8.10</td>
<td>7.30</td>
</tr>
</tbody>
</table>

Table 6.3 Characteristics of the sub-samples

The effectiveness and convergence of the backpropagation training algorithm with adaptive learning rate depend on the number of hidden nodes. To determine the optimum values, 20 experiments have been conducted with the number of hidden nodes varying from 1 to 20. All experiments were limited to a maximum of 1000 iterations. Training was stopped once the average absolute percentage error (AAPE) of the validation set starts to grow. This indicated that the model started to over-fit (Smith, 1993; Gurney, 1997). The resultant errors (AAPE) of the experiments are shown in Table 6.4. The numbers shown in the parentheses are the AAPE on validation set during the training stage.

The table shows that as the number of hidden units increase the AAPE of the training data set decreases converging to about 12 percent. In contrast, the validation data set attains minimum AAPE at 7 number of hidden units and then increases after the 7 number of hidden units, which indicated that the neural net started to over-fit. Therefore, it can be concluded that 7 hidden units lead to the best results. The resultant vectors are as follows.
<table>
<thead>
<tr>
<th>Number of hidden units</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
</tr>
<tr>
<td>17.6</td>
</tr>
<tr>
<td>(28.9)</td>
</tr>
<tr>
<td>11</td>
</tr>
<tr>
<td>12.4</td>
</tr>
<tr>
<td>(28.4)</td>
</tr>
</tbody>
</table>

The figures are the AAPE's of the training data set and those in the parentheses are AAPE's of the validation data set during training.

Table 6.4 AAPE obtained for different number of hidden units

\[
\mathbf{w} = \begin{bmatrix} w_0 & w_1 & w_2 & w_3 & w_4 & w_5 & w_6 & w_7 & w_8 \\
0.4440 & -0.3400 & 0.0026 & 0.2910 & -0.2820 & -0.0139 & 0.0516 & -0.2990 & -0.0979 \\
-2.0100 & 0.2710 & 0.2260 & 0.1890 & 0.3400 & -0.0525 & 0.0809 & 0.3140 & 0.0454 \\
0.9950 & -0.3420 & 0.0968 & 0.0969 & 0.0198 & 0.0029 & 0.1880 & -0.0518 & -0.0044 \\
1.9300 & -0.3230 & -0.3420 & -0.1590 & -0.0604 & 0.0396 & -0.1300 & -0.2310 & 0.0120 \\
0.5550 & -0.4160 & -0.0039 & 0.2430 & -0.1690 & -0.0001 & -0.1670 & -0.0783 & -0.1000 \\
1.3800 & -0.4040 & 0.2360 & -0.0611 & 0.0202 & -0.0177 & -0.0189 & 0.1180 & -0.0076 \\
1.1600 & -0.3240 & 0.0765 & 0.2500 & 0.0611 & 0.0023 & -0.0434 & -0.1710 & -0.0015 \\
\end{bmatrix}
\]

\[
\mathbf{v} = \begin{bmatrix} v_0 & v_1 & v_2 & v_3 & v_4 & v_5 & v_6 & v_7 \end{bmatrix} = \begin{bmatrix} 0.1080 & 0.2380 & -0.0984 & 0.2360 & -0.0602 & -0.3490 & -0.1320 & -0.0727 \end{bmatrix}
\]

6.4 Comparison with Other Models

To justify the proposed NNDHM approach, the model performance was compared with the Briggs’s model, Akcelik's model (described in Chapter 5) and a multiple regression model. The selected models were calibrated with the training data set and compared based on the test data set. For comparison purposes, the independent variables of the multiple regression model are the same as that of the NNDHM.
model. The adjusted $R^2$ and the standard error of the fitted regression model are 0.68 and 0.49.

### 6.4.1 Average discharge headway comparison

The Briggs's model and Akcelik's model estimated the average discharge headway by queue position. The regression model and the NNDHM model estimated the individual discharge headway and the average value by queue position was then derived. For each of the three models, the AAPE between the observed and estimated average headways by queue position were then computed. The results are listed in Table 6.5. The Akcelik's model give the largest error level, which is probably due to the large error induced for the first few vehicles. The Briggs's model and the regression model provide about 10% error on the average headway while the AAPE obtained from the NNDHM model is only 6.8%, which is the smallest among the four models.

<table>
<thead>
<tr>
<th></th>
<th>NNDHM model</th>
<th>Regression</th>
<th>Briggs's model</th>
<th>Akcelik's model</th>
</tr>
</thead>
<tbody>
<tr>
<td>AAPE (%)</td>
<td>6.8</td>
<td>10.4</td>
<td>9.4</td>
<td>12.53</td>
</tr>
<tr>
<td>C.V.*</td>
<td>0.693</td>
<td>0.697</td>
<td>0.855</td>
<td>0.698</td>
</tr>
<tr>
<td>Maximum (%)</td>
<td>21.96</td>
<td>29.84</td>
<td>32.16</td>
<td>44.57</td>
</tr>
<tr>
<td>Minimum (%)</td>
<td>1.13</td>
<td>0.91</td>
<td>0.36</td>
<td>0.24</td>
</tr>
</tbody>
</table>

* C.V. = Coefficient of variations of the absolute percentage error

Table 6.5 Comparison of model performance on average basis

It is noted that the Akcelik's model is not suitable for application in this study. The reason is that the model input parameter is the time since the start of the displayed green period. This parameter for the first queued vehicle plus the red/amber period is
exactly the discharge headway of it, which is what have to be estimated. The inclusion of the Akcelik's model in this chapter is purely for comparison purpose.

6.4.2 Individual discharge headway comparison

It has been shown that the NNDHM model provides the smallest AAPE on the average discharge headway among the three models under consideration. The NNDHM model, however, still needs to be tested on its ability to estimate individual discharge headway, which is the primary objective of this model. Since the Briggs's model is an on average value basis, a comparison is made between the regression and NNDHM models. The AAPE between observed and estimated individual vehicle discharge headways for the models were derived. It was found that the AAPE obtained from the regression and NNDHM models were 15.7% and 12.3%. Again, the NNDHM model produces smaller errors than the regression model.

In brief, the proposed NNDHM model gives the smallest error among the models compared on both average and individual vehicle bases. Therefore, it can be concluded that the NNDHM model can produce reasonable estimates on the individual queued vehicle discharge headway.

6.5 Sensitivity analysis

In order to establish the importance of individual variables in the model, the model was subjected to sensitivity analysis under a wide range of conditions. The base values for the sensitivity tests were:
1. Lane width = 3.25 meters;

2. Lane position = 1;

3. Turning radius = 0 (i.e. through movement);

4. Vehicle Type = Type I (passenger car) only;

The starting reaction times were generated from the Type I Extreme Value Distribution discussed previously. For each simulation run, 500 queues with 20 vehicles were simulated by the NNDHM model. When testing a certain variable, all other variables are fixed at the base values. The results were evaluated by queue position basis. The average values by queue position of the simulated discharge headway are shown in Figure 6.3, which shows the typical pattern obtained elsewhere.

Figure 6.3 Average simulated departure headway by queue position
The input variables of the NNDHM model can be classified into 3 categories, geometrical variables, attributes of the subject and preceding vehicle. Sensitivity analysis was conducted on each of the three categories.

6.5.1 Geometrical variables

The NNDHM model's geometrical variables include lane width ($X_1$) and lane position ($X_2$). Figure 6.4 and Figure 6.5 illustrate the influences of these two variables on the simulated discharge headway. Figure 6.4 shows the relationship between the discharge headway and lane width for values ranging from 2.75m to 5.50m. It is obvious that lane width has a significant effect on discharge headway. The discharge headway decreases as lane width increases and tends to stabilise at 5m. This pattern is distinct for the first few vehicles.

Figure 6.5 shows the average discharge headways for queued vehicles at lane positions varied from 1 to 5. It is clear that the largest discharge headway is obtained for the lane nearest to the kerb-side and then decreases progressively outwards. Many researchers pointed out that discharge headways correlate with lane positions as discharge headways in offside lanes are usually smaller than in kerb-side lanes, which receives a considerable amount of disturbance from kerb-side activities, such as pedestrian interruptions. Also, drivers in Hong Kong usually interpret the kerb-side lane as the slowest lane and the lane most far away from the kerb-side to be the fastest lane. The decrease in discharge headway towards the kerb-side lane is more significant at the front of the queue.
Figure 6.4  Illustration of the effect of lane width on departure headway by queue position

Figure 6.5  Illustration of the effect of lane position on departure headway by queue position
6.5.2 **Attributes of subject vehicle**

Attributes of the subject vehicle include the vehicle type ($X_3$), position in the queue ($X_4$) and the turning radius ($X_5$). The queue position demonstrated in earlier section that the NNDHM model could simulate the decreasing trend of the discharge headway. To investigate the effect of the turning radius, the model was tested on turning radius varied from 7.5m to 1000m, which is theoretically large enough to represent straight ahead movement. The results are shown in Figure 6.6. As expected, the discharge headway decreases as turning radius increases. For turning radii larger then 300m, the discharge headway converges to that of straight ahead movement. The reasons for this have been addressed elsewhere. Similar to the geometrical variables, this factor contributes less impact on the saturated headway.

