Studies of drivers' responses to ATIS in incidents : traffic-driving simulation systems and applications

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Studies of Drivers' Responses to ATIS in Incidents: Traffic-Driving Simulation Systems and Applications

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LIST OF ABBREVIATIONS

ATI: Advanced Traveller Information

ATIS: Advanced Traveller Information System

API: Application Programming Interface

ACI: ATIS Control Interface

AYE: Ayer Rajah Expressway

BT: Bukit Timah

CTE: Central Expressway

CAMTech: Centre for Advanced Media Technologies

CGF: Computer Generated Force

CNL: Cross-Nested Logit

ERP: Electronic Road Pricing

EMAS: Expressway Monitoring and Advisory System

FASTCARS: Freeway and Arterial Street Traffic Conflict Arousal and Resolution Simulator

GEV: General Extreme Value

GPS: Global Position System

HGV: Heavy Goods Vehicle

IGOR: Interactive Guidance On Routes

IIA: Independence from Irrelevant Alternatives

ITS: Intelligent Transportation Systems

KJE: Kranji Expressway

KPE: Kallang/Paya-Lebar Expressway

LCS: Lane Control Signs

LGV: Light Goods Vehicle

MCONTRM: CONtinuous TRaffic Assignment Model

MOE: Measurement of Effectiveness

MET: Microeconomic Theory

MSSD: Minimum Stopping Sight Distance

MNL: Multinomial Logit Model

NTU: Nanyang Technological University

NL: Nested Logit

PR: Passing Rate

RBBI: Radio Re-Broadcast and Break-In

RP: Revealed Preference

RGCONTRAM: Route Guidance CONtinuous TRaffic Assignment Model

SD: Standard Deviation

SP: Stated Preference

TRAVSIM: TRAVel SIMulator

VMS: Variable Message Signs

VE: Virtual Environment

VR: Virtual Reality

VLADIMIR: Variable Legend Assessment Device for Interactive Measurement of Individual Route choice

SUMMARY

Advanced Traveller Information System (ATIS) is one of the important sub-systems of Intelligent Transportation System (ITS) designed to provide real time traffic information to drivers, especially in cases of incidents. The Kallang/Paya Lebar Expressway (KPE) in Singapore is a predominantly underground expressway under construction at the time this study was carried out. KPE creates unique challenges for the prevention of incidents such as congestion, accidents and fire. Comprehensive message broadcasting schemes are to be introduced to broadcast traffic information via ATIS to provide advisory and warning information in cases of congestion, accidents, and emergency evacuation. However, knowledge on how drivers would respond to those schemes still remains insufficient. Such knowledge is essential, not only to fine-tune the schemes in KPE, but also for design and operation of similar ATIS systems in general.

The challenge remains on the methodology to collect sufficiently detailed data to understand drivers' responses to those schemes, which motivated the development of a traffic-driving simulator, integrating a driving simulator with a traffic simulator, which allows simulation of complicated scenarios in which the traffic information was broadcasted on different information devices according to the traffic schemes while drivers' responses were captured in great details. As applications of the simulator, driving behaviour surveys were carried out to study a number of issues relating to the tunnel expressway and the new information systems and schemes to be used.

The applications of the traffic-driving simulator in this study have demonstrated that the simulator can provide a critical observation basis for studies of driving behaviour in the presence of ATIS in incident contexts. Firstly, the traffic-driving simulator can be used to study drivers' behaviour in extreme conditions which may never be investigated in the field. Secondly, the simulator can allow collection of data at various levels of attributes in a high

degree of realism with driving experience similar to real situation. Thirdly, the simulator can allow optimal experiment control and data collection at different levels. With all the effects, the data collected contains rich information to support statistical analyses and development of behavioural models. The empirical results have shown that there are reasonable relationships between drivers' driving behaviour and the attributes of scenarios, such as ATIS information being provided and traffic conditions.

In the study of driving behaviour in the presence of ATIS information in a road accident resulting in lane closure, the results revealed that the ATIS scheme was effective not only in inducing an early diverging of traffic, but also in reducing risky lane changing. In the studies of fire emergency evacuation, the results indicated that visual messages by themselves may not be sufficient to provide compelling information to let drivers to realise the imminent threat of the fire incident and comply with the suggested evacuation instructions. When audio messages were also broadcasted together with the visual information provided by signage, high compliance to the combined information was observed. Drivers' route switching behaviour in the presence of ATIS information in road congestion was also studied. The results revealed that factors such as VMS messages describing extent of congestion and the cause of the congestion, speeds at decision points, attributes on alternative routes, e.g. familiarity, travel time and distance, and the location of drivers when they saw the VMS messages, were contributing to their route decisions. The above results are consistent with past study results, which further suggested that the traffic-driving simulator was able to capture drivers' route switching behaviour.

This research has made advancements into several substantive issues that have not been systematically investigated in previous studies. However, the limitations of the traffic-driving simulator in these applications cannot be overlooked. One important limitation is that the study results cannot be validated before the KPE is open to traffic. Validations of the results obtained in this simulation study with actual KPE traffic conditions will be an interesting extension. Other limitations and possible extensions of this study are discussed in this thesis.

CHAPTER 1. INTRODUCTION

1.1 Background

Intelligent Transportation Systems (ITS) are technologies that have attracted global interests from transportation professionals, industries, and governments. This is due to the potential of using ITS to provide enhanced mobility and accessibility for drivers without expanding the current transportation system. Other benefits, such as enhanced safety and better environmental quality, as well as growth in economy, are also widely reported in various studies.

As a major component of ITS, Advanced Traveller Information System (ATIS) may be defined as all possible systems which provide travellers with relevant information to help or to affect their travel and driving decisions. The benefit of ATIS in incident contexts is more evident. By providing advance traffic information, it is expected that travellers may avoid problematic roads or lanes so a high level of efficiency and safety could be maintained. However, as the definition of ATIS implies, the ability of the ATIS to achieve its objectives, critically depends on how drivers understand and respond to the information provided. The knowledge on drivers' responses to ATIS information is therefore essential for design and operation of ATIS.

1.1.1 ATIS in Singapore

The expressway system in Singapore is the backbone of the road network to support efficient movements of people and goods. In an effort to maintain a high level of efficiency and safety of the expressways, the Expressway Monitoring and Advisory System (EMAS) has been in operation since 1998. The EMAS monitors and provides real time traffic information regarding to traffic conditions on expressways via Variable Message Signs (VMS) mounted on expressways or arterial roads leading to expressways in cases of traffic incidents. By providing updated VMS information, it is expected that drivers will divert from problematic lanes or congestion areas. In this aspect, EMAS is an ATIS and drivers in Singapore are experienced users of an ATIS.

1.1.2 Information Equipment on a New Expressway in Singapore

The Kallang/Paya Lebar Expressway (KPE) is a predominantly underground expressway under construction at the time this study was carried out and is planned to open to traffic in 2008. KPE measures about 12 km, stretching from the South to the North East of Singapore. It is built to cater to the growing travel demand in the North East corridor and aims to provide better alternative routes between the city and the residential estates in the north of the island. Being built at an estimated cost of US$1.1 billion, the expressway includes about 9 km length of tunnel, which will be the longest underground expressway in South East Asia (Singapore Land Transport Authority, 2005).

Since many sections of the new expressway are underground road tunnels, it creates unique challenges for the management of congestion, accident and fire. Therefore, some broadcasting, signalling and surveillance equipment will be installed along the new expressway as part of the existing EMAS to maintain a high level of efficiency and safety. For example, VMS on open expressway sections, tunnel sections, arterial roads leading to entrances of expressways, Lane Control Signs (LCS), and Radio Re-Broadcast and Break-In (RBBI) are some information equipment to be used. Moreover, comprehensive message broadcasting schemes will be introduced to broadcast traffic information via these information equipment to provide advisory and warning information in cases of traffic incidents, such as congestion, accident with lane closure and emergency evacuation. It is expected that with the implementation of these equipment and the associated operational plans, a high level of efficiency and safety of the new expressway can be maintained.

However, the effectiveness of the information provided by these equipment to maintain a high level of efficiency and safety of the expressway depends on drivers' responses to the traffic information provided on them. Therefore, it is essential to understand drivers' driving behaviour in the presence of the traffic information before the actual implementation of the schemes controlling broadcasting such information in different situations. Such knowledge will not only benefit the operation of the new expressway, but also similar expressways with ATIS in general.

1.2 Problem Statement

Realising the importance to understand drivers' responses to traffic information, there is a need to carefully study drivers' driving behaviour in the presence of ATIS information which will be broadcasted according to traffic schemes in three critical incident contexts. Firstly, in case of an accident with lane closure, especially for the underground portion of the new expressway, the effectiveness of the traffic schemes guiding driver to avoid the problematic lane is unknown. Understanding the likely responses to the schemes is essential for accident management to maintain safety of the new expressway and other road tunnels in general. Secondly, in case of emergency evacuation, such as fire, on the underground section of the expressway or road tunnel in general, the effectiveness of the guidance information is critical for the minimisation of loss of properties and casualties. However, due to the proactive nature of the scheme, the behavioural response to such a scheme is never expected to be measured in real life situation and therefore the lack of behavioural inputs may result in less-than-optimal planning for road tunnel emergency evacuation schemes. Thirdly, the traffic information broadcasting schemes in cases of congestion for existing expressways will be extended to the new expressway. The effectiveness of the congestion management schemes in terms of diverting drivers from congested zone and the factors contributing to the route switching behaviour are still not sufficiently known. Such knowledge is essential to improve the design and effective operation of ATIS schemes to mitigate congestion on the new expressway as well as existing expressways.

For the above ATIS schemes in different incident contexts, the challenge remains that there are few well established references which can be used at the planning stage of these schemes. Although there is a growing body of scholarly contributions toward the general knowledge on drivers' responses to traffic information in different situations, the results remain limited, especially at a microscopic level where the results are applicable for daily traffic management with ATIS. This is to an extent due to the difficulties in measurement and observation of the actual travel and driving behaviours in a dynamic varying traffic conditions with information stimuli (Mahmassani, 1997). Therefore, the provision of an observation basis to study driving behaviour in the presence of ATIS information in the above incident contexts is the methodological breakthrough expected to support the realisations of substantive findings.

1.3 Motivation

As mentioned in above discussion, there are two major challenges that motivate the work described in this thesis:

(a) The challenge to study drivers' responses to different ATIS schemes for management of traffic, incident and emergency evacuation before their actual implementation in the new expressway.

The results could enable the authority to fine-tune the traffic information dissemination strategies in different situations. In addition, the behavioural data collected could provide scientific insights on the design and operation of traffic information system in general.

(b) The challenge to develop a test-bed which can support data collection to achieve the objective of the above challenge.

Firstly, the study of actual driving behaviour in the presence of ATIS under actual incident situations is not possible to be carried out in the field before the implementation of ATIS. Even with the deployment of ATIS, the unpredictable nature of incidents and lack of experimental controls make the field studies less attractive. Therefore, controlled laboratory experiments on a driving simulator may be an attractive alternative. However, to fully understand drivers' driving behaviour, especially the route switching behaviour in the presence of traffic information usually requires the observation of individual drivers' behaviour in a real time environment while the dynamics of network traffic and the information stimuli are presented and captured simultaneously (Mahmassani, 1997). Therefore, the essential characteristics for the driving simulator as an observation basis are that the driving simulator should be able to present and capture the dynamism of traffic and information stimuli in scenarios with incidents while the drivers' driving behaviour is captured in great detail. Such a level of realism and sophistication in traffic simulation of ambient traffic in driving simulator requires tremendous resource and effort to develop a traffic simulation model in a driving simulator.

1.4 Objectives

The two principal objectives of this study are:

(a) The applications of a traffic-driving simulator in studies of drivers' driving behaviour in the presence of ATIS information in the following incident contexts: congestion, accident with lane closure, fire emergency evacuation.

(b) Development of the traffic-driving simulator which is an integration of driving simulator and a traffic simulator. The system is capable of simulating operation of ATIS in different incident contexts, in which drivers' driving behaviour can be captured.

1.5 Scope of Study

The scope of the first objective is to use controlled laboratory experiments to study drivers' driving behaviour in the presence of ATIS in three incident contexts, which are the most critical to maintain a high level of safety and efficiency of KPE. Firstly, in the context of an accident which resulted in lane closure, drivers' driving behaviour with the availability of traffic information on VMS and LCS was studied. The scope is to test the effectiveness of LCS information in affecting drivers' lane changing behaviour and speed choice. Secondly, in a fire emergency evacuation context, the scope is to study drivers' responses to different evacuation plans. Furthermore, the effects of radio broadcasting in different plans were also tested. Lastly, in a congestion context, drivers' route switching behaviour in the presence of VMS messages on expressways or at entrances of expressways was studied. The scope of study is to find out factors affecting drivers' route switching behaviour in the presence of VMS messages. Drivers' socio-economic characteristics, VMS message provided, ambient traffic at decision points, attributes of alternative route are factors considered in this study.

The scope of the second objective is to develop and calibrate a traffic-driving simulator which is the integration of a traffic simulator and a driving simulator. The system should be capable of:

(a) Replicating a realistic driving environment: the system should be able to simulate the physical environment of driving. In addition, the system should be able to simulate the complicated incident scenarios in which ATIS is designed for.

(b) Allowing data collection at different levels of attributes: the system should be able to collect data on subject's driving behaviour, for example, route choice, lane choice, speed choice etc.. The traffic network statistics, for example, speed, flow, should also be controlled and collected by the system.

(c) Allowing optimal control of scenarios. For example, to allow repeating of the experiments and variation of variables.

With such efforts, the fidelity of the system and capabilities to generate complicated scenarios can be greatly enhanced. Subjects can have more realistic driving experience and they would behave more naturally. Some complicated scenarios can be simulated in a well controlled manner and such flexibility greatly facilitates the experimental design. Finally, data collected by the system at different level of attributes can support the statistical tests or discrete choice models which allow conclusion to be made statistically.

1.6 Overview of Research Methodology

With the objectives and scope defined in the previous section, this section discussed the issues in relation to the objectives and provides an overview of the research methodology to address these issues.

As discussed, the challenge to support study of drivers' behaviour in the presence of ATIS in incident contexts is the provision of an observation basis for data collection. The field experiments are not possible before the actual implementation of ATIS. The controlled laboratory experiments using a driving simulator are then the most promising method for the data collection. A driving simulator in Nanyang Technological University (NTU) was used to capture driving behaviour. However, as a platform for survey studies, the driving simulator should allow simulation and presentation of incident, traffic and operation of ATIS. This level of realism requires a sophisticated traffic simulation model to be developed in the driving simulator. Such development requires tremendous resource and effort which are not readily available in this study. Therefore, an alternative method to simulate the incident, traffic and ATIS is required.

To achieve this requirement, the driving simulator was integrated with a traffic simulator to allow sophisticated traffic simulation in an incident context while ATIS is in operation to broadcast messages regarding to the incident. However, the development of traffic-driving simulator requires a good understanding on the fundamentals of a driving simulator and traffic simulator. Due to the complexity of the integration, the idea was first tested with an earlier version of the traffic-driving simulator, with models developed for an existing expressway. The final version of the traffic-driving simulator at NTU was then implemented with the programmes established and using the new expressway, KPE, which was under construction at the time the study was carried out, as the modelling infrastructure for the simulation.

With integration of the traffic simulator and the driving simulator, another issue regarding the realism of the scenarios arises. It is very difficult, if not impossible, to predict the likely traffic characteristics on KPE before its opening to traffic, especially during situations that this study was targeted. Therefore, the traffic characteristics on other existing expressways were used as the base for calibrating the performance of the simulators. Based on this assumption, the traffic simulation model was calibrated with a stretch of expressway in Singapore to obtain key driving behaviour parameters. The key driving behaviour parameters which determine the traffic characteristics in the hypothetical scenarios, such as headway, reaction time were thus calibrated.

With key parameters for traffic simulation obtained, the traffic simulation models were integrated with the driving simulator with programmes developed for integration in the prototype system. Some modules were developed to allow control of ATIS and data collection. In addition, a real car model was used to allow better physical validity of the simulation. Other parameters, such as position of viewpoint, simulation time step were also calibrated.

With all the necessary development and calibration, the system was able to generate scenarios to simulate operations of ATIS in the contexts of incidents. However, the issues on performance of the system during the actual survey and verification of data collected motivated a pilot survey with the traffic-driving simulator. Furthermore, to obtain knowledge on drivers' perceptions on existing ATIS information and to recruit participants for the traffic-driving simulator survey, a paper-based perception survey was carried out prior to the laboratory experiments with the traffic-driving simulator.

With all the above efforts, the system was used to study drivers' driving behaviour in the presence of ATIS in different incident contexts.

Firstly, in order to study of drivers' driving behaviour with LCS in an accident context with lane closure, scenarios was simulated in which an accident happened and LCS were used to broadcast information on the lane closure information. Furthermore, to test the hypothesis that the LCS is an effective measure in such context, an identical scenario was simulated with LCS excluded and the driving behaviour was compared with the previous scenario with statistical tests.

Secondly, in order to study driver' driving behaviour in the presence of ATIS information in a fire emergency evacuation context, scenarios were simulated in which drivers were guided to leave the underground expressway with different evacuation plans. Furthermore, to test the effects of radio broadcasting, identical scenarios were created with radio broadcast purposely excluded and statistical tests were used to compare driving behaviour with and without radio broadcast.

Lastly, in order to find out factors affecting drivers' route switching behaviour in the presence of VMS messages in traffic congestion, a number of scenarios were simulated with different traffic conditions and VMS message provided. Drivers of different socio-economic characteristics were invited to drive in different scenarios. Because switching behaviour is affected by a number of factors and usual statistical tests could not capture the full picture, a random effect probit model was used to allow statistics tests on effect of each factor and the potential correlation of successive switching behaviour.

1.7 Significance of Research Objectives

Investigations to driving behaviour in the presence of ATIS provide significant insights to designs and operations of similar ATIS in general. This thesis provides the empirical evidences which can help ATIS designer and operator to understand the likely behaviour of drivers in the presence of ATIS in different incident contexts. With such behavioural inputs, the schemes to broadcast ATIS information in different situations can be optimised and the benefit of ATIS to maintain a high level of efficiency and safety could be maximised. For example, in an emergency evacuation in the tunnel, the effects of radio information could help traffic operator to understand the importance of such information and determine whether it should be compulsory for motorists to turn on the car radio unit in the tunnel. The effects of LCS could help traffic operator to determine the required level of education on motorists. The responses of motorists to VMS messages on congestion could help traffic operator to determine the most effective VMS messages to be displayed in different circumstances.

However, there are considerable difficulties to measure drivers' driving behaviour in the presence of ATIS. The traffic-driving simulator developed, however, is an excellent observation basis for studies of driving behaviour, especially in incident contexts with ATIS in operation. The traffic-driving simulator provides a platform for experimentation and allows rigorous testing of new information technologies in the new traffic infrastructure, for example, the new expressway in this study. It can simulate large scale traffic corridor and allow users to "drive" with the generated traffic. This advantage was achieved by integration of a driving simulator and a traffic simulator. With calibration done based on Singapore traffic conditions, the system is able to simulate scenarios close to reality and various studies can be carried out based on the simulated scenarios. The dynamism of traffic and ATIS could be captured and presented to drivers. Furthermore, data of different levels, from the network statistics to drivers' driving behaviour, can be collected in great detail. The data collected provide a rich pool of information to understand drivers' behaviour in the presence of ATIS information in different situations.

1.8 Structure and Overview of the Thesis

This thesis is structured as follows. Firstly, the introduction chapter gives an overview on the problem statement, motivation, objectives, followed by reviews on the literatures in Chapter 2. Chapter 3 gives an overview on the overall methodology and experimental design while Chapter 4 presents the overall structure, calibration and data verification of the traffic-driving simulator. Chapter 5 presents the survey results of the paper-based survey prior to the experimental survey with the traffic-driving simulator. Chapter 6 presents the experimental results on drivers' driving behaviour to the ATIS in cases of an accident with lane closure. Chapter 7 presents the experiment results for study of drivers' responses to traffic information in cases of emergency evacuation. Chapter 8 presents results on drivers' switching behaviour in the presence of ATIS information in road congestion. The switching behaviour is modelled and the modelling results are also discussed in Chapter 8. The major findings and future works are summarised and concluded in Chapter 9.

CHAPTER 2. LITERATURE REVIEW

Chapter 2 presents a literature review on topics which are strongly related to this research. The purpose of the review is two-fold. Firstly, it is expected that through the literature review the background knowledge for this research can be delivered to readers. Secondly, the achievements and limitations of some relevant past studies are reviewed with regard to this research.

Section 2.1 reviews the past studies on drivers' responses to traffic information to understand the essential factors affecting the decision process in the presence of traffic information in different conditions. Three major parts are included. In the first part the drivers' responses to VMS message in terms of route switching is reviewed. The drivers' lane choice in responses to LCS information is reviewed in the second part. In the third part, studies on drivers' responses in fire evacuations are reviewed. Section 2.2 reviews the data collection methods for behavioural studies. This review gives a background on the research methods by outlining approaches adopted by various behavioural researchers. In addition, the advantages and limitations of different methods are highlighted. Based on the nature of the problems to be solved in this research, explanations are also given why the simulation approach is selected. Section 2.3 reviews past traffic simulators, travel simulators and driving simulators. The advantages and limitations of each type of simulator are presented and the field of applications of different simulators are discussed. The review on this section further gives support on the motivation to develop the traffic-driving simulator. Section 2.4 reviews the discrete choice modelling framework. The review is targeted to give readers background information on the models being used in this study.

2.1 Response to Traffic Information

Traffic information displayed on different types of VMS could be in different formats, for example, symbols, numerical travel time information and textual descriptive information on different types of VMS. Other than text information on VMS, the traffic information can also be audio information, for example, public announcement on radio. Information of different formats are designed to convey different messages to drivers in cases of different traffic situations and targeted to affect drivers' driving behaviour and travel decisions.

In the presence of traffic information, drivers may expect to reduce their journey times and the transportation systems are expected to have enhanced service performance. These potential and benefits are more evident in an incident context with congestion. For example, Levinson (2003) explored the value of ATIS with simulation models and suggested that typical information benefits were at a maximum when the traffic was nearly-saturated, when vehicles were arriving at a rate of 95% of the capacity. For the less-than-capacity traffic, the ATIS has few opportunities to improve system performance. In addition, it was found that the benefits of ATIS in non-recurring congestion were much more significant than recurring congestion. Furthermore, it was also concluded that the ATIS could reduce variation of travel time, which made the private vehicle transportation more reliable. In another study, Emmerink et al. (1995) investigated the potential benefits of the ATIS in non-recurrent congestion with a simulation model in which the route switching behaviour was modelled with boundedly rational principles. The results indicated that if drivers were not provided with information regarding to the non-recurrent congestion, the road network would not be used efficiently in terms of travel time. Therefore, ATIS has potential to improve the traffic network performance. However, such potential to improve network performance was found to be dependent on the level of market penetration, the quality of the information and the en route switching propensity.

Findings from the above studies suggest that in general the traffic information would bring enhanced service of the traffic system, especially at incident contexts with congestion. Furthermore, the full benefits of such traffic information systems could only be realised if the drivers' preferences and responses are fully understood by designers and operators of such information systems. In particular, the effectiveness of traffic information and the factors affecting drivers' responses to the traffic information are essential for design and operation of the traffic information systems. Reviews on past studies can shed some background knowledge.

2.1.1 Route Switching Behaviour in Response to VMS

VMS is probably one of the most visible devices in ATIS, which provide real-time traffic information to drivers. VMS is a programmable traffic control device mounted on roadside, and designed to provide drivers updated traffic information. VMS is one of the information devices to be studied in this study. Regarding to the effectiveness of VMS message in influencing drivers' route switching behaviour, past studies have shown some evidences to support that VMS could effectively divert drivers from congested routes. For example, Tarry and Graham (1995) reported that diversion rates of 25-80% for message reporting congestion and instructing use of alternative route and 10-25% for messages reporting congestion without instructing use of alternative route. Yim and Ygnace (1996) used loop detector data to study the effectiveness of VMS and found that it influenced drivers to choose less congested routes when drivers were provided with real-time traffic information. With reported level of congestion in terms of queue length in the morning peak, there was 7%, 11%, 17% and 31% diversion rates for queue lengths of 1km, 2km, 3km and 4km, respectively. Their results suggested that a queue length of 3km seems to be the threshold at which a driver would choose to divert to alternative routes. Nijkamp et al. (1996) presented a case study on effectiveness of VMS in Netherlands and suggested that the benefits of the VMS were not only confined on the reduction in travel time, but also on the reduction of uncertainty. Wardman et al. (1997) used a Stated Preference (SP) survey to undertake assessments of effect of VMS messages on drivers' route choice. Their results showed that route choice can be strongly influenced by the provision of traffic information. Based on the forecasted diversion rate with the modelling results, the diversion rate could be up to about 90%, depending on content of messages shown. Chatterjee et al. (2002) also found that VMS message can affect travellers' route choice in another stated preference survey. Drivers said they would divert in 24% of message scenarios. However, the actual diversion rate was only one-fifth of the number of drivers diverted compared to that expected from the results of the survey. Chatterjee and McDonald (2004) reviewed past studies on effectiveness of VMS in European countries. The results indicated that in general, most drivers (80% to 100%) would read and understand information provided by VMS. However, in terms of awareness of VMS information on specific VMS signs, there were relatively fewer drivers (33% to 89%) who noticed the information displayed. In terms of diversion, the average diversion rate was 11% for 13 cases. The diversion rates in 5 cases out 13 cases were not statistically significant, while in rest of the cases the diversion rates were significantly different. These evidences have shown that travellers' route choices were affected by provision of VMS information. In addition, the impacts of aggregated travel response to VMS on network performance were addressed in other studies. For example, Lam and Chan (2001) developed a time dependent traffic assignment model to study the impact of dynamic information provided by VMS on traveller route choice model. Their findings suggested that the effects of providing dynamic travel time information in the situation of non-recurrent congestion were more significant, compared with situation of recurrent congestion.