![Figure 6.6 Illustration of the effect of turning radius on departure headway by queue position](image)

205
The effect of heavy vehicles was examined by adjusting the vehicle compositions in the simulation to have only one vehicle type. The results are shown in Figure 6.7. The average headways obtained from large vehicles (Type IV) are greater than small vehicles (Type I). This effect is obviously more significant than the geometrical variables and is detected throughout the whole queue.

![Graph showing average headway by queue position]

Figure 6.7 Illustration of the effect of vehicle type on departure headway by queue position

6.5.3 Attributes of preceding vehicle

The effects of the attributes of the preceding vehicle (i.e. actual discharge headway ($X_6$), vehicle type ($X_7$), turning radius ($X_8$)) on the discharge headway of the subject vehicle are focused on queue position 2 to 20 as the first queued vehicle has no leading vehicle. Figure 6.8 shows the average discharge headway of Type I vehicles with different leaders. It is obvious that the type of the $X_7$ has significant effect on
the discharge headway. With reference to the type of subject vehicle \((X_4)\), \(X_7\) has greater impact on the discharge headway of the first few vehicles.

![Figure 6.8 Illustration of the effect of type of preceding vehicle on departure headway of the subject vehicle by queue position](image)

![Figure 6.9 Illustration of the effect of turning radius of the preceding vehicle on departure headway of the subject vehicle by queue position](image)
For mixed lanes, straight through vehicles are delayed by turning vehicles. The model was tested on the turning radii of the proceeding vehicle varied from 7.5m to 34.0m and the results were plotted in Figure 6.9. The pattern is similar to that of $X_3$ in which the discharge headway increases with the increases of the turning radius.

Figure 6.10 Illustration of the effect of departure headway of the preceding vehicle on departure headway of the subject

Figure 6.10 shows the relationship between the discharge headway of the subject and preceding vehicles. The discharge headway of the preceding vehicles varied from 1.5 seconds to 6.0 seconds. The results show a strong correlation between the discharge headway of the subject and preceding vehicles. The larger the headway of the preceding vehicle, the larger that of the subject vehicle. The correlation is smaller at the latter part of the queue but it is still very significant.

The sensitivity analysis further validated the applicability of the model. It is
demonstrated that the NNDHM model can capture the effects of the selected variables to produce interesting results and revealed relationships that would not have been highlighted.

6.6 Concluding Remarks

In this chapter, the NNDHM model was trained, validated and tested against field data. It was demonstrated that the model has the ability to estimate the discharge headway. Results showed that the NNDHM model, with 7 hidden units yielded average absolute percentage error of about 12 percent. The NNDHM model was also compared with the regression model and Briggs's model. It was found that the NNDHM model produced the smallest error in estimating the discharge headway on both average and individual vehicle bases. Sensitivity analysis on the input variables further validated the applicability of the NNDHM model. It can be concluded that the proposed NNDHM model provides reasonable results in simulating individual discharge headway.
CHAPTER 7
TREFSIM MODEL RESULTS AND DISCUSSIONS

7.1 Introduction

Conventional macroscopic traffic simulation and emission models are not sensitive to vehicle modal operation, which occurs frequently in the urban areas, and the embedded emission models are usually derived from laboratory data. The development of the TREFSIM model could be a useful predictive and design tool for the evaluation of urban traffic signal junctions. The measures of effectiveness (MOE) considered by the model are:

1. Average journey time (sec per vehicle)
2. Average speed (kph per vehicle)
3. Average total delay (sec per vehicle)
4. Average stopped delay (sec per vehicle)
5. Vehicle fuel consumption factor (g/km per vehicle)
6. CO, HC, NOx and PM emission factors (g/km per vehicle)

All the analyses in this chapter are based on these measures. In general, a proposed model should be validated against field data. However, some of the above MoE, such as fuel consumption factors and emission factors, are difficult to collect in the field. Thus, in this chapter, the TREFSIM model results are compared with results from one macroscopic (or mesoscopic) SATURN and one microscopic PARAMICS model. The TREFSIM model has been encoded in Delphi programming language.
Finally, a simulation study is performed and results are then further evaluated to highlight some important findings. Results by using NNDHM vehicle generation method and the Distribution generation method are also compared.

7.2 **Comparison with PARAMICS and SATURN**

PARAMICS (Parallel Microscopic Simulation) is a commercial traffic simulation software used to model the movement and behaviour of individual vehicles on urban road networks. Since it is a commercial software, limited materials on the model development have been published. All the descriptions on PARAMICS in this chapter are based on the user manual (2000).

It is a time-based microscopic traffic simulation model with dedicated 2D and 3D visualisation and the standard time stop is 0.5 of a second. The movement of individual vehicles within PARAMICS is governed by three interacting models representing the vehicle following, gap acceptance and lane changing. All three basic model types are of a form well documented in transport research. Vehicle dynamics are relatively simple, combining a mixture of driver behaviour and some limitations based on vehicles' physical type and kinematics (e.g. size, acceleration/deceleration).

Travel demand in PARAMICS is summarised by vehicle trip matrices. The simulated random release of vehicles onto the road network is constrained by the trip matrices and demand profiles. Vehicle attributes (e.g. length) are allocated using default distributions. Individual driver behaviour is determined through the random allocation of aggression and awareness characteristics to the driver of each vehicle.
The road network data for an urban PARAMICS simulation model include (a) digitised map data for the entire study area. Detailed layouts for junctions might show lane markings, stop lines and so on; (b) digitised OD traffic zone boundaries; (c) access restrictions; (d) areas of on-street parking; (e) traffic signal phases and synchronisation, including pedestrian light phase timings; and (f) detailed information on such as bus priority measures, extent of bus lanes, bus detection at traffic signals, location of bus stops. The users can define the physical properties of the road network, such as lane widths, lane arrangements including permitted turns, and junction signal timings.

The model’s output includes link counts, queue lengths, stop time and pollution information. PARAMICS estimates noise and exhaust gas emissions in relation to instantaneous engine speed and vehicle acceleration rate as well as parameters that are available only when modelling at the single vehicle level. PARAMICS contains a pollution emissions model, and outputs indicators relating to the level of emissions of CO, CO2, HC, NOx, PM, fuel consumption and noise.

The choice PARAMICS for comparison is because it has been validated against some traditional software like ARCADY, PICADY and TRANSYT. It is also currently used in UK, Japan, Singapore and Argentina by several consultants. In Hong Kong, PARAMICS is being used by a consultant to evaluate the traffic impact of the construction of the Hong Kong Disneyland.

For details of the SATURN simulation model refer to Chapter 2. The SATURN model was chosen for comparison because it is one of the most traditional traffic
simulation models. It is of great interest to compare the TREFSIM model with a traditional macroscopic traffic simulation model.

7.2.1 Model features comparison

Features of these two models together with the TREFSIM model are summarised in Table 7.1. Comparisons are focused on the traffic signal junction simulation modules of these models while assignment and route choice are not considered.

<table>
<thead>
<tr>
<th></th>
<th>TREFSIM</th>
<th>PARAMICS</th>
<th>SATURN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modelling Technique</td>
<td>- microscopic</td>
<td>- microscopic</td>
<td>- macroscopic</td>
</tr>
<tr>
<td></td>
<td>- time based</td>
<td>- time based</td>
<td>- time based</td>
</tr>
<tr>
<td>Level of Details</td>
<td>- individual vehicle</td>
<td>- individual vehicle</td>
<td>- platoon dispersion</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vehicle Types</td>
<td>- cars, vans, trucks and buses</td>
<td>- flexible</td>
<td>- cars and buses</td>
</tr>
<tr>
<td>Vehicle Generation</td>
<td>- distribution or NNDHM</td>
<td>- distribution</td>
<td>--</td>
</tr>
<tr>
<td>Method</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Demand Modelling</td>
<td>- vehicle flow at boundary nodes</td>
<td>- OD matrices</td>
<td>- OD matrices</td>
</tr>
</tbody>
</table>

Table 7.1 Comparison between TREFSIM, PARAMICS and SATURN

All the three models are time-based where TREFSIM and PARAMICS are microscopic and SATURN is macroscopic. TREFSIM and PARAMICS model the traffic as detailed as individual vehicle moving in the road network whereas SATURN models the traffic dynamics by platoon dispersion.

The innovative aspect of TREFSIM is the ability to model boundary nodes as signal controlled junctions. Vehicle arrival headways are modelled by the NNDHM model
whereas PARAMICS randomly generates vehicle headway from distributions. This feature of TREFSIM makes it more suitable to be applied for simulating small urban road networks where the majority of junctions are signal controlled.