A number of factors may affect travellers' responses to VMS messages. Khattak et al. (1993) examined short-term commuter response to unexpected (incident-induced) congestion, and the following information and factors were found to increase the probability of diversion: delay information received from radio traffic reports as opposed to observation of congestion, longer delays and longer travel times, and number of alternate routes used in the past, location of home in the city as opposed to the suburbs. In addition, risk seekers and male were more likely to divert. However, anticipated congestion on the alternate route inhibited drivers from diverting. Finally, drivers who had longer commute trips were more likely to return to their regular routes. Emmerink et al. (1996) confirmed earlier findings that women are less likely to be influenced by traffic information. In addition, they found that frequent commuters were less likely to be influenced by information provided. Lastly, they found that impacts of radio traffic information and VMS information on route choice behaviour were very similar. Benson (1996) examined the attitude of travellers towards the content of VMS and found that demographic variables except those related to education appear to have little influence on driver attitudes toward VMS. Wardman et al. (1997) concluded that impacts of VMS information depended on: the content of the message, drivers' characteristics and local circumstances, such as ambient traffic. Peeta et al. (2000) investigated the effects of different message contents on driver response under VMS and suggested that content of message in terms of level of detail significantly affected travellers' willingness to divert. More relevant information would result in higher diversion rate. Bonsall and Palmer (1999) gave a review on past studies, most of which were controlled experiments with stated preference and travel simulator techniques. Their reviews showed that the diversion rates critically depended on content of messages provided on VMS. In addition, the following factors were identified as those which would result in increased diversion rate: a clear advisory message, a reported long delay, the report on an accident as opposed to a roadwork and visible queue on intended route. Other factors, such as advisory information without cause, a reported short delay, a visible queue on alternative route, reported longer travel time on alternative route as opposed to normal condition, proportion of unfamiliar drivers if information is difficult to interpret and previous unreliable information were identified as factors which may result in decreased diversion rates. In a similar study by Abdel-Aty and Abdalla (2004), it was also reported that providing traffic information increased the probability of drivers' diversion from their normal routes. In particular, en-route and pre-trip information with or without advice increased the diversion probability. High travel time on the normal route and less travel time on the diverted route increased the probability of diversion. In addition, highly educated drivers were less likely to divert. Expressway users were more likely to divert from their normal routes under ATIS. Furthermore, drivers' familiarity with the device that provides the information and high number of traffic signals on the normal route increased the diversion probability

Among factors affecting travellers' route choice in provision of VMS, the content of message is the primary concern. There were a number of studies addressing how provision of different types VMS messages affected drivers' responses. Chatterjee and Mcdonald (2004) gave a review on European studies and concluded that different types of information may affect drivers' reaction differently. For incident information, the factors affecting drivers' diversion included the reported severity of the problem, the location of incidents and availability of alternative route. For route guidance information, it was concluded that substantial diversions occurred when route advice were given differently from normal, otherwise the diversions were negligible. This implied that advisory information should not be given in normal situations. Otherwise, the effectiveness of advisory information may be reduced in more critical situations. For the continuous information reporting of traffic status on a major route, the usage of the route increased if there was no reported traffic problem on the route. The usage of alternative route tended to reduce at the same time. For the travel time information, they were well regarded by drivers and effective in inducing route changes. Jou et al. (2005) examined the impacts of provision of different types of real time information on drivers' switching behaviour. Qualitative, quantitative information with and without guidance information were given in a stated preference survey and it was found that quantitative information with guidance information tended to be more acceptable by travellers. Other than message type, Srinivasan and Mahmassani (2003) also found that the users' route-switching behaviour was influenced by the nature, timeliness, and extent of real-time information, as well as quality of the information. The information quality of ATIS may strongly affect commuters' compliance behaviour. Chen et al. (1999) studied the effects of information quality on compliance behaviour of commuters and their results suggested that the highest compliance was obtained for reliable, predicted information based on prevailing condition and the least compliance for random generated information.

As a summary, the past studies have indicated that traffic information displayed on VMS has considerable impacts on drivers' route switching behaviour. A number of factors were identified in the past studies as factors which may affect drivers' route switching behaviour in response to VMS messages. These factors include, content and reliability of VMS messages, socioeconomic characteristics of drivers and local circumstances. Despite the substantial discussion on impacts of VMS messages and socioeconomic characteristics on drivers' switching behaviour, the impacts of local circumstances, such as ambient traffic, are not well identified. This is due to the difficulties in simultaneous data collection on drivers' driving behaviour and network traffic, which will be discussed in later sections.

2.1.2 Lane Changing Behaviour in Response to LCS

Another challenge to maintain a high level of safety of an underground expressway is the management of lane closure in an accident context, which requires knowledge on drivers' lane changing behaviour in the presence of traffic information. There are considerable amount of studies on drivers' lane changing behaviours. For example, Al-Kaisy et al. (1999) reported simulated study carried out to validate the simulated lane changing behaviour with empirical data. Their study results suggested that the simulated lane changing behaviour was consistent with observed behaviour. In another study, Sheu and Ritchie (2001) proposed a stochastic system modelling approach to estimate time-varying lane-changing fractions and queue lengths for real-time incident management on surface streets. Similarly, Gipps (1986) proposed a structure to connect the decisions which a driver has to make before changing lanes. These studies focused on lane changing behaviour in case of lane blockage, which can be observed or recorded at existing surface roads. However, in this study, the concern is on the lane changing behaviour in the presence of traffic information on LCS in an underground expressway which was under construction when this study was carried out. In such a case, even after the expressway is in operation, it would be very difficult to trace the actual behaviour over a segment of expressway because the expressway is underground.

The difficulties in data collection may be the reason that only a sparse set of literature on lane changing behaviour in response to LCS is available. The reported studies on lane management with traffic control systems focused on the aggregated impacts of LCS on the traffic pattern. Traffic simulation was utilised in these studies. For example, Schaefer et al. (1998) used a traffic simulation model to examine the level of compliance required to maintain the efficiency of the freeways. Jha et al. (1999) used simulation experiment to investigate the impact of the lane control signals on the resulting traffic patterns in the case of freeway lane closures. The validity of the result critically depends on the models for simulating the drivers' responses to LCS in studies of this type. However, due to the limited field data, the above studies were based on various assumptions to establish the level of compliance of the drivers. This makes the study of drivers' response to LCS a knowledge gap to be filled before one can go further to study the aggregated impacts of LCS.

In order to bridge this gap, Wohlschlaeger et al. (1995) used paper-based survey data to gather drivers' understanding on the different LCS symbols. There were two symbols, the yellow cross symbol and the yellow downward diagonal arrow symbol that were tested. The study showed the yellow downward diagonal arrow symbol was interpreted more consistently and "correctly" given its intended use than the yellow cross symbol. Their results provided a good indication on drivers' interpretation on messages displayed on LCS. However, the interpretation may not be a good representation of actual behaviour and therefore of limited use. Firstly, in many cases, a traffic scheme in the event of lane blockage may require display of messages on an array of LCS upstream the blocked lane. The dynamism of displaying symbols on an array of LCS therefore could not be captured with a paper-based survey. Furthermore, in terms of responses, paper-based survey results may be less significant due to the contextual effects. The validity of survey critically depends on the contextual realism of the survey instruments. When participants were in actual driving, their reactions may be different from what they stated since the actual driving task requires a certain level of work load due to the tasks of manoeuvring a vehicle. Lastly, the response captured in a paper-based survey may not be sufficiently detailed. The captured response only can answer the question on "whether" certain actions would be taken. If the question is on "How", "When" or "Where" certain actions would be taken, the paper-surveyed cannot give answers. To allow data collection of greater detail, data should ideally be collected either from the field or in a well controlled experimental environment, such as a driving simulator with high fidelity if it is available. However, no field studies or even driving simulator studies on responses to LCS were found in published literature, which may be ascribed to practical difficulties to obtain such data.

2.1.3 Responses to Guidance Information in Fire Emergency Evacuation

The damage to properties and loss of lives as a direct consequence of a fire inside a road tunnel are tremendous. Therefore, road tunnel fire safety is always on the top agenda at the design and construction stage of a road tunnel (Ingason and Wickstrom, 2006). The fire protection of a road tunnel requires considerations of different aspects. Human behaviour should be one of the main considerations to be integrated in the design and emergency planning of a road tunnel, failing which would result in the ineffectiveness of the guidance information provided in the emergency evacuation plan (Ingason and Wickstrom, 2006). For example, in a road tunnel vehicle fire reviewed, the public announcement system did not give the correct information on the fire and drivers were found not leaving their cars until the fire fighters knocked at their car windows and forced them to evacuate via the emergency exits (Chow and Li, 2001). Rhodes (2007) reviewed that on the Mont Blanc Tunnel Fire, it was found that during the fire, some undesirable drivers' responses were observed. Those undesirable responses included: car drivers entering the tunnel in spite of the red signal and siren; drivers continuing to drive only until the fire and smoke were seen; drivers staying in their cars; few drivers using the emergency exits. These undesirable behaviours may cause serious consequences. In order to avoid the undesirable behaviour, information should be provided in a way to guide drivers to behave correctly, i.e., they should not have any of the above mentioned undesirable behaviours. However, what guidance messages to be provided by the transport operator to guide drivers to evacuate in a desired manner to prevent loss of lives and properties is an essential question to be answered at the planning stage of the evacuation plans. Therefore, knowledge on how drivers would respond to different guidance information and whether the provided information is effective enough to avoid undesirable behaviour during emergency is essential for the fine-tuning of the evacuation plan.

Several studies were carried out in Europe on the tunnel fires, for example, the FIT (European Thematic Network on Fire in Tunnel, 2007) programme which is targeted to improve tunnel safety and reliability. Tunnel fires in different aspects, from fire safety design to fire response management are studied in the programme. However, these publications are not in the public domain. Most published studies on the behavioural responses in fire have focused on the human's behaviour in building fire (Bryan, 2002). In many of these studies, the six psychological and physical processes appeared to be the critical factors in the perception of a fire (Bryan, 1971). The six processes include: a) Recognition, b) Validation c) Definition d) Evaluation e) Commitment and f) Reassessment. Recognition is an individual's identification of ambiguous fire cues and awareness of the fire incident. Validation is the attempt to validate an initial perception of the fire cues. The definition is the attempt to relate the obtained information to characteristics of fire, such as the magnitude and location of fire. Evaluation is the attempt of an individual to evaluate alternative strategies to escape from the fire, while commitment is the attempt to initialise the strategies. The reassessment is the attempt to formulate alternative egress strategies in cases of failure of the previous egress strategies. However, whether the findings on human behaviour in building fire can be generalised into drivers' behaviour for a road tunnel fire is unknown since in road tunnel drivers are in their cars and some may think that staying in the car is safer.

2.2 Data Collection Methods

In behaviour research, experiment and survey are methods usually used. However, experiment and survey are different in application of the study results. Experimenters in behaviour science are more interested in the human nature in general. Therefore, the samples immediately available are usually used, which is called opportunity samples. For most experiments, a sample size is usually less then 30, or as long as the results can give statistical significance. However, surveyors are more interested in generalising the results to a specific pool of individuals, which are usually named as 'population'. Therefore, a large sample representative of targeted population is normally used (Rosnow and Rosenthal, 2002).

In this research, for the study of drivers' route switching behaviour, it is expected that the results can be generalised into the driving population who are users of Singapore expressways. Therefore, the data collection method is considered as surveys, such as the paper-based survey, and the experimental survey with a driving simulator. However, for the study of drivers' responses to accident management scheme with LCS and emergency evacuation, the research interest is more on human's nature in general. Therefore, the studies are considered as experiments.

In the following sections, data collection methods are reviewed. The objective is to review the advantages and limitations of different ways to obtain data in general, regardless of whether the method is considered as survey or experiment.

In general, behavioural data can be collected through a variety of methods. In terms of nature of data collected, the past data collection methods in the study of travel or driving behaviour can be classified into Revealed Preference (RP) and stated preference (SP) methods. RP methods reveal what a driver actually did (i.e. through field experiment), while SP methods reveal what a driver would do in hypothetical situations (Hensher, 1994). RP data, though convincing, suffer from lack of experiment controls and are therefore in many cases not sufficient to draw a conclusion (Bonsall, 2000). Furthermore, RP methods cannot be used to study ITS information systems that will only be deployed in the future. Due to these drawbacks, SP methods gained their popularity in travel behaviour studies although improvements are still required to increase their validities to represent real-life behaviour.

The most commonly used method to collect RP and SP data is the paper-based RP and SP survey. RP surveys reveal travellers' actual responses to traffic information in real life. For example, in two reported studies, Firmin and Bonsall (1999) used questionnaire survey and Richard et al. (1999) used travel diary to survey drivers' actual responses to VMS messages, as reviewed by Chatterjee et al. (2002). The RP surveys provide important feedbacks on the design of information content, as well as expected diversion. For example, Swann et al. (1995) found that drivers divert in 16% of the cases when a message indicated a problem on their route in Scotland. However, RP data are limited by the availability of VMS messages and local circumstances. Firstly, it is impossible to predict happenings of accidents or some incidents. Secondly, the physical designs of VMS and messages shown on VMS cannot be varied to suit the objectives of the surveys. Finally, other external factors, such as travel time, traffic conditions, are not controllable in field studies. These limitations of RP data motivate the collection of SP data as alternative source to understand drivers' driving and travel behaviour.

SP surveys are normally used to obtain users' responses in hypothetical scenarios in which incidents or accidents were designed and associated VMS messages were presented with pictures or textual descriptions. Hensher (1994) gave a review on the developments in the application of SP models in demand modelling and prediction. The SP techniques were introduced to transportation researchers in the 1970s. A number of papers were published, which showed the interests of researchers to use the technique in travel behaviour and demand modelling (Davadson, 1973; Golob and Dobson, 1974). However, the application of the techniques by travel behaviour researchers has happened slowly due to the difficulties in SP design and analysis of SP data with behaviour models. In the 1990s, the application of SP has increased substantially, as a result of the incorporation of SP variables into discrete choice models (Stopher and Zmud, 2001). Clear emergence of SP methods for measuring various aspects of behavioural responses was shown (Hensher and Battlellino, 1997). Other application of SP techniques includes work by Wardman et al. (1997) and Hidas and Awadalla (2003), who used SP survey to obtain users' responses to VMS messages. SP survey is very flexible and different VMS messages under different traffic conditions can be tested. In addition, external factors can be carefully controlled with desired level of variations. However, in SP surveys, the scenarios are normally presented with pictures or textual descriptions, and respondents have to imagine the complex scenarios. Thus, biases may be introduced by presenting pictures or textual descriptions on designed scenarios. Furthermore, what drivers stated may be different from what they actually would do. For example, as mentioned earlier, it was reported that only one fifth of the expected number of drivers diverted as opposed to that predicted by a model calibrated with data obtained in the stated preference survey (Chatterjee et al., 2002). Although the validation studies on SP survey have shown encouraging signs to use this technique (Fowkes and Tweddle 2000; Louviere, 1988; Smyth, 2000; Wardman, 1988), the paper-based survey is still less convincing because it requires subjects to hypothesise their responses.

Network monitoring is another indirect method used to study VMS information impacts. For example, Tarry and Graham (1995) monitored the downstream traffic of a key decision point, where VMS was mounted and accident information was given. 27-40% diversion rate was measured with a VMS message reporting accident and divert suggestions, while 2-5% diversion rate was measured with a VMS message merely reporting congestion. Network monitoring gives reliable measurement on actual conditions. However, it requires a wide range monitoring on traffic network, which is not practically feasible in most situations. Furthermore, it is difficult to differentiate whether the observed behaviour is the effects of VMS messages or other factors because of the absence of experimental controls. For example, in the case that the diversion rate was modest, it may be difficult to determine statistically significant changes in link flows, given normal traffic variability (Chatterjee et al., 2002). Even if significant changes were observed at one site, they are not directly transferable to other sites due to different OD patterns. Dynamic traffic assignment models may be the potential alternatives to overcome the limitations of network monitoring. For example, MCONTRM (CONtinuous TRaffic Assignment Model) (TRL, 1999) and RGCONTRAM (Route Guidance CONtinuous TRaffic Assignment Model) (McDonald et al., 1995) were used to study VMS strategies on motorways. By comparing the base line incident-free scenario with incident scenarios with different traffic assignment strategies, the impacts of VMS on traffic network could be studied (Bonsall and Hounsell, 1994). The approach could be used to examine the sensitivities of traffic impacts by different diversion rate and the optimal diversion rates in different situation can be determined. With information on diversion rate by different content of information, the optimal information strategies can be planned. However, the accuracy of such approach still depends on the underlying models which require capturing drivers' behaviour in response to VMS messages.

The field experiment is another way for direct observation of drivers' response to VMS messages. It can give the most reliable results while drivers' socio-economic status data can be obtained. Drivers' responses, including their route choices, lane choices and speed changes can be recorded with in-vehicle measurement devices or Global Position System (GPS) devices. For example, Li and McDonald (2002) used a GPS equipped probe car to obtain real-time travel time. In another study on effects on the in-car speed limiter, Varhelyi and Makinen (2001) used an instrumented car to conduct speed choice study in field. However, field experiments can only be used to test existing facilities. Furthermore, experimental controls are limited in field and therefore data collected are of limited usage in most cases.

The simulation approach is a widely used alternative of the paper-based survey and field experiment. In terms of fidelity, a simulator could be a low fidelity travel simulator which is primarily targeted to study route choice behaviour or a high fidelity driving simulator which can be used to study human factor aspects of driving behaviour. A travel simulator could allow subjects to "drive" through a representation of road network in carefully designed scenarios (Bonsall et al., 1997), which provides better control on situational and environmental variables than traditional SP questionnaire. For example, the consequence of last travel decision could affect the cost or travel time to the next decision point and therefore affecting the decision at the decision point. This dynamism is unable to be captured by a SP survey. There were a number of travel simulator studies carried out. For example, Vaughn et al. (1995) used a travel simulator to study route choices in parallel roads in the presence of travel advice information. The FASTCARS (Freeway and Arterial Street Traffic Conflict Arousal and Resolution Simulator) project is a more sophisticated travel simulator (Adler and McNally, 1994) designed to study drivers' responses to traveller information system. The FASTCARS allows plan views of road network along which subjects could "drive" in controlled scenarios with traffic information provided. The IGOR (Interactive Guidance On Routes) (Bonsall and Parry, 1991) is a prototype of subsequent development of two Travel Simulators: VLADIMIR (Variable Legend Assessment Device for Interactive Measurement of Individual Route choice), TRAVSIM (TRAVel SIMulator) (Bonsall et al., 1994), which have been successfully used to capture driver response to route guidance information, VMS information and road pricing.

Although the validation studies have shown that a well designed travel simulator can obtain higher validity data than from a paper-based survey (Bonsall et al., 1997; Bonsall, 2004), the limitations of travel simulator are that the local circumstances are displayed by static pictures, which overlooks the fact that drivers' travel behaviour may be affected by their driving experience within the ambient traffic. Koutsopoulos et al. (1995) reviewed on past studies based on travel simulators and have shown that they still to an extent failed to represent the real life behaviour and suggested a driving simulator with a windscreen view may be a better tool to collect travel behaviour data. In addition to validity issues, the travel simulator can only study travellers' behaviour such as route choice behaviour and not suitable to study drivers' behaviour which may require the presentation of driving behaviour in continuous terms, for example, lane changing behaviour, speed changing behaviour. Therefore, studies on lane changing behaviour in responses to LCS may require data collection on a driving simulator that is more sophisticated and can capture changes of behaviour in much greater detail.

Driving simulators are basically Virtual Reality (VR) systems which try to realistically replicate the complete driving task. Driving simulators allow controlled experiment in which drivers can interact with the virtual environment and users' manoeuvre of the virtual vehicle can be recorded in great detail. The use of driving simulator to study impacts of new technologies has become increasingly popular in recent years. For example, a driving simulator was used to study the adverse condition warning system by Gupta et al. (2002). Their results suggested such a system may provide advantages in terms of vehicle control. Another driving simulator reported in Liu (2000) was used to investigate the effect of Advanced Traveller Information (ATI) and found that the multi-modality display of ATI was optimal, particularly for older drivers. Hanowski and Kantowitz (1997) used their driving simulator to study drivers' comprehension and memory retention of information given by in-vehicle information systems and suggested that younger drivers performed better than older drivers when messages were in the format of symbols and text. Yang et al. (1998) used a driving simulator to study the information impact on driver and concluded that ideal type of ATIS information should reduce a driver's uncertainty regarding traffic conditions instead of overwhelming him or her with unnecessary data. Alexander et al. (2002) used a driving simulator to study factors influencing of the probability of an incident at a junction. Dutta et al. (2004) used a driving simulator to evaluate and optimise factors affecting understandability of VMS. They found that if an obstruction was present, drivers clearly benefited when a biphasic message was repeated in the legibility zone. Boyle and Mannering (2004) used a driving simulator to collect data on drivers' speed behaviour under different advisory-information conditions. They found that messages are significant in reducing speeds. However, in the area of adverse conditions, drivers tend to compensate for this speed reduction by increasing speeds downstream when such adverse conditions do not exist. The effectiveness of a warning system was studied with a driving simulator by Yamada and Kuchar (2006). Their results suggested that driving performance may not be necessarily related to the rated system quality by subjects. All the above studies suggest that driving simulator is an effective tool for design of innovative technologies, such as the new traffic information system in this study. With well controlled experiments, driving simulator could provide a good test bed for study of drivers' responses to traffic information. However, traditional driving simulator has some limitations in generating traffic scenarios in which realistic traffic flow is needed. This suggests that a traffic simulation module in the driving simulator may be required for research topics that require controllable and realistic presentation of traffic conditions. Therefore, more details of traffic simulator and driving simulator will be reviewed in the following section.

2.3 Simulators

In this section the traffic simulator and driving simulator will be reviewed. Both types of simulators are used in traffic studies widely, as reviewed in previous sections.

2.3.1 Microscopic Traffic simulator

Microscopic simulation of road traffic has been used more and more widely in solving problems that cannot be solved by traditional analytical methods. Many traffic problems, such as congestion and incident management, signal control optimisation cannot be modelled with traditional analytical methods due to the complexity and dynamism of the urban road transport system. Microscopic simulators make possible the whole system in its complexity as well as various traffic management alternatives to be modelled and evaluated in order to determine the optimum solution for any traffic scenarios (Hidas, 2005). According to the level of detail with which the simulation model represents the traffic system, simulation models can be classified into microscopic, mesoscopic and macroscopic models. A microscopic model describes both the system entities and their interactions at a high level of detail, which captures the behaviours of each individual vehicle. Mesoscopic and macroscopic models describes entities and their activities and interactions at a lower level of detail (Lieberman and Rathi, 2002). In this research, the traffic simulation of interest is the microscopic simulation in which behaviour of individual vehicle is required to be modelled. A microscopic traffic simulation model generally includes traffic infrastructure, such as roadway network, traffic control system, as well as demand information. Other components, such as vehicle characteristics and driving behaviour models, are important parameters in a traffic simulation model.

There have been a number of microscopic traffic simulation tools developed in recent years, for example, MITSIM (Yang and Koutsopoulos, 1996), Paramics (Quadstone, 2003), VISSIM (PTV, 2001), to name a few. These simulation systems provide a platform on which traffic models can be developed and calibrated with a specific traffic corridor or network. Calibration refers to a process with which model parameters are adjusted until reasonable correspondence between model data and field data is achieved (Chu et al., 2003). The trial-and-error method based on engineering judgement or experience is usually most common for model calibration. More systematic approaches, which apply optimisation methods to search parameter value which best satisfies the objective function defined are also used, for example, the gradient approaches (Hourdakis et al., 2003) and Genetic Algorithms (Cheu et al., 1998; Ma and Abdulhai, 2001). However, depending on applications of the micro-simulation and desired levels of accuracy, the criteria for calibration vary in different micro-simulation model.

Microscopic traffic simulation models have been used widely in traffic studies. For example, as reviewed in previous sections, microscopic traffic simulation models were used to study drivers' responses to traffic information (Schaefer et al., 1998). However, traffic simulation systems are targeted to simulate traffic scenarios in which individual vehicles are modelled at a microscopic level. This suggests that micro-simulation model may be integrated with other software to perform the desired functions, for example, the integration of a micro-simulation module with a dynamic traffic assignment model (Sahraoui and Jayakrishnan, 2005). The integration of a traffic simulator into a driving simulator can provide an interface which allows users' interaction with simulated scenarios.

2.3.2 Driving simulator

A driving simulator is a VR tool that gives a driver on the board impression that a real vehicle is being driven through predicting vehicle motion by driver input and feeding back corresponding visual, motion, audio and other sensual cues to the driver (Lee et al., 1998). The driving simulators, having their roots on flight simulators, dated back to 1970, when they started to appear in more primitive forms (Gruening et al.,1998). The advent of computer hardware and software capabilities recently leads to new opportunities for use of driving simulators.

A number of high fidelity driving simulators were developed to support training, design and research related to driving behaviour, vehicle safety and human factors. For example, the DaimlerChrysler Driving simulator (DaimlerChrysler, 2006) and the National Advanced Driving Simulator at The University of Iowa (University of Iowa, 2005) are high fidelity driving simulators. Many applications of driving simulator in traffic studies have been reviewed in previous sections.