7.2.2 Model results comparison

The comparison made in this section is based on results from SATURN version 9.1 and PARAMICS version 3.0. Output from SATURN 9.1 includes:

1. Total delay (sec per PCU)
2. Average journey time (sec per PCU)
3. Average speed (kph per PCU)
4. Fuel consumption (L per PCU)

Outputs from PARAMICS 3.0 includes:

1. Total vehicle flows
2. Average journey time (sec per vehicle)
3. Average speed (kph per vehicle)
4. Average stopped delay (sec per vehicle)
5. Total distance travelled for all vehicle (m)
6. Total fuel consumption for all vehicle (L)
7. Total CO, CO2, HC, NOx and PM emissions for all vehicle (g)

Therefore, emission factors can be obtained easily by dividing the total emissions by the total vehicle flows and total distance travelled. However the units of fuel consumption output from PARAMICS and SATURN in Litre is different from
TREFSIM's output. Hence, the comparison is made as listed in the following:

1. Comparison of average journey times and average speeds from TREFSIM, PARAMICS and SATURN.
2. Comparison of flow patterns, stopped delay and various emission factors from TREFSIM and PARAMICS.
3. Comparison of average total delay from TREFSIM and SATURN.

7.2.2.1 Description of the modelled road network

The network chosen for study is a proposed network in the Central - Wanchai Reclamation Area. Figure 7.1 shows a detailed layout of the study network. It consists of 4 signal controlled junctions named as Node 10 to Node 13. The signal staging and timing of these nodes are given in Figure 7.2 to Figure 7.5. The shaded nodes (Nodes 21 to 26) are the network sources while Nodes 31 to 36 are the network sinks.

The vehicle demand data shown in Table 7.2 were taken from Ching (2000) and were derived based on Annual Traffic Census 1998. The total flow at boundary nodes is 1371 veh/hr. In TREFSIM and PARAMICS, proportions of the four vehicle types being simulated were assigned randomly and are the same for both models. The Distribution method was used in generating vehicle into the network for TREFSIM. All or nothing assignment method was chosen for both PARAMICS and SATURN models.
Figure 7.1 Layout of the test network
Figure 7.2  Stage diagram of Node 10
Figure 7.3 Stage diagram of Node 11
Figure 7.4 Stage diagram of Node 12
Figure 7.5 Stage diagram of Node 13

<table>
<thead>
<tr>
<th>Source</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle arrival rate (veh/hr)</td>
<td>377</td>
<td>81</td>
<td>153</td>
<td>154</td>
<td>254</td>
<td>298</td>
</tr>
<tr>
<td>Type I proportion</td>
<td>0.60</td>
<td>0.70</td>
<td>0.60</td>
<td>0.65</td>
<td>0.55</td>
<td>0.70</td>
</tr>
<tr>
<td>Type II proportion</td>
<td>0.25</td>
<td>0.15</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
<td>0.20</td>
</tr>
<tr>
<td>Type III proportion</td>
<td>0.10</td>
<td>0.15</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
<td>0.10</td>
</tr>
<tr>
<td>Type IV proportion</td>
<td>0.05</td>
<td>0.00</td>
<td>0.10</td>
<td>0.05</td>
<td>0.15</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Table 7.2 Vehicle demand data
The network described above was simulated and tested for different cycle times. The duration of each simulation run was 60 minutes. All the signal junctions were assigned to a common cycle time, which was varied from 45 to 120 seconds.

7.2.2.2 Results

The simulated average journey times and average speeds for the three models are shown in Figure 7.6 and Figure 7.7 respectively. The figures show that among the three models TREFSIM gives the largest average journey time and smallest average speed. The simulated journey times and average speeds given by TREFSIM are 10% longer and 5% slower respectively. In both figures it can be seen that the three models demonstrate the same trend. Minimum journey times are observed at cycle times of about 70 to 80 seconds.

![Figure 7.6 Simulated average journey time from TREFSIM, PARAMICS and SATURN](image)

Figure 7.6 Simulated average journey time from TREFSIM, PARAMICS and SATURN
Figure 7.7  Simulated average speed from TREFSIM, PARAMICS and SATURN

<table>
<thead>
<tr>
<th>Cycle Time (sec)</th>
<th>45</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefsim</td>
<td>1246</td>
<td>1262</td>
<td>1294</td>
<td>1300</td>
<td>1300</td>
<td>1287</td>
<td>1282</td>
<td>1283</td>
<td>1290</td>
</tr>
<tr>
<td>Paramics</td>
<td>1220</td>
<td>1237</td>
<td>1171</td>
<td>1213</td>
<td>1221</td>
<td>1250</td>
<td>1191</td>
<td>1254</td>
<td>1200</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Cycle Time (sec)</th>
<th>9.1%</th>
<th>8.0%</th>
<th>5.6%</th>
<th>5.2%</th>
<th>5.2%</th>
<th>6.1%</th>
<th>6.5%</th>
<th>6.4%</th>
<th>5.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Trefsim</td>
<td>11.0%</td>
<td>9.8%</td>
<td>14.6%</td>
<td>11.5%</td>
<td>11.0%</td>
<td>8.9%</td>
<td>13.1%</td>
<td>8.5%</td>
<td>12.5%</td>
</tr>
<tr>
<td>Paramics</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 7.3  Comparison between TREFSIM and PARAMICS simulated total flow and their differences with total input flow (veh/hr)

The simulated total flows for TREFSIM and PARAMICS at different cycle times and their discrepancies with the input total flows are shown in Table 7.3. The table shows that the simulated total flows from all three models are smaller than the input total flow and those of TREFSIM are closer to the input total flow than those of PARAMICS. TREFSIM's simulated total flows are smaller than the input total flow by less than 10% while the largest difference input flow and PARAMICS's simulated total flows is about 15%.
Figure 7.8 to Figure 7.11 show the estimated CO, HC, NOx and PM emission factors from TREFSIM and PARAMICS. The figures show that TREFSIM gives slightly higher emission factors than PARAMICS. However, both demonstrate the same trend, that the relations of CO, HC and NOx emissions with cycle time are more significant than that of PM emission with cycle time.

![Graph showing CO emission factors from TREFSIM and PARAMICS](image)

**Figure 7.8** Simulated CO emission factors from TREFSIM and SATURN

![Graph showing HC emission factors from TREFSIM and PARAMICS](image)

**Figure 7.9** Simulated HC emission factors from TREFSIM and SATURN
Figure 7.10  Simulated NOx emission factors from TREFSIM and SATURN

Figure 7.11  Simulated PM emission factors from TREFSIM and SATURN

Figure 7.12 illustrates the stopped delays estimated by TREFSIM and PARAMICS. The estimated stopped delay differences between the two models are generally smaller than 10% and the largest percentage difference is 16% at a cycle time of 70. Both results show the same trend that minimum stopped delays are observed at cycle time of about 70 to 80 seconds.
Figure 7.12  Simulated stopped delay from TREFSIM and PARAMICS

A comparison of simulated total delay from TREFSIM and SATURN is given in Figure 7.13. Results from both models are close to each other and show the same trend.

Figure 7.13  Simulated total delay from TREFSIM and SATURN
The above comparisons indicated that TREFSIM could provide reasonable results in simulating vehicle movements at urban traffic signal controlled road networks.

7.3 Comparison with SIDRA

SIDAR is one of the well-known analytical models of signalised junctions. It is of great interest to compare an analytical model with TREFSIM results. The comparison made in this section is based on results from SIDRA version 4.0. Useful output from SIDRA 4.0 includes:

1. Average delay (sec per vehicle)
2. Average speed (km/h)
3. Total Fuel consumption (g/h per vehicle)
4. Total CO, HC, NOx emission (g/h per vehicle)

Since the units of emissions and fuel consumption output from SIDRA are different from TREFSIM's output. Hence, the comparison is made with average delay and average speeds from TREFSIM and SIDRA. The test network is the single node number 10 in the previous section. Results are shown in Figure 7.14 and Figure 7.15

The results are similar to those comparisons with PARAMICS and SATURN. In both figures it can be seen that both models demonstrate the same trend. It indicated that TREFSIM could provide consistent results with traditional analytical models.
Figure 7.14 Simulated total delay from TREFSIM and SIDRA

Figure 7.15 Simulated average speed from TREFSIM and SIDRA

7.4 Simulation Study

In this section, simulation experiments are performed to test the model in more details. Results are then further evaluated to highlight some important findings. The modelled network is the same as described in Section 7.2.2.1.

7.4.1 Repeatability

To evaluate different signal settings at a certain road network, it is necessary for the
simulation model to provide similar vehicle arrival pattern in each simulation run. In TREFSIM, there are a number of random components so that there are variations across runs. To evaluate this variation, 5 simulation runs were performed with the same settings. The results are shown in Table 7.4 and Table 7.5. The table shows that the coefficient of variations (C.V.) of model outputs are generally smaller than 0.05 and the variations are within 7% except the PM emission factor. It is generally acceptable to consider hourly and daily fluctuations in traffic flows. The larger deviations of PM emissions may be because of the relatively smaller proportions of diesel vehicles being simulated.

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Mean</th>
<th>Std.Dev</th>
<th>C.V.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Flow</td>
<td>1300</td>
<td>1297</td>
<td>1285</td>
<td>1266</td>
<td>1259</td>
<td>1281.4</td>
<td>18.31</td>
<td>0.01</td>
</tr>
<tr>
<td>Journey Time</td>
<td>79.45</td>
<td>77.41</td>
<td>76.80</td>
<td>74.60</td>
<td>76.78</td>
<td>77.01</td>
<td>1.73</td>
<td>0.02</td>
</tr>
<tr>
<td>Average Speed</td>
<td>22.71</td>
<td>23.10</td>
<td>23.16</td>
<td>22.39</td>
<td>23.28</td>
<td>22.91</td>
<td>0.41</td>
<td>0.02</td>
</tr>
<tr>
<td>Average Running Speed</td>
<td>34.24</td>
<td>34.39</td>
<td>34.36</td>
<td>34.20</td>
<td>34.65</td>
<td>34.37</td>
<td>0.18</td>
<td>0.01</td>
</tr>
<tr>
<td>Total Delay</td>
<td>46.60</td>
<td>44.76</td>
<td>44.10</td>
<td>45.88</td>
<td>43.65</td>
<td>45.00</td>
<td>1.23</td>
<td>0.03</td>
</tr>
<tr>
<td>Stopped Delay</td>
<td>33.88</td>
<td>32.42</td>
<td>31.66</td>
<td>32.03</td>
<td>31.40</td>
<td>32.28</td>
<td>0.97</td>
<td>0.03</td>
</tr>
<tr>
<td>Total F.C.</td>
<td>29.31</td>
<td>28.67</td>
<td>28.88</td>
<td>29.88</td>
<td>29.21</td>
<td>29.19</td>
<td>0.46</td>
<td>0.02</td>
</tr>
<tr>
<td>Total CO</td>
<td>6.98</td>
<td>6.89</td>
<td>7.02</td>
<td>7.09</td>
<td>6.86</td>
<td>6.97</td>
<td>0.09</td>
<td>0.01</td>
</tr>
<tr>
<td>Total HC</td>
<td>0.654</td>
<td>0.634</td>
<td>0.676</td>
<td>0.694</td>
<td>0.639</td>
<td>0.660</td>
<td>0.03</td>
<td>0.04</td>
</tr>
<tr>
<td>Total NOx</td>
<td>0.818</td>
<td>0.897</td>
<td>0.913</td>
<td>0.904</td>
<td>0.862</td>
<td>0.879</td>
<td>0.04</td>
<td>0.04</td>
</tr>
<tr>
<td>Total PM</td>
<td>0.117</td>
<td>0.154</td>
<td>0.143</td>
<td>0.127</td>
<td>0.122</td>
<td>0.132</td>
<td>0.02</td>
<td>0.12</td>
</tr>
<tr>
<td>F.C. Factor</td>
<td>70.89</td>
<td>69.92</td>
<td>70.68</td>
<td>72.35</td>
<td>69.94</td>
<td>70.76</td>
<td>0.99</td>
<td>0.01</td>
</tr>
<tr>
<td>CO Emission Factor</td>
<td>17.06</td>
<td>17.00</td>
<td>17.39</td>
<td>17.00</td>
<td>16.62</td>
<td>17.09</td>
<td>0.32</td>
<td>0.02</td>
</tr>
<tr>
<td>HC Emission Factor</td>
<td>1.626</td>
<td>1.597</td>
<td>1.714</td>
<td>1.721</td>
<td>1.573</td>
<td>1.646</td>
<td>0.07</td>
<td>0.04</td>
</tr>
<tr>
<td>NOx Emission Factor</td>
<td>2.037</td>
<td>2.245</td>
<td>2.301</td>
<td>2.254</td>
<td>2.100</td>
<td>2.187</td>
<td>0.11</td>
<td>0.05</td>
</tr>
<tr>
<td>PM Emission Factor</td>
<td>0.317</td>
<td>0.405</td>
<td>0.382</td>
<td>0.340</td>
<td>0.312</td>
<td>0.351</td>
<td>0.04</td>
<td>0.12</td>
</tr>
</tbody>
</table>

Table 7.4 Model output of five simulation runs

7.4.2 **Comparison of NNDHM and distribution generation method**

The innovative aspect of TREFSIM is the ability to model boundary nodes as signal controlled junctions. Vehicle arrival headways are modelled by the NNDHM model in stead of random generation from distributions. To test the ability of the NNDHM generation method, the four-junction network described in Section 7.2.2.1 was
modified to 3 junctions. Node 13 was considered as a boundary node and tested with the two vehicle generation methods. The vehicle arrival rate of Node 13 is 79 veh/hr so that the total vehicle flow rate becomes 1162 veh/hr.

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Max</th>
<th>Min</th>
</tr>
</thead>
<tbody>
<tr>
<td>Total Flow</td>
<td>-0.015</td>
<td>-0.012</td>
<td>-0.003</td>
<td>0.012</td>
<td>0.017</td>
<td>0.017</td>
<td>-0.015</td>
</tr>
<tr>
<td>Journey Time</td>
<td>-0.032</td>
<td>-0.005</td>
<td>0.003</td>
<td>0.031</td>
<td>0.003</td>
<td>0.031</td>
<td>-0.032</td>
</tr>
<tr>
<td>Average Speed</td>
<td>0.009</td>
<td>-0.008</td>
<td>-0.011</td>
<td>0.027</td>
<td>-0.016</td>
<td>0.027</td>
<td>-0.016</td>
</tr>
<tr>
<td>Average Running Speed</td>
<td>0.004</td>
<td>-0.001</td>
<td>0.000</td>
<td>0.005</td>
<td>-0.008</td>
<td>0.005</td>
<td>-0.008</td>
</tr>
<tr>
<td>Total Delay</td>
<td>-0.036</td>
<td>0.005</td>
<td>0.020</td>
<td>-0.020</td>
<td>0.030</td>
<td>0.030</td>
<td>-0.036</td>
</tr>
<tr>
<td>Stopped Delay</td>
<td>-0.050</td>
<td>-0.004</td>
<td>0.019</td>
<td>0.008</td>
<td>0.027</td>
<td>0.027</td>
<td>-0.050</td>
</tr>
<tr>
<td>Total CO</td>
<td>-0.004</td>
<td>0.018</td>
<td>0.011</td>
<td>-0.024</td>
<td>-0.001</td>
<td>0.018</td>
<td>-0.024</td>
</tr>
<tr>
<td>Total HC</td>
<td>0.008</td>
<td>0.038</td>
<td>-0.025</td>
<td>-0.052</td>
<td>0.032</td>
<td>0.038</td>
<td>-0.052</td>
</tr>
<tr>
<td>Total NOx</td>
<td>0.069</td>
<td>-0.021</td>
<td>-0.039</td>
<td>-0.028</td>
<td>0.019</td>
<td>0.069</td>
<td>-0.039</td>
</tr>
<tr>
<td>Total PM</td>
<td>0.120</td>
<td>-0.163</td>
<td>-0.078</td>
<td>0.041</td>
<td>0.081</td>
<td>0.120</td>
<td>-0.163</td>
</tr>
<tr>
<td>F.C. Factor</td>
<td>-0.002</td>
<td>0.012</td>
<td>0.001</td>
<td>-0.023</td>
<td>0.012</td>
<td>0.012</td>
<td>-0.023</td>
</tr>
<tr>
<td>CO Emission Factor</td>
<td>0.002</td>
<td>0.005</td>
<td>-0.017</td>
<td>-0.018</td>
<td>0.028</td>
<td>0.028</td>
<td>-0.018</td>
</tr>
<tr>
<td>HC Emission Factor</td>
<td>0.013</td>
<td>0.030</td>
<td>-0.041</td>
<td>-0.046</td>
<td>0.045</td>
<td>0.045</td>
<td>-0.046</td>
</tr>
<tr>
<td>NOx Emission Factor</td>
<td>0.069</td>
<td>-0.026</td>
<td>-0.052</td>
<td>-0.031</td>
<td>0.040</td>
<td>0.069</td>
<td>-0.052</td>
</tr>
<tr>
<td>PM Emission Factor</td>
<td>0.097</td>
<td>-0.154</td>
<td>-0.087</td>
<td>0.032</td>
<td>0.112</td>
<td>0.112</td>
<td>-0.154</td>
</tr>
</tbody>
</table>

Table 7.5 Percentage errors of output from five simulation runs with the mean

<table>
<thead>
<tr>
<th></th>
<th>45</th>
<th>50</th>
<th>60</th>
<th>70</th>
<th>80</th>
<th>90</th>
<th>100</th>
<th>110</th>
<th>120</th>
</tr>
</thead>
<tbody>
<tr>
<td>Distribution</td>
<td>1118</td>
<td>1123</td>
<td>1114</td>
<td>1090</td>
<td>1116</td>
<td>1146</td>
<td>1107</td>
<td>1117</td>
<td>1098</td>
</tr>
<tr>
<td>NNDHM</td>
<td>1175</td>
<td>1205</td>
<td>1200</td>
<td>1201</td>
<td>1182</td>
<td>1199</td>
<td>1162</td>
<td>1190</td>
<td>1215</td>
</tr>
<tr>
<td>Distribution</td>
<td>3.8%</td>
<td>3.4%</td>
<td>4.1%</td>
<td>6.2%</td>
<td>4.0%</td>
<td>1.4%</td>
<td>4.7%</td>
<td>3.9%</td>
<td>5.5%</td>
</tr>
<tr>
<td>NNDHM</td>
<td>1.1%</td>
<td>3.7%</td>
<td>3.3%</td>
<td>3.4%</td>
<td>1.7%</td>
<td>3.2%</td>
<td>0.0%</td>
<td>2.4%</td>
<td>4.6%</td>
</tr>
</tbody>
</table>

Table 7.6 Comparison of simulated total flows by using NNDHM and Distribution methods and their differences with total input flow (veh/hr)

The simulated total flows using the two vehicle generation methods are shown in Table 7.6. It was found that the simulated total flows using the NNDHM model generation method is closer to the input total flow than those by using the Distribution method.
Comparisons of the model outputs are plotted in Figure 7.16 to Figure 7.24. The figures illustrate that results, using the two vehicle generation methods, are close to each other and the largest difference between the results from these two vehicle generation methods are observed for estimated average speed.