In general, a driving simulator consists of at least four major components (Gruening et al., 1998):

(a) A simulation of vehicle dynamics on road

(b) A simulation of the driving environment, including the road elements and other vehicles

(c) A control panel for system operator

(d) Control devices, for example, steering wheel, brake pedal and throttle

The vehicle dynamics models are a set of nonlinear differential equations which capture inputs from the control devices, such as steering wheel, brake pedal and throttle. The driving environment includes geometric representations which set the constraints and references to calculate the vehicle dynamics, as well as the interaction of different vehicles. The control panel provide scenario controls, in which the predefined events are defined.

As a data collection tool, the validity of the driving simulator is another consideration on applications of driving simulation in behavioural studies. Whether users would behave the same in the simulator as what they would in the real situation is critical to the validity of the simulator in behaviour studies. A number of validation studies has been done to verify the validity of different driving simulators in respective research task, for example, driving behaviour in road tunnel (Tornros, 1998), validation for speed research (Godley et al., 2002). These validation studies showed that in general, with some exceptions, there are considerable correlations between real driving and simulated driving. Though there may be differences in absolute numerical values on driving performance, such as speed, lateral position, the relative correlation is well established, which is sufficient for most research objectives.

Also there are a number of challenges faced by developers and users of driving simulator, especially in generation of scenarios. Firstly, the behaviour of vehicles must be modelled in a microscopic level and be consistent with driver's expectations. Secondly, the macro properties of traffic, such as density, flow and speed, must be controlled in a realistic manner. Thirdly, modelling of specific situations and events requires coordinated actions of groups of vehicles (Cremer et al., 1996). These challenges motivated the integration of traffic simulation model in a driving simulator. For example, a microscopic traffic model was developed for implementation in a driving simulator (Maroto et al., 2006). However, the microscopic traffic is relatively less comprehensive and flexible compared with those traffic simulators reviewed in the previous section.

Simulation sickness is another issue in the development and applications of driving simulator in scientific research. The phenomenon of simulation sickness is similar to motion sickness, of which symptoms such as nausea, disorientation, dizziness and so forth are usually observed (Duh et al., 2004). A well-known and widely accepted approach to explain these phenomena is the cue-conflict theory (Griffin, 1990), which hypothesises that simulation sickness results from disagreement between visual cues that indicate, for example, that an observer is moving, and inertial cues, which indicate that the observer is stationary. "Postural Instability Theory" is an alternative theory proposed to explain the simulation sickness (Riccio and Storffregen, 1991). The theory suggests that maintenance of postural stability is one of the major goals of animals. An animal may become sick in circumstances where he or she has not learned strategies to maintain his/her balance. Therefore, in a virtual environment, people need to learn new "patterns" to control the postural stability, and until this learning is completed, they may experience simulation sickness symptoms, which are caused by postural disequilibrium. Based on above theories, it seems that as long as subjects are exposed to a virtual environment, the simulation sickness cannot be totally removed. However, the simulation sickness can be mitigated so that the impacts can be minimised. For example, it is reported that subjects' symptoms of simulation sickness decreased with repeated Virtual Environment (VE) exposures (Kennedy and Fowlkes, 1990), therefore, trial runs before the actual experiments may mitigate the simulation sickness symptoms during experiments. Anti-motion-sickness drugs are another common method to treat and prevent simulation sickness (Harm, 2002). However, the side effects of the anti-motion-sickness drugs are unknown and sometimes even problematic. Game developers suggest that improvement of system performance, such as frame rate and resolution may mitigate the simulation sickness (Wen, 2000).

As a summary, even though driving simulator can offer a high fidelity environment to allow rigorous tests to be carried out, the limitations should not be overlooked. Driving simulator takes considerable resource and effort to develop. Furthermore, no matter how much resources and efforts are expanded in the development and calibration of a driving simulator, the absolute validity can hardly be achieved due to the random nature of the research problems. However, transport sciences are not exact sciences and the relative validity is sufficient for most research topics, which usually is able to be achieved by driving simulator (Kaptein et al., 1996).

Another challenge for driving simulator developer and users is to model the scenario in which ambient traffic can be realistically controlled. This motivates the integration of the traffic simulation module in driving simulators. Lastly but not least, the simulation sickness is another issue that should be born in mind by the driving simulator users when they design their experiments.

2.4 Discrete Choice Models

The discrete choice model (Ben-Akiva and Lerman, 1985) is a data analysis tool to model drivers' route switching behaviour in response to VMS messages in this study. Since the route switching behaviour is discrete while the attributes of alternative route can be discrete or continuous, a modelling framework is required to map the observed choice with the attributes of each alternative. Discrete choice models allow the dependent variable (choices) to be discrete while the independent variables (attributes of alternatives) can be discrete or continuous. In addition, discrete choice models allow statistical tests on whether an attribute of an alternative has significant impacts on the choice. Furthermore, by observing the signs and relative magnitudes of estimated coefficient values, whether the impacts are positive or negative and the relative magnitudes of the impacts could be identified.

Discrete choice models have their roots from the Microeconomic Theory (MET), which focuses on the behaviour of individuals, assuming that they behave rationally. Under this principle, the approach of MET to study the choice behaviour is to determine all available decision alternatives facing decision makers, and to assign preferences to each of the various alternatives to choose the most preferred alternative which maximises the utility of the decision maker. Utility is a continuous function associated with each alternative and describes the level of satisfaction. The MET later was developed and had some important extensions, based on the assumption of the nature of alternative and decision maker from homogenous to heterogeneous. It was proposed that it is the attributes of the alternatives and character of decision maker that determine the utility they provide, and therefore utility can be expressed as a function of the attributes of the alternatives and characteristics of decision maker (Lancaster, 1966; McFadden, 1974). The concept of random utility theory was first proposed as a law of comparative judgment to describe imperfect discrimination (Thurstone, 1927). The model was later generalised to random utility maximization over multiple alternatives and was introduced to economics (Block and Marschak, 1960; Marschak, 1960). In this approach, utility is modelled as a random variable, consisting of an observable and unobservable random component. A utility can be presented as:

$$U = V + \varepsilon \tag{2-1}$$

V is a systematic component, which is the combination of a vector of functions based on attribute values, with the associated coefficients to indicate the commensurability of different attributes. The systematic component can be written in the following linear form:

$$V = \sum_{k=1}^{K} \beta_k x_k \tag{2-2}$$

where x_k are the attributes associated with the various alternatives. β_k are the coefficients associated with each attribute. K is the number of attributes and ε is the random component to reflect the random the uncertainties. Four sources of uncertainty were identified as unobserved alternative attributes, taste variations, measurement errors, and instrumental variable (Manski, 1977).

Take a binary choice model as an example, for choice set i and j, the probability that an alternative i is chosen is given by:

$$P_n(i) = \Pr(U_{in} \geq U_{jn}) = \Pr(V_{in} + \varepsilon_{jn} \geq V_{in} + \varepsilon_{jn}) = \Pr(\varepsilon_{jn} - \varepsilon_{in} \leq V_{in} - V_{jn}) \tag{2-3}$$

The assumption on distribution of the random error leads to different families of discrete choice model. If it is assumed that the $\varepsilon_n = \varepsilon_{jn} - \varepsilon_{in}$ is logistically distributed, namely:

$$F(\varepsilon_n) = \frac{1}{1 + e^{-\mu\varepsilon_n}}, \quad \mu > 0, \quad -\infty < \varepsilon_n < \infty, \tag{2-4}$$

$$f(\varepsilon_n) = \frac{\mu e^{-\mu\varepsilon_n}}{(1 + e^{-\mu\varepsilon_n})^2} \tag{2-5}$$

where μ is a positive scale parameter. The models developed based on this assumption fall in the family of Logit. The independent and identically distributed Gumbel distribution of the random error in Logit models leads to an important property of Logit models. The property of Independence from Irrelevant Alternatives (IIA) is foundation of the probabilistic choice model (Luce, 1959). IIA states that the ratio of the choice probabilities of any two alternatives is unaffected by other alternatives. This property is important to later development of the tractable Multinomial Logit (MNL) model (McFadden, 1978). However, IIA also has distinct disadvantage in that the model will perform poorly when alternatives are correlated (Debreu, 1960). In order to relax the IIA assumption, many variations of discrete choice were developed aiming at doing this. For example, Nested Logit (NL) (Ben-Akiva, 1973) was derived as a random utility model as a special case of General Extreme Value, or GEV (McFadden, 1978; McFadden, 1981). NL explicitly allows correlation within sets of mutually exclusive groups of alternatives and still retains an extremely tractable closed form solution, and therefore is widely used. Cross-nested Logit (CNL) relaxes the error structure of nested Logit by allowing groups to overlap (McFadden, 1978; Small, 1987; Vovsha, 1997). MNL, NL, and CNL are all members of the GEV, a general and elegant model in which the choice probabilities still have tractable Logit form but do not necessarily hold to the IIA condition.

If the random error is assumed to be normally distributed, namely,

$$P_n(i) = \Pr(\varepsilon_{jn} - \varepsilon_{in} \le V_{in} - V_{jn}) = \int_{\varepsilon=-\infty}^{V_{in}-V_{jn}} \frac{1}{\sqrt{2\pi\sigma}} \exp\left[\frac{-1}{2}\left(\frac{\varepsilon}{\sigma}\right)^2\right] d\varepsilon, \sigma > 0,$$

$$= \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{(V_{in}-V_{jn})/\sigma} \exp\left[-\frac{1}{2}u^2\right] du = \Phi\left(\frac{V_{in}-V_{jn}}{\sigma}\right), \tag{2-6}$$

The model families will be called probit. The early investigations of probabilistic choice models (Aitchison and Bennett 1970; Bock and Jones, 1968) are examples of models under the probit family. The probit models are extremely flexible and there is no need to relax IIA assumption in probit model. However, the lack of a close form solution makes it less popular than its sibling: Logit models. Daganzo (1979) and Hausman and Wise (1978) provided a thorough examination of Probit models. There are some studies to tackle the difficulties in the estimation of probit Models, for example, Lam (1991) used the Monte Carlo simulation in a parallel environment to calculate the Multinomial probit probability. Hajivassiliou and Ruud (1994) also tried to use simulation for estimation. A summary of simulation methods was given in a review by Hajivassiliou et al. (1996). Other than simulation method, there were efforts to allow simpler computation of probit model. One particularly attractive development in discrete choice models is the Mixed-Logit Model (MNL) (Ben-Akiva and Bolduc, 1996), in which the unobserved disturbance is the sum of two error terms. One error term is multivariate normally distributed while the other one is Gumbel distributed. With such a specification on the disturbance, the MNL combines the flexibility of the probit structure with the computational simplicity of the logit model. McFadden (2000) provided an excellent review of the history and future directions of discrete choice theory.

2.5 Summary

In this chapter, background information relating to this research, including past studies on drivers' responses to traffic information, and data collection methods to support such studies were reviewed. There were significant literature contributions on studies of drivers' responses to traffic information. However, existing data collection methods limited the development of studies on drivers' responses to traffic information. Through the reviews on data collection method, it was identified that a driving simulator may be the best tool for data collection, especially in cases that new information technologies are studied. However, the challenge to generate realistic traffic scenario motivated the integration of a traffic simulation module into a driving simulator. Finally, the discrete choice modelling framework is presented as a tool to help us understand the impacts of different factors on drivers' route switching behaviour.

In view of the limitations of past studies, in the following chapter, the methodology to achieve the research objectives and the experimental designs in this research will be discussed.

CHAPTER 3. METHODOLOGY AND EXPERIMENTAL DESIGN

Based on the findings of literature reviewed in Chapter 2, this chapter is targeted to discuss the methodology and experimental design and procedure in this study. Study methods and data requirement to support the study objectives are discussed, followed by descriptions on the survey instruments, experimental design, sampling, experiment procedures and data analysis methods.

3.1 Methodology

As discussed in Chapter 1, the objectives of this study are to develop a traffic-driving simulator as a critical observation basis to study drivers' responses to traffic information in cases of congestion, accident with lane closure and fire emergency evacuation. The reason to investigate these three cases is that they are the most critical incidents which may affect efficiency and safety of expressways significantly. Furthermore, drivers' behaviours in these unusual circumstances are normally not able to be observed in field and therefore few past studies are available, especially for accident and fire emergency evacuation cases. That is the reason why a traffic-driving simulator was developed as a critical observation basis for this study. This section is going to discuss the methodology in great detail.

(a) Development of a traffic-driving simulator

As discussed, the challenge to support study of drivers' behaviour in the presence of ATIS in incident contexts is the provision of an observation basis for data collection. As an observation basis, it should allow simulation and presentation of incident, traffic and operation of ATIS. This desired level of realism motivated the development of a traffic-driving simulator, which integrated a traffic simulator into a driving simulator.