Figure 7.16  Comparison of simulated average journey time

Figure 7.17  Comparison of simulated average speed
Figure 7.18  Comparison of simulated total delay

Figure 7.19  Comparison of simulated stopped delay

Figure 7.20  Comparison of simulated fuel consumption factors
Figure 7.21  Comparison of simulated CO emission factors

Figure 7.22  Comparison of simulated HC emission factors

Figure 7.23  Comparison of simulated NOx emission factors
The traditional method of random generation from statistical distribution may be applicable to model vehicle arrival pattern from highways. However, in the city centre, vehicle arrival patterns may no longer be random. Network boundary nodes may be a signal controlled junction so that the vehicle arrival pattern will be impeded. It is believed that the NNDHM model can provide a more realistic vehicle arrival pattern by simulating boundary nodes as signal junctions.

7.5 Concluding Remarks

In this chapter, the TREFSIM model was validated against PARAMICS and SATURN. Results from different models demonstrated similar trends that cycle time does have important bearing on the model results. Simulated total flows for TREFSIM are closer to the input total flow than those of PARAMICS. These results indicated that TREFSIM could provide reasonable results in simulating vehicle movements in urban signal controlled road networks.
Further evaluation of the model results demonstrated the model's repeatability that the TREFSIM model could generate similar results across runs, given the same set of model inputs. It is believed that the NNDHM vehicle generation method could provide a more realistic vehicle arrival pattern in modelling boundary nodes as signal controlled junctions.
CHAPTER 8

APPLICABILITY OF TREFSIM

8.1 Introduction

The TREFSIM model has been developed in this research and the model outputs have been compared with well-known models. Results comparisons show that the TREFSIM model outputs are consistent with these models. In this chapter, the applicability of the model will be discussed and an outline of the operating procedure will be given for practical purpose.

8.2 Model Applicability

TREFSIM is intended to be applied to estimate delay, emissions and fuel consumption of vehicle travelling in urban signalised road networks. Simulation with different data sets indicates that there is a clear relationship between the model outputs (such as average delay, travel time, emissions as well as fuel consumption) and cycle times. Thus the simulation program can be used in offline optimisation applications such as the determination of optimum cycle time.

The TREFSIM model is especially suitable to simulate small signal road network in the urban area. To evaluate a small urban signal network, boundary nodes are usually signal controlled. The NNDHM vehicle generation method embedded in TREFSIM could be applied to provide more realistic vehicle arrival patterns.

235
Comparing traditional models, the microscopic structure of TREFSIM and the embedded ON-ROAD modal emission and fuel consumption model have the potential to provide more realistic emission and fuel consumption estimates when it is fully developed. Although, at the present stage, the emission and fuel consumption was developed on the basis of four test vehicles only, it can provide good approximation and give useful indication of vehicle emission and fuel consumption levels.

8.3 Data Preparation

For practical purpose, a list of procedures for using TREFSIM is outlined in this section. The first step is to prepare all relevant data summarised as follow:

1. Network Layout
   (a) Lane Data
      (i) Length (m)
      (ii) Speed limit (km/h)
      (iii) Lane regulation (whether lane change is allowed or not)
      (iv) Manoeuvre (the type of traffic (left, through or right) that can use this lane)
   (b) Movement Data
      (i) Length (m)
      (ii) Turning radius (m)
      (iii) Movement type (left, through, right or combined)
   (c) Junction Data
(i) Method of control (allocation of movements to each signal stage)

(ii) Signal data (stage based)

(I) cycle time (s)

(II) all red time for each stage (s)

(III) stage split (%) (percentage of cycle time occupied by each stage)

(IV) offset (s)

(d) NNDHM Data at boundary nodes

(i) Details of the lanes that vehicles flowing into the network at the boundary nodes

(ii) Signal data of the corresponding boundary nodes

2. Volume data

(a) Volume counts in vehicles per hour and each boundary node

(b) Traffic composition (% of the four types of vehicles at each boundary node)

(c) Lane use proportion (%) (the percentage of vehicles carried by the lane with respect to the total number of vehicles travelling in the corresponding link)

(d) Turning proportions (%)

3. Control files

Make sure that a folder that contains headway data for random vehicle generation method and emission/fuel consumption data is present in the same directory as the TREFSIM program.

When all the relevant data are prepared, the user can start the input coding process.
8.4 Network Coding

The TREFSIM program has three sub-programs, "Lane Editor", "Node Editor" and "Simulator". The lane editor and node editor are used to code the prepared data into input files for the simulator to perform simulation. When the TREFSIM program starts, a main menu with four buttons as shown in Figure 8.1 will be popped up. The buttons represent three sub-programs.

![The main menu in TREFSIM](image)

Figure 8.1 The main menu in TREFSIM

8.4.1 Lane editor

The option "Lane Editor" is used to input or edit lane, link and movement data. When the "Lane Editor" button is selected, a lane editor window as shown in Figure 8.2 will be popped up. The screen is grouped into 3 categories, lanes, links and movements. The data input boxes are basically self-explanatory, but for clarity purpose, descriptions of each options in the lane editor screen is given below.
Figure 8.2  The lane editor screen in TREFSIM

8.4.1.1  File menu

This menu offers various options for TREFSIM input file handling. Use the option "New" to open a new data file. Existing data files can be edited by the option "Open". After all the data are entered, save the data with the original filename by the option "Save" and with a new filename by the option "Save As". Use the option "Exit" to quit the lane editor and back to the main menu. Three data files ".lan", ".lin" and ".mov", storing lane, link and movement data respectively, will be created for saving data in the lane editor window.

8.4.1.2  Lane data group

Lane Id – Assigned lane identification number. Lanes are numbered from kerb-side lane to offside lane.
Link Id – The identification number of the link that the subject lane belongs to.

Left and Right Lane Id – The lane identification number of adjacent lanes. If there is no lanes beside the subject lane, 0 should be entered.

Length – Length of the lane (m)

Speed Limit – Speed limit of the lane (km/h)

Lane Use Pro. – Lane use proportion (as described above)

Turning Pro. – Turning proportion (as described above)

Short Lane Dist. – Length of short (storage) lanes (enter 0 for normal lanes) (m)

Lane Change Regulation (Left)/(Right) – Turning regulation to adjacent lanes

Manoeuvre – the type of traffic (left, through or right) that can use this lane

Lane Connected to – Indicate whether the lane is connected to upstream or downstream nodes or both

After entering required data for a lane, press "Add Lane" to add a lane to the pull down box at the bottom of the lane data group. At the same time the lane is added to the list box on the left of the link data group. Added lanes can be edited by selecting appropriate lane in the lane pull down box. After editing, simply press "Add Lane" to save the revised settings. "Delete Lane" will delete the lane being selected in the lane pull down box while "Clear Lane" will delete all the added lanes.

8.4.1.3 Link data group

Link Id – Assigned link identification number

Start Node Id – Identification number of node at the upstream end of the lane
End Node Id – Identification number of node at the downstream end of the lane

Lanes – Select lanes for this link from the list box on the left side of the link box

Press "Add Link" to add a link after entering required data. Added links can be edited by selecting appropriate link in the link pull down box. After editing, simply press "Add Link" to save the revised settings. "Delete Link" will delete the link being selected in the link pull down box while "Clear Lane" will delete all the added links.

8.4.1.4 Movement data group

Movement Id – Assigned movement identification number

Subject Lane Id – Identification number of the lane connected to the upstream end of the movement

Target Lane Id – Identification number of the lane connected to the downstream end of the movement

Path Length – Length (m)

Path Radius – Turning radius (m)

Movement Type – Left, right or straight through

Press "Add Move" to add a movement after entering required data. Added movements can be edited by selecting appropriate movement in the movement pull down box. After editing, simply press "Add Move" to save the revised settings. "Delete Move" will delete the movement being selected in the movement pull down box while "Clear Move" will delete all the added movements.
8.4.2 Node editor

The option "Node Editor" is used to input or edit node data. When the "Node Editor" button is selected, the node editor window as shown in Figure 8.3 will be popped up. The screen is grouped into 2 categories, junction and sources. The data input boxes are basically self-explanatory, but for clarity purpose, descriptions of each options in the node editor screen is given below.

![Node Editor Screen](image)

Figure 8.3 The node editor screen in TREFSIM

8.4.2.1 File menu

This menu offers various options for TREFSIM node data file handling. Use the option "New" to open a new data file. Existing data files can be edited by the option "Open > Node Files". The option "Open > Lane Connection Table" is used to open a
movement data file for defining junction method of control. After all the data are entered, save the data with the original filename by the option "Save" and with a new filename by the option "Save As". Use the option "Exit" to quit the lane editor and back to the main menu. It is noted that the node data filename should be the same as the names of lane data files.

8.4.2.2 Junction group data

Basic node data

*Node Id* – Assigned node identification number

*Node Name* – Name of the node

*Node Type* – Node type (junction or sink)

*Cycle Time* – The total time for a signal to complete one cycle (sec)

*Ref. Node* – Identification number of the critical node in the corresponding co-ordinated signal system

*Ref. Stage* – The starting stage of the *Ref. Node* in a co-ordinated signal system

*Offset* – The time difference between the start of the first stage at the subject signal junction as related to the *Ref. Stage* of the *Ref. Node* (sec)

Method of control

To define the method of control, a movement data file defined using the Lane Editor is needed. Use the option "Open > Lane Connection Table" to open a movement data file. The imported movement data are displayed in the left list box of the method of control data group.
Stage – Stage Id (should be numbered by A, B, C, ....)

Stage Split – Proportion of the cycle time assigned to the corresponding stage (%)

All Red – Length of the all red period (sec)

Movements – Select movements for current stage from the movement list box

The junction data group is used to define junction and sink. For junction definition, all the above mentioned data are required. For sink definition, only the Node Id, Node Name and Node type is needed.

After entering required data for a junction, press "Add Node" to add a node to the pull down box on top of the node data group. Added nodes can be edited by selecting appropriate lane in the node pull down box. After editing, simply press "Add node" to save the revised settings. "Delete node" will delete the node being selected in the lane pull down box while "Clear node" will delete all the added nodes.

8.4.2.3 Source data group

Source Id – Assigned source node identification number

Vehicle Generation – Method of vehicle generation (NN method or distribution)

In addition to volume data, a set of NN model generation data is needed for NN method of vehicle generation. For distribution generation method, only volume data is needed.
Volume data

Mean Flow – Vehicle arrival flow rate at the source node (veh/hr)

Vehicle Compositions – Percentage of the four types of vehicle Car, SGV, MGV and Bus and LGV

NN model data

Cycle Time – Cycle time of the NN source (sec)

Ref. Node – Identification of the critical node in a co-ordinated signal system

Ref. Stage – The starting stage of the Ref. Node in a co-ordinated signal system

Offset – The time difference between the start of the first stage at the subject source node as related to the Ref. Stage of the Ref. Node (sec)

Length – Length of the NN Lanes (NN lanes are lanes that vehicles flow into the network from the source node) (m)

Width – Width of the NN Lanes (m)

Position – Position of the NN Lanes (1, 2, numbered from left to right)

Stage Id – Identification number of the stage that the NN Lane belongs to

Turn Rad. – Turning radius of NN Lanes

Turn Pro. – Proportion of vehicles carried by the NN Lane that will flow into the network (%)

Green Time – Displayed green time of the stage that the NN Lane belongs to (sec)

All Red – All red time of the stage that the NN lane belongs to (sec)

After entering the required data for a source, press "Add Source" to add a source to the pull down box on top of the source data group. Added sources can be edited by
selecting appropriate source in the source pull down box. After editing, simply press "Add Source" to save the revised settings. "Delete Source" will delete the source being selected in the source pull down box while "Clear Source" will delete all the added sources.

After saving the data, four data files ".nnl", ".nod", ".sou" and ".stg", storing NN lane, node, source and staging data respectively will be created. In addition, a text file with name "xxxxx (network).txt" containing all the network data will also be generated. The "xxxxx" is the filename of the data files.

8.4.3 Simulator

After the network coding process, the simulation can be started by selecting the option "Start Simulation" from the main menu. When the "Start Simulation" button is selected, a simulation window as shown in Figure 8.4 will be popped up.

![Figure 8.4 The simulation screen in TREFSIM](image)

To start simulation, use the option "Select > Network" to import a set of data files
with the same filename. Then, enter the duration of simulation (in minute) in the box "Simulation Period" and press "Start" to start simulation.

During the simulation, summary statistics of the model outputs are displayed on the simulation window, which include, total number of vehicle entered and exited, total number of vehicle in network as well as average delay, journey time, fuel consumption and emission rates.

Three output text files will be generated at the end of the simulation. The file "xxxxx (History).txt" stores the average value of MoE at each simulation second (i.e. the statistics displayed on the simulation window during simulation). The file "xxxxx (Summary).txt" contains the summary statistics of both input and output data. The file "xxxxx (VehHist).txt" collects the summary statistics of each vehicle exited the simulation network. Examples of output text files are shown in Figure 8.5 to Figure 8.8.

<table>
<thead>
<tr>
<th>1</th>
<th>0.00</th>
<th>0.00</th>
<th>0.0000</th>
<th>0.0000</th>
<th>0.0000</th>
<th>0.0000</th>
<th>0.0000</th>
<th>0.0000</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>3</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>4</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>5</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>6</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>7</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>8</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>9</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>10</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>11</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>12</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
<tr>
<td>13</td>
<td>0.00</td>
<td>0.00</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

Figure 8.5 Sample output file of "xxxxx (History).txt"
### Junction: 10

<table>
<thead>
<tr>
<th>Name: Node</th>
<th>Cycle Time: 70</th>
<th>Offset: 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ref. Node:</td>
<td>10</td>
<td>Ref. Stage: A</td>
</tr>
</tbody>
</table>

#### Stage | Split(%) | AllRed | Movements |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>20.0</td>
<td>0</td>
<td>1001 1002 1003</td>
</tr>
<tr>
<td>B</td>
<td>55.0</td>
<td>2</td>
<td>1002 1001 1004 1006 1007 1008</td>
</tr>
<tr>
<td>C</td>
<td>25.0</td>
<td>2</td>
<td>1004 1005</td>
</tr>
</tbody>
</table>

#### Movement | SubLane | TarLane | MoveType | Length | Radius |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1001</td>
<td>1101</td>
<td>1301</td>
<td>T</td>
<td>23.50</td>
<td>0.00</td>
</tr>
<tr>
<td>1002</td>
<td>1102</td>
<td>1302</td>
<td>T</td>
<td>23.50</td>
<td>0.00</td>
</tr>
<tr>
<td>1003</td>
<td>1103</td>
<td>202</td>
<td>R</td>
<td>30.00</td>
<td>15.50</td>
</tr>
<tr>
<td>1004</td>
<td>101</td>
<td>1201</td>
<td>L</td>
<td>17.00</td>
<td>7.50</td>
</tr>
<tr>
<td>1005</td>
<td>102</td>
<td>1303</td>
<td>R</td>
<td>30.50</td>
<td>14.00</td>
</tr>
<tr>
<td>1006</td>
<td>1401</td>
<td>201</td>
<td>L</td>
<td>15.00</td>
<td>6.50</td>
</tr>
<tr>
<td>1007</td>
<td>1402</td>
<td>1202</td>
<td>T</td>
<td>24.50</td>
<td>0.00</td>
</tr>
<tr>
<td>1008</td>
<td>1403</td>
<td>1203</td>
<td>T</td>
<td>24.50</td>
<td>0.00</td>
</tr>
</tbody>
</table>

#### Link | StNode | EndNode | LTPr | StPr | RTPr | Lanes |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>25</td>
<td>10</td>
<td>0.50</td>
<td>0.00</td>
<td>0.50</td>
<td>101 102</td>
</tr>
<tr>
<td>11</td>
<td>26</td>
<td>10</td>
<td>0.00</td>
<td>0.65</td>
<td>0.35</td>
<td>1101 1102 1103</td>
</tr>
<tr>
<td>14</td>
<td>21</td>
<td>10</td>
<td>0.30</td>
<td>0.70</td>
<td>0.00</td>
<td>1401 1402 1403</td>
</tr>
</tbody>
</table>

#### Lane | Length | SpdLtm | LnUse | TurnPro | Man | L_Chg | R_Chg | L_Lane | R_Lane | LinkId |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>101</td>
<td>100.00</td>
<td>50.00</td>
<td>0.50</td>
<td>1.00</td>
<td>L</td>
<td>N</td>
<td>Y</td>
<td>0</td>
<td>102</td>
<td>1</td>
</tr>
<tr>
<td>102</td>
<td>100.00</td>
<td>50.00</td>
<td>0.50</td>
<td>1.00</td>
<td>R</td>
<td>Y</td>
<td>N</td>
<td>101</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>1101</td>
<td>100.00</td>
<td>50.00</td>
<td>0.50</td>
<td>1.00</td>
<td>T</td>
<td>N</td>
<td>Y</td>
<td>0</td>
<td>1102</td>
<td>11</td>
</tr>
<tr>
<td>1102</td>
<td>100.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>T</td>
<td>Y</td>
<td>Y</td>
<td>1101</td>
<td>1103</td>
<td>11</td>
</tr>
<tr>
<td>1103</td>
<td>100.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>R</td>
<td>Y</td>
<td>N</td>
<td>1102</td>
<td>0</td>
<td>11</td>
</tr>
<tr>
<td>1401</td>
<td>150.00</td>
<td>50.00</td>
<td>0.30</td>
<td>1.00</td>
<td>L</td>
<td>N</td>
<td>Y</td>
<td>0</td>
<td>1402</td>
<td>14</td>
</tr>
<tr>
<td>1402</td>
<td>150.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>T</td>
<td>Y</td>
<td>Y</td>
<td>1401</td>
<td>1403</td>
<td>14</td>
</tr>
<tr>
<td>1403</td>
<td>150.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>T</td>
<td>Y</td>
<td>N</td>
<td>1402</td>
<td>0</td>
<td>14</td>
</tr>
</tbody>
</table>