The integration of traffic-driving simulator requires a good understanding on the fundamentals of a driving simulator and traffic simulator. The existing driving simulator in NTU is a very sophisticated system. Therefore, to test the ideas of integration on that system is not feasible. Therefore, a PC-based prototype driving simulator was developed from scratch to test the ideas of integration of a driving simulator and a traffic simulator. The PC-based driving simulator is less complicated and could be fully customised to test the integration. The first challenge of integration is to allow data conversation and exchange between these two systems so that vehicles simulated in the traffic simulator can be seen in the driving simulator. The traffic simulator and the driving simulator use different coordination system and therefore some computer programmes were developed for data conversion. To allow data exchange, some computer programmes were developed to allow the traffic simulator and driving simulator to access a shared database. Another challenge for integration is the development of visual database. The road infrastructure in the traffic simulation model and in the visual database of the driving simulator should be identical. Otherwise, the vehicles generated in the traffic simulation model may "fly" in the driving simulator. To allow such challenge to be achieved, computer programmes were written to allow the coordinates of critical points extracted from the visual database in the driving simulator to be read by the traffic simulator during the development of the traffic simulation model. With such effects, the coordinates of the road structure are identical in both systems. The third challenge is to allow the interaction of the car driven by a subject to interact with traffic generated by the traffic simulator. A number of computer programmes were written to allow the interaction of other vehicles with vehicle controlled by a subject. For example, computer programmes to detect collision, to control speed of other vehicles, etc.. Lastly, an ATIS control module was developed to allow simulation of ATIS operation in each scenario. These computer programmes developed in the prototype for different functions were later used in the driving simulator in NTU.

With development of the traffic-driving simulator, another issue regarding the realism of the scenarios arises. The new expressway was under construction and traffic control and management measures of the new expressway, for example, the speed limits have not been determined by the time this study was carried out. Therefore, the traffic characteristics were difficult to determine. In view of this, an assumption was made that in the hypothetical scenarios going to be developed based on the new expressway, the traffic characteristics on the new expressway are consistent with the traffic characteristics on existing expressways. This assumption was made based on the fact that the driving population who will drive on the new expressway are the driving population who has been driving on the existing expressway. Therefore, the key driving behaviour parameters which determine the traffic characteristics, such as headway, reaction time are the same, especially in cases that the traffic was heavy and the traffic was constrained by the congestion rather than the speed limits. Furthermore, it is expected that the study results can be generalised to similar expressway of its kind, especially in studies of drivers' route switching behaviours in road congestion. Therefore, it is reasonable to assume that the new expressway has similar traffic flow characteristics as existing expressways in the hypothetical scenarios to be simulated.

Based on above assumptions, calibrations on the traffic simulation models were carried out with an existing expressway which has similar geometry design as the new expressway. Field traffic surveys were carried out and essential traffic statistics, such as travel times and flow rates were extracted. This information was used to optimise the parameters in the traffic simulator model so the results in simulation and field are closely matched. In addition, a real car model was used to allow better physical validity of the simulation. Other parameters, such as position of viewpoint, simulation time step were also calibrated. With above development and calibrations done, the system performance and data collection were verified in a pilot survey with the traffic-driving simulator. The major modules for the traffic-driving simulator and the calibration and the verification will be presented in Chapter 4.

With all the necessary development and calibration, the system was able to generate scenarios to simulate operation of ATIS in incident contexts. However, the issues on performance of system during the actual survey and verification of data collected motivated a pilot survey with the traffic-driving simulator. Furthermore, knowledge on drivers' perceptions on existing ATIS information was important to facilitate the experiments design for the traffic-driving simulator survey. To obtain such knowledge, a paper-based perception survey was carried out prior to the laboratory experiments with the traffic-driving simulator. The paper-based perception survey was carried out by interviewers at various locations near the busiest expressway in Singapore. The paper-based survey was also a recruitment drive which targeted to obtain contacts of potential subjects for the following traffic-driving simulator survey.

With all the above efforts, the system was used to study drivers' driving behaviour in the presence of ATIS in different incident contexts. As discussed, three cases were critical to efficiency and safety of the new expressway and they were investigated.

(b) Study of drivers driving behaviour in an accident context with lane closure

In study of drivers' driving behaviour in an accident context with lane closure, the major concern is how VMS and LCS information would affect drivers' lane changing behaviour and speed choice in an event of accident with lane closure in an underground expressway. In order to study effectiveness of ATS in such a context, a typical scenario was simulated in which an accident happened and VMS and LCS upstream of the accident were used to broadcast information on the lane closure information. In order to measure the effectiveness, drivers' longitudinal clearances from the blockage and speed were used as Measurement of Effectiveness (MOE). Furthermore, to test the hypothesis that the LCS is effective to affect drivers' lane changing behaviour and speed choice in such a context, an identical scenario was simulated with LCS excluded and the MOE was compared with the previous scenario with statistical tests.

(c) Study of driver' driving behaviour in a fire emergency evacuation context

In study of driver' driving behaviour in a fire emergency evacuation context, the major concern is the effectiveness of guidance information provided by different information equipment. Scenarios were simulated in which drivers were guided to leave the underground expressway with different evacuation plans. In order to capture drivers' driving behaviour, data logs are used to analyse whether drivers follow the instruction given by different information devices. Furthermore, to capture the reason that drivers did not follow the instruction given by different information equipment, a short post scenario was carried out after each scenario. Furthermore, to test the hypothesis that radio broadcasting may result in different behavioural responses of drivers in such extreme conditions, identical scenarios were created with radio broadcast purposely excluded. Statistical tests were used to compare driving behaviour with and without audio information broadcasted by radio.

In study of drivers' driving behaviour in an accident context with lane closure and study of driver' driving behaviour in a fire emergency evacuation context, the research interest is more on human nature rather than generalise the results to certain population. However, in the study of drivers' route switching behaviour in the presence of VMS message in traffic congestion, it is expected the results can be generalised into route switching behaviour of Singapore driving population on existing expressway system. In that sense, the study on route switching behaviour can be considered as a survey. In the following parts of this thesis, the second wave survey with traffic-driving simulator will be referred as "the traffic-driving simulator survey".

(d) Drivers' route switching behaviour in the presence of VMS messages in traffic congestion

In study of drivers' route switching behaviour in the presence of VMS messages in traffic congestion, the major objective is to find out factors affecting drivers' route switching behaviour in such a context. The results of this study are expected to be generalised to existing expressways for Singapore driving population. Therefore, the traffic simulated in the hypothetical scenarios was based on traffic conditions on existing expressways. A number of hypothetical scenarios with traffic congestion of different extent were simulated, in which different VMS messages reporting the observed congestion were provided. As reviewed in Chapter 2, the following factors were reported in past studies (Bonsall and Palmer, 1999; Wardman et al., 1997) as important factors which may affect drivers' route switching behaviour and they were taken as independent variables in this study:

(i) Attributes of expressway studied and attributes of the alternative routes to destination. The attributes could be distance, travel time, road pricing, etc.

(ii) Traffic conditions at decision points. Speed and density at decision points are typical variables to describe traffic conditions.

(iii) Message content

(iv) Drivers' characteristics: Age, gender, etc..

Above variables are independent variables identified to support model development. Variations of the above independent variables were manipulated in the experimental design, which govern the generation of different scenarios. The observed drivers' route switching behaviour was recorded in each scenario as the dependent variable. The details of the traffic-driving simulator survey will be discussed in Chapter 8. Drivers of different socio-economic characteristics were invited to drive in different scenarios and their route switching behaviour was recorded. However, challenges arise in modelling drivers' route switching behaviour due to the complexity and dynamic nature of the process. The switching behaviour was affected by a number of factors and usual statistical tests could not capture the full picture. Secondly, the tests on correlation of the successive switching behaviour are required. To accommodate, the random effects of Probit models were used to allow statistical tests on effect of each factor and the correlation of successive switching behaviour.

3.2 Instruments

As mentioned, there were two waves of surveys and two traffic-driving simulator experiments carried out in this study to collect required data. The first wave survey was a paper-based survey. The survey instruments were colour printed cards and questionnaire. In the second wave survey, the developed traffic-driving simulator was used as the instrument to facilitate the collection of data on drivers' route switching behaviour. Other experiments designed to study drivers' responses to accident management scheme and emergency evacuation scheme, were carried out on the traffic-driving simulator as well.

The traffic-driving simulator is an integration of a traffic simulator and a driving simulator, which allows rigorous testing of new technologies before actual implementation. The traffic-driving simulator has advantages of both traffic simulator and driving simulator and is capable of collecting data required for this research. In addition, the traffic-driving simulator is flexible to model different scenarios according to the experimental design. The network traffic statistics, such as average speed, flow rate, can be obtained in the simulator as well. Subject's driving behaviour is collected through the logged data, which trace drivers' speed and movement at a frequency of 30Hz. The details of the traffic-driving simulator will be discussed in Chapter 4.

3.3 Experimental Design and Sampling

There were two waves' surveys and two experiments carried out in this study. The design of the paper-based will be discussed separately in Chapter 5. The paper-based survey was targeted to study drivers' understanding and stated responses to existing VMS messages used on expressways in Singapore. The questionnaires were divided into four groups to allow variations of VMS messages presented. A total of around 1000 drivers were interviewed.

In second wave traffic-driving simulator survey and experiments with the traffic-driving simulator, there were different scenarios designed for different study objectives, with different experimental design strategies. The traffic-driving simulator survey to study drivers' route switching in response to VMS display scheme were factorial experiments designed with technique which was similar with stated preference survey (Louviere et al., 2000), in which desired variations of independent variables in different scenarios were required for calibrations of discrete choice models. The details of the independent variables will be discussed in Chapter 8. More than 200 participants were invited to the laboratory where the traffic-driving simulator was located. Due to the simulation sickness, results of 170 participants were effectively used for data analysis. On average, each participant drove in 5 runs which were different scenarios designed to capture route switching behaviour in different congestion contexts. Random sampling strategies were used to randomise the scenarios participants had to go through.

For the study of drivers' lane changing behaviour in response to traffic information in a lane closure context, factorial experimental design was used to differentiate the effects of LCS. There were two scenarios simulated. Scenario 1 was the control scenario, in which all LCS signs were intentionally removed while Scenario 2 was the experimental scenario, in which LCS signs were used. The between-subject factor was the availability of the LCS, and other factors were exactly the same in the two scenarios. The reason for the simplistic design is to isolate the effects of other factors. The details of scenario information will be given in Chapter 6.

In the fire evacuation of a road tunnel, drivers will either be guided to take the impending exit slip road or to abandon their cars and escape via the emergency exits on the side walls of the tunnel. An important concern is the effect of audio information broadcasted by the RBBI in this two evacuation methods. Therefore, a 2×2 factorial experimental design was used to capture drivers' responses to emergency evacuation information and effects or RBBI. The two between-subject factors were the evacuation methods and the availability of RBBI. Each of the factors had two levels and there were four scenarios designed and the details of scenarios information will be presented in Chapter 7.

In both above experiments, the interest is to study human nature rather than generalize the results to a population. Therefore, opportunity samples, which were immediately available in controlled experiments, were used. The sample size depends on experimental design and statistical methods used to interpret the results (Rosnow and Rosenthal 2002). In the study, the data collected in above two experiments were suitable to be interpreted by the selected statistical tests, which implied that the sample size was sufficient.

3.4 Experiment and Survey Procedure

As discussed, in this research, paper-based survey and driving simulation experiments and surveys were carried out. In the paper-based survey, interviewers were trained and dispatched to shopping malls, parking lots to interview drivers. The details of the paper-base survey will be discussed in Chapter 5.

For the traffic-driving simulator surveys and experiments with the traffic-driving simulator, subjects were invited to Nanyang Technological University Virtual Reality laboratory where the traffic-driving simulator is located. A pilot survey was conducted to test the experiment procedure and to verify the system performance and data collected. 10 participants were invited for pilot experiments and surveys. For each participant, there were five runs to be completed. The five runs were randomly selected from scenarios based a section of KPE, with morning peak traffic conditions and operation of VMS simulated. It took more than 1 hour for each participant to finish the five scenarios. There was no major problem with the system performance and data collection. Data collected from a sample scenario will be presented in Chapter 4. However, there were 2 participants who suffered simulation sickness and could not complete all the runs. As for other participants, it was commented by participants that if they were exposed to scenario which took a long time to complete, or in the scenarios of stop-and-go congestion, they too would be more prone to suffer simulation sickness.

As reviewed in Chapter 2, the longer exposure time to the driving simulator would result in the higher chance that a subject would suffer the simulation sickness. Therefore, in the main survey, some scenarios with the long section of expressway were replaced by scenarios with a shorter section of expressway and severely congested scenarios were replaced by less congested scenarios. Furthermore, in scenarios designed to study drivers' switching behaviour, as soon as a decision was made to switch to an alternative route and there was no further decision to be made, the scenario would be stopped to reduce the exposure time of the driver. During each scenario, drivers were allowed to take a break until he or she wanted to start the next run.