#### Link | StNode | EndNode | LTPr | StPr | RTPr | Lanes |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>13</td>
<td>10</td>
<td>31</td>
<td>0.00</td>
<td>0.65</td>
<td>0.35</td>
<td>1301 1302 1303</td>
</tr>
</tbody>
</table>

#### Lane | Length | SpdLtm | LnUse | TurnPro | Man | L_Chg | R_Chg | L_Lane | R_Lane | LinkId |
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>1301</td>
<td>150.00</td>
<td>50.00</td>
<td>0.30</td>
<td>1.00</td>
<td>T</td>
<td>N</td>
<td>Y</td>
<td>0</td>
<td>1302</td>
<td>13</td>
</tr>
<tr>
<td>1302</td>
<td>150.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>T</td>
<td>Y</td>
<td>Y</td>
<td>1301</td>
<td>1303</td>
<td>13</td>
</tr>
<tr>
<td>1303</td>
<td>150.00</td>
<td>50.00</td>
<td>0.35</td>
<td>1.00</td>
<td>R</td>
<td>Y</td>
<td>N</td>
<td>1302</td>
<td>0</td>
<td>13</td>
</tr>
</tbody>
</table>

### Source: 21

#### Vehicle Generation Method: Distribution

Mean Flow: 377
Car: 60.00  SGV: 25.00
MVU: 10.00  Bus: 5.00

---

Figure 8.6 Sample output file of "xxxxx (Network).txt"
Summary Results

Input Network

Nodes:
10  NodeCycle Time: 70

Sources:
21  Distribution 377 vehicle/hour
25  Distribution 354 vehicle/hour
26  Distribution 290 vehicle/hour

Sinks:
31  Sink
35  Sink
36  Sink

TOTAL SIMULATION TIME = 60 Mins

VEHICLE GENERATION INFORMATION

Vehicle Generated into the Network = 874

Vehicle Exited the Network:
- Passenger Car (Type I) = 559
- Vans and Small Goods Vehicle (Type II) = 223
- Medium & Heavy Goods Vehicle (Type III) = 51
- Buses and Coaches (Type IV) = 20

Total = 941

LANE CHANGE PROPORTION = 0.00

TOTAL NUMBER OF LANE CHANGING = 400

VEHICLE STATISTICS

Average Journey Time (sec/veh) = 41.19
Average Speed (km/h) = 31.09
Average Running Speed (km/h) = 39.73
Total Delay (sec/veh) = 21.25
Stopped Delay (sec/veh) = 16.41

Emissions and Fuel Consumption:

<table>
<thead>
<tr>
<th></th>
<th>(g/veh)</th>
<th>(g/km)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Consumption*</td>
<td>16.5753</td>
<td>64.4709</td>
</tr>
<tr>
<td>Carbon Monoxide (CO)**</td>
<td>3.9214</td>
<td>15.3334</td>
</tr>
<tr>
<td>Hydrocarbons (HC)**</td>
<td>0.3940</td>
<td>1.4577</td>
</tr>
<tr>
<td>Nitrogen Oxides (NOx)**</td>
<td>0.5086</td>
<td>2.0025</td>
</tr>
<tr>
<td>Particulates (PM)***</td>
<td>0.0924</td>
<td>0.3717</td>
</tr>
</tbody>
</table>

* Averaged for Type I, II and III vehicles only
** Averaged for all vehicles
*** Averaged for Type III and IV vehicles only

Figure 8.7 Sample output file of "xxxxx (Summary).txt"
### Traffic Emission and Fuel Consumption SIMulator

**Summary of Individual Vehicle History**

<table>
<thead>
<tr>
<th>Input Network</th>
<th>10 AttemptCycle Time: 0</th>
</tr>
</thead>
<tbody>
<tr>
<td>Models:</td>
<td>10</td>
</tr>
<tr>
<td>Sources:</td>
<td>25</td>
</tr>
<tr>
<td>Links:</td>
<td>36</td>
</tr>
<tr>
<td>Lane Change Prop:</td>
<td>0.00</td>
</tr>
</tbody>
</table>

**Vehicle History**

**Abbreviations:**
- ID: Vehicle Identification Number
- Typ: Vehicle Type (1=Car, 2=Van, 3=Truck, 4=Bus)
- NoChg: Number of Lane Changing Performed
- 0: Origin
- D: Destination
- Jct_D (sec): Total Delay
- Stg_D (sec): Stopped Delay in (s) Time
- Jct_T (sec): Journey Time
- Mov_T (sec): Moving Time (in which the vehicle is in motion)
- FTT (sec): Free Flow Time
- Dist (m): Total Distance Traveled
- A_Spd (kph): Average Speed
- AM_Spd (kph): Average Moving Speed
- A_FPS (kph): Average Free Flow Speed
- Fuel (g/km): Fuel Consumption Factor
- CO (g/km): CO Emission Factor
- HC (g/km): HC Emission Factor
- NOx (g/km): NOx Emission Factor
- PM (g/km): PM Emission Factor

<table>
<thead>
<tr>
<th>ID</th>
<th>Typ</th>
<th>Len</th>
<th>Chg</th>
<th>D</th>
<th>Jct_D</th>
<th>Stg_D</th>
<th>Jct_T</th>
<th>Mov_T</th>
<th>FTT</th>
<th>Dist</th>
<th>A_Spd</th>
<th>AM_Spd</th>
<th>A_FPS</th>
<th>Fuel</th>
<th>CO</th>
<th>HC</th>
<th>NOx</th>
<th>PM</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1</td>
<td>34</td>
<td>1</td>
<td>21</td>
<td>36</td>
<td>1.34</td>
<td>2.06</td>
<td>3.06</td>
<td>4.06</td>
<td>5.06</td>
<td>6.06</td>
<td>7.06</td>
<td>8.06</td>
<td>9.06</td>
<td>10.06</td>
<td>11.06</td>
<td>12.06</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>1</td>
<td>36</td>
<td>1</td>
<td>21</td>
<td>21</td>
<td>1.01</td>
<td>0.38</td>
<td>1.76</td>
<td>2.06</td>
<td>2.36</td>
<td>2.66</td>
<td>2.96</td>
<td>3.26</td>
<td>3.56</td>
<td>3.86</td>
<td>4.16</td>
<td>4.46</td>
<td></td>
</tr>
<tr>
<td>6</td>
<td>1</td>
<td>36</td>
<td>1</td>
<td>21</td>
<td>21</td>
<td>1.34</td>
<td>2.06</td>
<td>3.06</td>
<td>4.06</td>
<td>5.06</td>
<td>6.06</td>
<td>7.06</td>
<td>8.06</td>
<td>9.06</td>
<td>10.06</td>
<td>11.06</td>
<td>12.06</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>2</td>
<td>36</td>
<td>1</td>
<td>21</td>
<td>36</td>
<td>1.34</td>
<td>2.06</td>
<td>3.06</td>
<td>4.06</td>
<td>5.06</td>
<td>6.06</td>
<td>7.06</td>
<td>8.06</td>
<td>9.06</td>
<td>10.06</td>
<td>11.06</td>
<td>12.06</td>
<td></td>
</tr>
<tr>
<td>10</td>
<td>2</td>
<td>36</td>
<td>1</td>
<td>21</td>
<td>36</td>
<td>1.34</td>
<td>2.06</td>
<td>3.06</td>
<td>4.06</td>
<td>5.06</td>
<td>6.06</td>
<td>7.06</td>
<td>8.06</td>
<td>9.06</td>
<td>10.06</td>
<td>11.06</td>
<td>12.06</td>
<td></td>
</tr>
</tbody>
</table>

Figure 8.8 Sample output file of "xxxxx (VehHist).txt"
8.5 The Practical Aspect

The model methodology basically has no limitation on the network size. It can virtually handle infinite number of nodes. However, the required time for simulation increases as network size, traffic volume and congestion increase. In general, a four-junction network requires about an hour to finish a 60 minutes simulation run on a Pentium III computer.
CHAPTER 9

CONCLUSIONS AND RECOMMENDATIONS

9.1 Introduction

The evaluation of traffic control schemes currently relies on the mobile source emission factor models, such as MOBILE and MVEI, which are not sensitive to vehicle modal operations (i.e. acceleration, cruising, deceleration and idling). These behaviours occur frequently at urban signal controlled junctions and contribute significantly to the total vehicle emissions and fuel consumption. Subsequently, modal emission models have been developed and incorporated in traffic simulation models. However, these modal emission models are developed based on laboratory collected data, which may not be representative of actual driving conditions.

The research described in this thesis has devised a modal approach to model emission and fuel consumption data collected on-road. This approach makes the estimated emissions and fuel consumption at urban signal controlled junctions sensitive to the interaction between vehicles and operations of traffic signals. The use of the neural network approach in modelling network boundary nodes as signal controlled junctions has been one of the significance in this study. This would provide the modelled network with more realistic vehicle arrival patterns. By incorporating the sub-models developed in this research, a new traffic simulation model TREFSIM has been developed to estimate delay, emissions and fuel consumption of vehicles travelling in urban signal controlled junctions.
9.2 Conclusions

The main result of the research is to have (a) developed an urban driving cycle for Hong Kong, which can provide a general understanding of the driving characteristics in the urban areas of Hong Kong; (b) performed on-road vehicle tests to collect instantaneous (second-by-second) speed, emissions and fuel consumption data as well as developed a modal ON-ROAD vehicle emission and fuel consumption model which is sensitive to modal changes of vehicles at signal junctions; (c) developed a neural network based discharge headway model (NNDHM) to simulate vehicle arrival pattern at network boundary nodes impeded by signal controlled junctions; (d) developed a time-based microscopic traffic signal simulation model that deals with individual vehicles in the network; (e) integrated the emission and traffic simulation models to provide estimates of instantaneous emissions and fuel consumption rates at urban signal controlled junctions.

9.2.1 Driving cycle for Hong Kong

A standard urban driving cycle, previously non-existence in Hong Kong, has been developed in the present study. The driving cycle was developed based on empirical speed data collected by an instrumented test vehicle. Nine commonly used assessment criteria parameters have been employed to analyse the empirical data and to assess the driving characteristics in the urban areas of Hong Kong. The local values of these parameters were compared with those of well-known driving cycles for Europe, Australia, Japan and the USA. It was found that none of the driving cycles could satisfactorily resemble the Hong Kong driving characteristics.
Therefore a standard driving cycle, which characterised the driving pattern in the urban areas of Hong Kong, was developed.

The driving cycle for Hong Kong indicated that driving in the urban areas of Hong Kong would experience the following characteristics:

1. Low average speed
2. Long idle times
3. Extremely small cruising times

9.2.2 ON-ROAD emission and fuel consumption model

Four instrumented vehicles were used to conduct on-road emission and fuel consumption tests. Instantaneous emission concentrations were measured directly from the tailpipe of the on-road test vehicles. Emission and fuel consumption rates (g/s), factors (g/km) as well as indices [g/(kg fuel)] were then derived. The emissions and fuel consumption factors being used in Hong Kong were developed in USA and Europe, but the driving cycle developed for Hong Kong indicated substantial difference with those in USA and Europe. Therefore, the emission and fuel consumption factors obtained in this study can be used in Hong Kong to estimate vehicular emissions and fuel consumption.

Modal emission and fuel consumption rates, factors as well as indices for each standard driving mode (i.e. acceleration, cruising, deceleration and idling) were also derived. It was found that the transient driving modes (i.e. acceleration and deceleration) were significantly more polluting than steady speed driving modes (i.e.
cruising and idling) in terms of (g/km) and (g/s), except for the bus.

Based on the collected emission and fuel consumption data, an ON-ROAD modal emission and fuel consumption model for vehicles travelling in the urban areas has also been developed. Piecewise interpolation functions have been developed to estimate non-idling emission and fuel consumption rates. Idling emissions and fuel consumption are estimated with a regressed negative exponential function of idle time. Comparison of estimated and observed results indicated good agreements. In particular, the proposed negative exponential function of idle time was found to perform significantly better than the traditional average value method in predicting instantaneous idling emission and fuel consumption rates. The microscopic structure of the emission model makes it sensitive to vehicle modal activities which occurs frequently at urban signal controlled junctions.

9.2.3 Neural network discharge headway (NNDHM) model

A new discharge headway model (NNDHM) has been developed by the neural network approach and unlike other previous headway models, this model does not need to pre-specify or presume the explicit form of the relationship among the dependent and independent variables. Those input variables have been carefully selected such that they are representative and can be measured easily with the available equipment. It was demonstrated that the model could estimate the discharge headway of individual vehicles based on the selected variables. Comparison of results from mandatory models showed that the NNDHM model performed better.
The NNDHM model is an ideal tool to investigate the effect of some variables such as lane width and turning radius on saturation flows and capacities that would not be easily characterised by direct measurement. When conducting a survey, it is difficult to isolate a variable of interest from the disturbances of other factors. In the NNDHM model, however, variables could be fixed at certain values so that any changes in the simulated discharge headway would be solely caused by the variable of interest.

9.2.4 The TREFSIM traffic simulation model

A microscopic traffic simulation model, TREFSIM, has been developed for the estimation of vehicle journey time, average speed, delay, fuel consumption and emissions at urban traffic signal controlled junctions. It is a time-based model that deals with each individual vehicle travelling in the simulated network. Vehicle movements are governed by a car following logic and a lane-changing algorithm. The model incorporates the developed ON-ROAD modal emission and fuel consumption model. The microscopic structure of the model makes the simulated vehicle emissions and fuel consumption sensitive to changes in vehicle behaviours due to traffic signals.

Another significant characteristic of TREFSIM is the use of neural network approach in modelling vehicle arrival pattern at network boundary nodes. In microscopic traffic simulations, vehicle arrival headways are randomly generated from probability distributions. In fact, the arrival patterns may not be completely random
because it may be affected by the junctions located at the upstream of the road section of interest. For many urban cities, such as Hong Kong, the majority of the intersections are signal controlled. The developed NNDHM can be directly applied to simulate the discharge headway of each queued vehicle. The simulated discharge headway from the NNDHM can be interpreted as the arrival pattern of the downstream road sections. Comparison of simulation results found that the NNDHM vehicle generation method performed better than Distribution generation method.

Validation of TREFSIM was performed by comparing simulation results with those calculated by PARAMICS and SATURN. It was found that TREFSIM could provide reasonable results in simulating the vehicle movements at urban signal controlled road networks.

TREFSIM is intended to be applied to estimate delay, emissions and fuel consumption of vehicle travelling in urban signal road networks for a given signal timing setting. Simulation with different data sets indicates that there is a clear relationship between the model outputs and cycle times. Thus the simulation program can be used in optimisation applications such as the determination of optimum cycle time.

The TREFSIM model is especially suitable to simulate small signal road network in the urban area. To evaluate a small urban signal network, boundary nodes are usually signal controlled. The NNDHM vehicle generation method embedded in TREFSIM can be applied to provide more realistic vehicle arrival patterns.
9.3 Strength and Weakness of the TREFSIM Model

Comparing with other microscopic models, the main strength of the TREFSIM Model are:

1. Provide second-by-second emission estimates calculated by ON-ROAD emission and fuel consumption model developed based on on-road data. While many microscopic models can provide emission estimates, but they are calculated based on laboratory emission data.

2. Use of neural network approach (the NNDHM Model) to model vehicle discharge headway at boundary nodes. It provides more realistic arrival patterns by considering the effect of the signal junctions at the simulation network boundary.

The TREFSIM model has the following two main weaknesses:

1. The emission model was developed on the basis of on-road data with limited number of test vehicles. Emission data from more vehicles are needed to enhance the current ON-ROAD emission and fuel consumption model.

2. Traffic conditions considered in the TREFSIM model are limited. In TREFSIM, only fixed-time co-ordinated signals can be simulated while most of the new generation of microscopic traffic simulation model provides the capability of adaptive traffic signal control.

9.4 Recommendations for Further Development

In this study, owing to budget limitation, only four test vehicles have been used to
calibrate the developed emission model thus, in its present form, the model cannot be
generalised to the whole vehicle fleet in Hong Kong. However, the obtained results
indicate that on-road driving emission measurement is feasible. To achieve more
definitive results, more instrumented vehicles can be tested under different
conditions and then sub-models for each vehicle types can be derived.

It is recommended to consider more traffic conditions in the TREFSIM model. For
simplicity, at the current stage TREFSIM only considered limited number of traffic
conditions. Modelling of other traffic conditions like permitted right turn and public
transport routes can help to enhance the current version of TREFSIM.

The neural network modelling approach has high flexibility in considering different
traffic conditions. In the present NNDHM model, eight influencing factors have been
proposed to be the input variables. In fact, the model can accommodate more input
variables. The reason of not introducing more variables in this study is that there are
several constraints in data collection such as equipment restrictions. The NNDHM
model methodology is however completely transferable. Once sufficient local
headway data is available for the training of the model, it can simulate discharge
headway profile under specific traffic conditions.
REFERENCES


*Transportation Research*, Vol. 12, pp. 147-152.


Transport and Road Research Laboratory, LR909, Crowthorne, TRRL.


*SAE Paper* 730553.


Quadstone Limited (1999) Paramics Modeller V3.00 user guide.


Troutbeck, R.J. (1986) Average delay at an unsignalised intersection with the major streams each having a dichotomised headway distribution. Transportation Science, Vol. 20, No. 4, pp. 272-286.


Texas Transportation Institute (1996) PASSER maximizes progression along roadways. (http://tti.tamu.edu)