The main experiments and surveys were carried out with measures to minimise the simulation sickness. In the main survey, for each participant, a test drive was carried out before the designed scenarios. Participants who were prone to simulation sickness during the test drive were advised not to participate. Furthermore, participants were instructed to stop immediately if they felt unwell during the experiments. Together with the sample collected in the pilot survey, there were 200 participants of whom 170 participants completed all scenarios. All participants were in possession of valid driving licences with at least one year of local driving experience. Participants received a small token for their participation in the experiment.

A number of scenarios were modelled in the traffic-driving simulator to allow data collection of drivers' driving behaviour in different incident contexts. Each participant was asked to go through 7 runs, of which 5 runs were targeted to study drivers' route switching responses, while the other 1 or 2 runs were targeted to study drivers' responses to information in an accident with lane closure and emergency evacuation, respectively. Some participants only had go to through 6 runs since the emergency scenarios results were statistically significant after a certain number of samples and those scenarios were no longer carried out. The sequences of the 7 scenarios were randomised for each participant.

A protocol was developed to control the experiment procedure. Each participant was requested to fill a consent form and a short questionnaire prior to the start of the experiment. The consent form was targeted to inform participants the objective of this survey and seek their consent for voluntary participation. An S$11 (about US $7) token was given to each participant after the consent form was signed and participants were told they could stop the experiments anytime if they felt unwell. The questionnaire was designed to capture drivers' socioeconomic characteristics. Each participant was asked to have a test drive after the questionnaire was completed. Before each run, some relevant background information was provided, for example, the time of the trip, trip origin and destination and attributes of available alternative routes. However, participants were not explicitly told what is going to happen in the run. Participants were asked to complete the run as they would generally do in real driving. They were told that they would be able to choose alternative routes to the destination if they wish and they were not instructed to stay on a particular route or lane. After each scenario, a few questions were asked to capture participants' familiarity on alternative routes. For the emergency evacuation scenario, additional questions were asked to capture the reasons for not following instructions. After each run, participants were told to take a few minutes' break until they felt comfortable to take the next run. The total length for one participant to go through all the scenarios was about1 hour.

3.5 Data Analysis

The data collected by surveys and experiments were analysed with descriptive statistics, statistical tests and discrete choice models. For the survey data collected in the paper-based survey, the results will be analysed with descriptive statistics and statistical test so drivers' understanding on the current message used could be known.

In the experimental survey with the traffic-driving simulator, drivers' route switching responses were analysed with descriptive statistics and discrete choice models. However, in the experiments to study drivers' responses to traffic information in a lane closure context and emergency evacuation, the results were analysed with descriptive statistics and statistical tests.

3.6 Summary

The chapter discussed the methodology and experimental design and procedure used in this research, in view of challenges to achieve research objectives highlighted in Chapter 1 and limitations of traditional research methods reviewed in Chapter 2. The challenges to achieve the research objectives are that drivers' likely responses to ATIS are studied before its implementation and tradition data collection methods are somehow limited to collect sufficiently detailed data to support the research objectives. Therefore, a traffic-driving methodology was adopted in this study. The driving simulator can generate realistic driving scenarios in which drivers driving behaviour can be captured in great detail. Such advantages make the driving simulator a suitable instrument to capture drivers' behaviour in presence of ATIS in an accident context and a fire evacuation context. The integration of a traffic simulator into the driving simulator was another important step, which allows congestions in traffic network to be realistically simulated in the driving scenarios. This is particularly important to study drivers' route switching behaviour in congestion.

After highlighting the importance of the traffic-driving simulator methodology to achieve the research objectives, the detailed experimental design and sampling were then discussed and experiment approach and procedure were presented. This discussion also gives the reader an impression on magnitude of data collected in this study.

The details of the scenarios and analysis of the survey and experiments results will be presented together in detail in Chapters 5 to 8 so readers do not need to refer to this chapter for details on scenarios when they are reading the results. In the following chapter, the design and calibration of the traffic-driving simulator will be discussed in detail.

CHAPTER 4. TRAFFIC-DRIVING SIMULATOR

The methodology of this research is discussed in the previous chapter. In this chapter, the major components of the traffic-driving simulator as the experiment instrument are discussed. Furthermore, the calibration of the system and examples of data collected are provided.

As discussed in Chapter 3, there were two generations of simulation system developed. The first generation system was a PC-based prototype system, which was self developed from scratch, through which the fundamentals of the driving simulator were well understood and the knowledge and computer programmes on integration were established. It took more than one and half years to develop those computer programmes.

The second generation system was based on a SGI platform, which allows a more realistic driving environment in the actual survey. Running on a powerful SGI workstation, sophisticated vehicle dynamics, ambient traffic, as well as details of scenes could be simulated without additional lags. Furthermore, a front cabin view from a car was created by making use of a portion of a real car. The set up of this system was located at the Reality Theatre laboratory at NTU. Additionally, advanced display devices were used to allow "nearly real size" projection of simulated objects. With the essential programmes developed and tested for integration in the prototype system, the SGI-based traffic-driving simulator was developed and calibrated. It took the author and a supporting team from Centre of Advanced Media Technologies one year to develop all programmes, as well as a traffic model and the visual database for KPE.

4.1 Major Modules of the Traffic-Driving Simulators

The system structure of the first generation and the second generation systems is similar, although the second generation system is much more sophisticated in each module. In both the first generation and second generation systems, the traffic simulator was based on Paramics (Quadstone, 2003). The driving simulator of the first generation system was developed in house based on a third party VR platform, World Up (Engineering Animation Incorporation, 2000). Substantial programming and modelling works were carried out to develop the first generation simulation system. The second generation is a SGI-based driving simulator system. The hardware of the driving simulator in the second generation was more powerful than the first generation system. In the following sections, the major modules of the traffic-driving simulators are discussed.

Figure 4-1 illustrates the major modules of the traffic simulator and the driving simulator and how data are exchanged from each component. The main modules of the system include a Geographic Database, a Visual Database, Traffic Simulation Models, the Simulation Engine, the Graphic Engine, Data Output Module, the Display and Car Model and ATIS Control Interface. The functions of each module are discussed as follows.

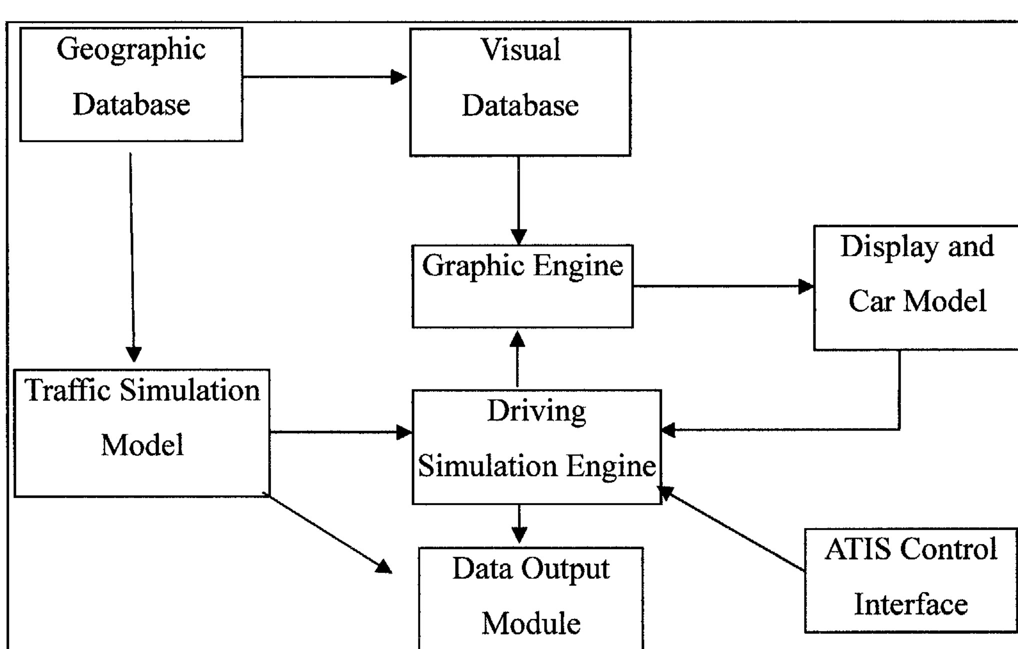

Figure 4-1 Conceptual Design of the Traffic-Driving Simulator

4.1.1 Geographic Database

Geographic Database stores the geographic content of the simulated traffic networks. This information was shared by both the traffic simulator and the driving simulator to develop the traffic network infrastructure. The geographic data were collected using various sources, for example, local map, design drawings and field surveys. For the first generation system, the geographic information was obtained from local maps and a number of field surveys. For the second generation system, since the KPE was still under construction, the geographic data were collected and digitalised from design drawings.

4.1.2 Traffic Simulation Models

The traffic simulation models were developed using Paramics, which provided the microscopic simulation of traffic, incidents and operations of ATIS on the simulated expressways. The traffic infrastructure and ATIS components, for example, VMS and other information equipment were added with reference to the geographic database. With the simulation network developed, the demand and incidents (if any) on the traffic network could be specified. A number of programmes were developed to customise and to facilitate calibration of the simulation model through the Application Programming Interface (API) provided by Paramics. For example, a programme was developed to extract some traffic statistics while another programme was developed to allow automatic multi-runs of the simulation model. Furthermore, data exchange mechanism between the traffic model and the driving simulation engine was also developed using API, which is the essential step for the integration of the traffic model and the driving simulator. One difficulty encountered was that Paramics and the driving simulator use different coordination system. Therefore, the mapping of coordinates between the two systems was essential for the data exchange between the two systems. In a 3D system, the positions of a physical object are defined by its location and orientation. Mapping of coordinates include the mapping of location and orientation. The mapping of location is relatively straightforward while mapping of orientation is somehow more complicated. In Paramics, orientations are presented in terms of bearing and gradient values. However, most simulation software packages, such as WorldUp and the second generation driving simulator, use Quaternions (Kuipers 1999) to represent the orientation. Quaternions have 4 dimensions and it is an efficient way to represent orientation. A programme was developed to map Paramics coordinates to the driving simulator coordinates.

4.1.3 Visual Database

The visual database stores 3D spatial and texture mapping information of every visible element in the driving scenarios, such as expressways, buildings, trees, vehicles and so on. The visual database was loaded by the driving simulation engine at the start of a simulation run as the virtual world displayed to users. On the other hand, the visual database was used to set the constraints and references of movements of vehicles controlled by the system and the driver. Furthermore, the visual database provides a reference to calculate the drivers' location and speed during post-experiment analysis.

The creation of the driving simulator visual database was rather tedious and required considerable amount of work on calibration of fundamentals, especially on the road created so as to ensure that the visual database was identical to the traffic model. The visual database was created with different 3D modelling software. The first generation system used 3DMax (Discreet, 2002) for visual modelling, while the Maya (Alias, 2005) was used with the help of the Centre for Advanced Media Technologies (CAMTech) at NTU for the second generation system since it allows generations of more optimised visual models.

4.1.4 Driving Simulation Engine

The Driving Simulation Engine is the core of the simulator. It manages the operations of all the modules in the driving simulator and provides the data exchange of each module in real time. There are four major functions controlled by the simulation engine; (a) Ownship dynamics control, (b) Computer Generated Force (CGF) control, (c) ATIS control and (d) Data collection.

An ownship refers to the vehicle controlled by a driver in the simulation. The ownship dynamics allows motions in 6 degrees of freedom motion, based on a driver's driving behaviour and environment. There are a number of models used to simulate the motion of the ownship, for example, the engine model computes the engine status, such as engine speed, engine torque, engine transition torque based on inputs from steering device and travelling speed of the ownship. Steer and tyre models control wheel steering angle, tyre friction and sideslip according to road status. Suspension models compute the spring force and damper friction while drag models compute the rolling drag and air resistance drag from current travelling speed and vehicle weight and shape. Brake models calculate braking force for each wheel and the braking torque from braking force. These models capture the interaction of driving behaviour, vehicle and environment and calculate the motion of the ownship.

A CGF refers to a vehicle controlled by the computer in the simulation. The CGF control component loads the data from the traffic models and controls the interaction between the CGF and the ownship. Since the traffic simulator is working offline with the driving simulator, the control of interaction of ownship and CGF is controlled by the driving simulator. Sophisticated computer programmes have been developed to allow the interaction between the ownship and the immediate CGF. For example, if the ownship blocks the way a CGF is travelling, the CGF will slow down and wait until the ownship leaves. The CGF will then slowly pick up its speed until it reaches the place it is supposed to be in the traffic simulation model. This is a subtle process and appears quite realistic in the driving simulator.

The ATIS control component receives commands from the ATIS Control Interface (ACI) and controls the operations of the ATIS components such as VMS, LCS, in-vehicle unit and traffic signals. The messages shown can be updated manually with the ACI or based on the simulation results of the traffic models.

The simulation engine also collects the data on drivers' driving behaviour at a frequency of 30 Hz. The data are output into a database for further analysis.

4.1.5 Data Output

The data collected by the driving simulation engine include simulation times, ownship positions, orientations and speeds, accelerations, braking and steering behaviour. Other information like lane choice and route choice can be obtained by the position data of the ownship, with reference to the visual database.

4.1.6 Graphics Engine

The graphics engines for both systems were implemented by OpenGL, which is a cross-platform standard for graphics hardware. OpenGL renders two and three dimensional objectives into a frame buffer to achieve optimal performance, which allows high fidelity renderings of traffic objects, such as traffic signs and VMS. A driver therefore could recognize those objects by their shapes, sizes or textures. Furthermore, the real-time perspective of a driver is maintained to provide authentic depth perception and distant vision of traffic signs.

4.1.7 Display and Car Model

In the first generation system, the rendered images were projected onto a hemispherical display, as shown in Figure 4-2. In the second generation system, the rendered images were projected onto a 2.66m-high, 150-degree cylindrical screen (Figure 4-3). The car model is a front half of a real car with a LCD monitor installed in the car. Participants were sitting in the car model, with the driver's seat positioned at the focus of the screen, as shown in Figure 4-4.

Figure 4-2 The Hemispherical Display in the First Generation System

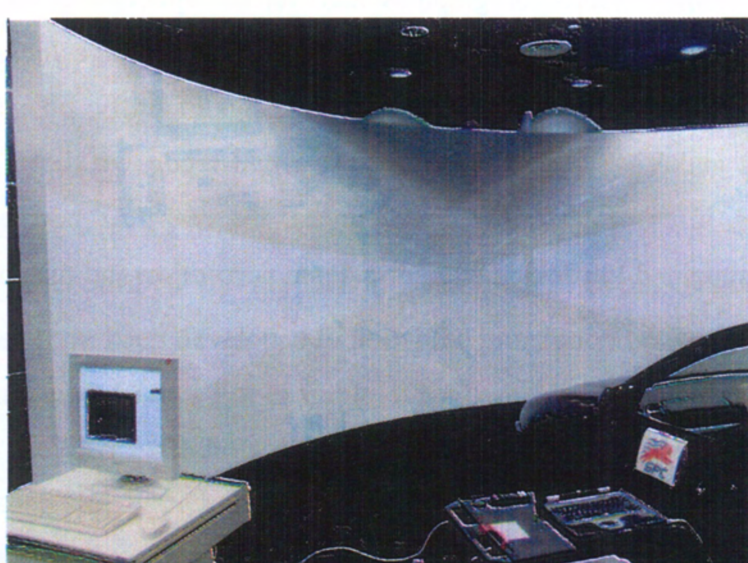

Figure 4-3 The Cylindrical Screen in the Second Generation System

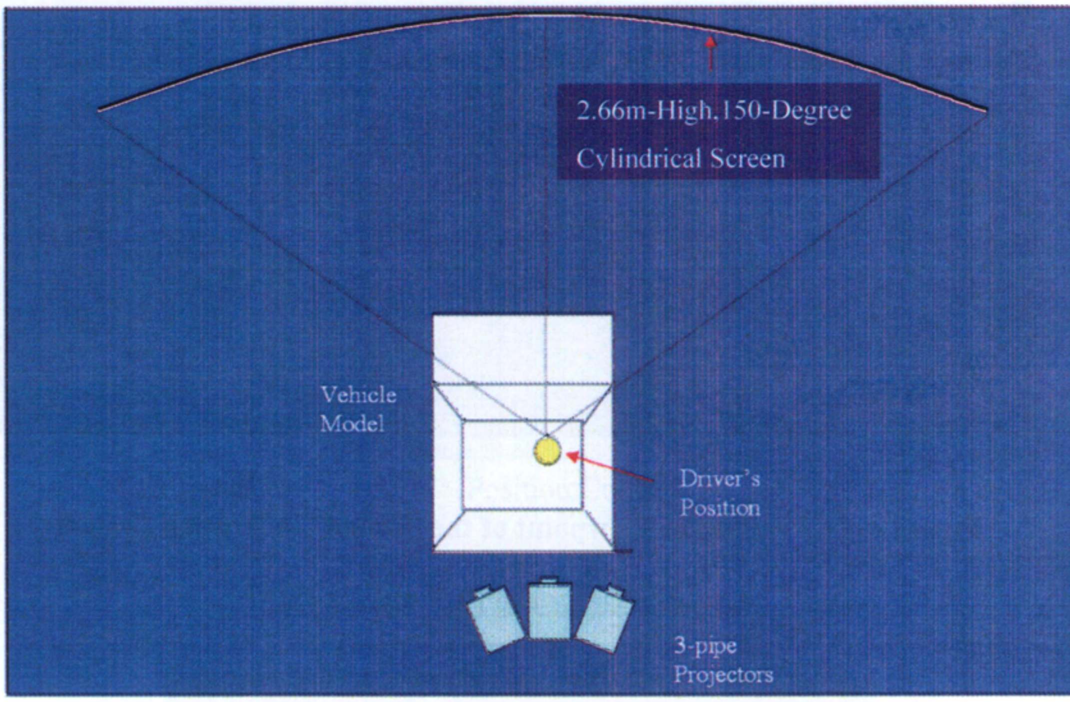

Figure 4-4 Schematic Illustration of the Second Generation System Setup

The position of the car and the driver's seat depends on how the viewpoint was defined in the traffic-driving simulator. The viewpoint defines the position and orientation of a virtual camera in a virtual vehicle controlled by a driver in a driving simulator. The camera was placed at the position of a driver's head (Figure 4-5), rather than the centre of the virtual car. Therefore, the rendered images are from a perspective of a driver who is sitting at the driver's seat. That is the reason the position of car model is fixed at a position where a driver is sitting at focus of the screen. Three overhead projectors are used for projection of simulated images at a resolution of 1024 by 768 pixels. The positions of projectors are calibrated so the joints of the pictures by different projectors are seamless. The projected objects are almost in real dimensions if a driver views them from the inside of the car model (see Figure 4-6). These high-end display devices and the car models invoke a strong immersive feeling of driving.

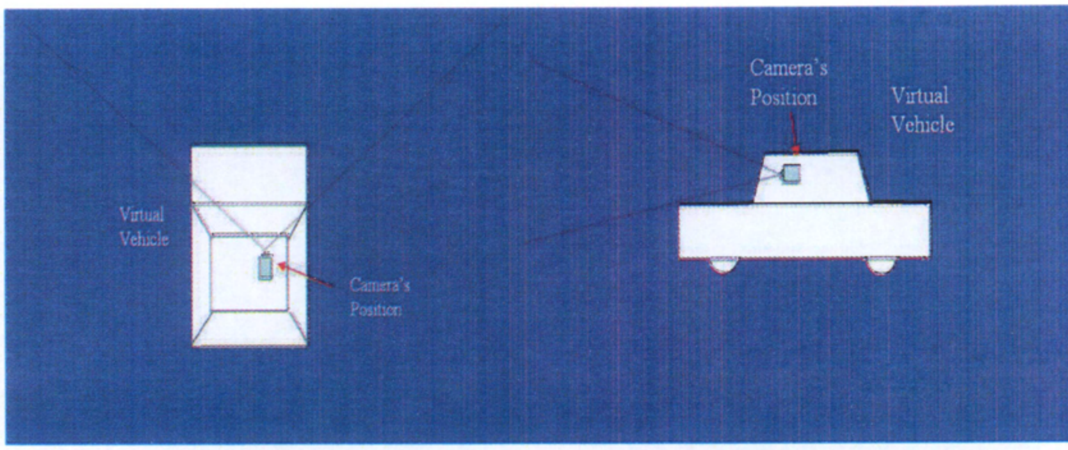

Figure 4-5 Position of Viewpoint of the Second Generation System

Figure 4-6 The Windscreen View of the Second Generation Traffic-Driving Simulator

4.1.8 ATIS Control Interface

ATIS Control Interface (Figure 4-7) controls the simulation of operation of signage or information equipment. Traffic messages on VMS, LCS, RBBI are examples of signage or information equipment evaluated. The ATIS control interface allows the deployments of signage at any locations in the developed scenarios. Furthermore, the physical design of a signage, for example, the font and colour of the display texts on VMS can be changed through ATIS control interface when simulation is running. These flexibilities allow the evaluations of signage in different aspects.

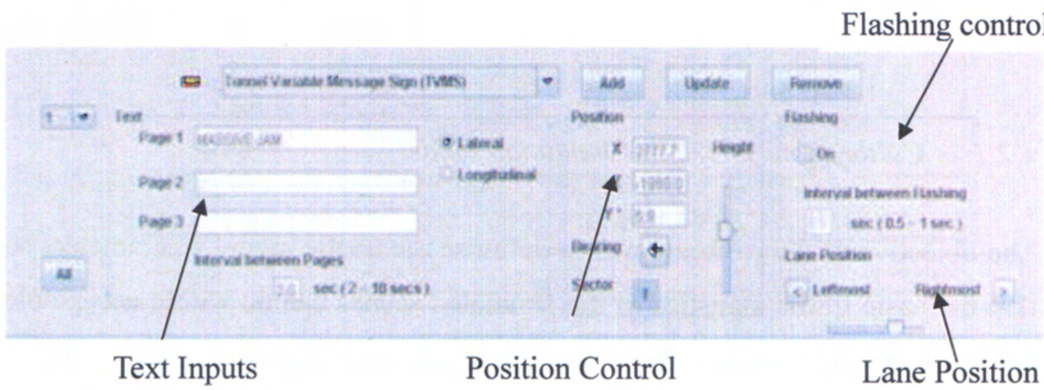

Figure 4-7 ATIS Control Interface

In addition to the control of the physical attributes of individual signage, the ATIS control interface also allows the display of traffic information according to proposed traffic management schemes in each scenario. For example, operations of VMS and LCS in an accident scenario can be simulated according to different traffic management plans, which can be stored in the configure file for the scenario and pre-loaded by the ATIS control interface when the scenario was loading into the system. Drivers could be invited to drive in the scenarios and their driving behaviour can be observed and analysed. The findings can help to establish optimal traffic management plan.

Above are major modules of the system development. It took substantial efforts to set up every module from the baseline. Some technical details, such as definition of Quaternion, is available in the reference quoted in this section. Therefore, such details are not presented in this section. In the following section, the calibrations of the system are the focus.

4.2 Calibration of the System

Calibration is a critical step in the overall development of the traffic-driving simulator. The driving simulator was calibrated based on Hyundai Sonata sedan (Hyundai Auto Service, 1998). Therefore, the calibration is more on the traffic simulation model and other parameters, such as frame rate, viewport and so on.

4.2.1 Calibrations of Traffic Simulation Model

The objective of the calibration is to optimise the traffic model's parameters so that the basic traffic statistics of the simulated scenes can be within acceptable level of confidence of their respective observed values under similar circumstances. However, the targeted simulated area was an expressway being constructed and the traffic management and control measures have not been decided yet by the time this study was carried out. Therefore, it was not even possible to decide how the traffic characteristics would be like at the planning stage, not to mention that the calibration needs to be based on field observation. Therefore, the basic assumption of this study is that the new expressway would have similar traffic characteristics with an existing expressway and the parameters obtained for that existing expressway can be good representation of traffic characteristics of the new expressway. Although the new expressway was used as infrastructure in this study, it is expected that the study results could be generalised to other expressways in Singapore. Based on such assumption, the calibrations for the traffic model based on traffic conditions of an existing expressway are discussed.

A stretch of Kranji Expressway (KJE) was selected as the simulation area to calibrate the parameters of the traffic simulation model. KJE is located closer to NTU and it took less resource for site surveys. KJE is heavily used in the morning peak hour. The selected stretch of expressway was a dual three lanes segment by the time this study was carried out, which has similar design as the new expressway. Furthermore, there are many overhead roads and pedestrian bridges which allow recording of traffic conditions. As shown in Figure 4-8, two cameras were mounted on two overhead pedestrian bridges as observation stations to collect traffic data. The expressway segment between the two cameras was the selected stretch, which was 576 metres long in length. The schematic of main lanes, entrance and exit are also illustrated in Figure 4-8. The calibration of traffic model included calibration of infrastructure and traffic characteristics.

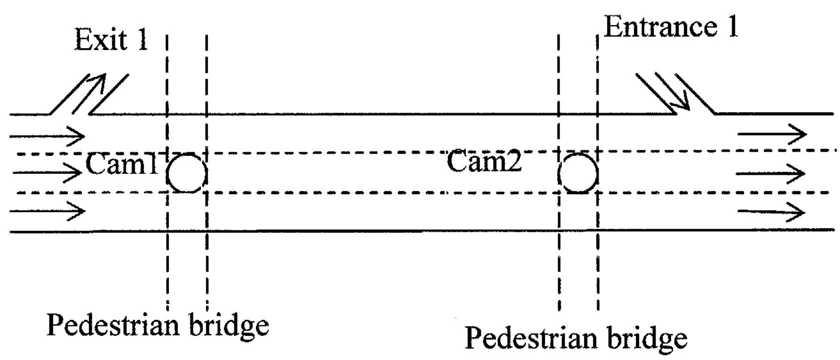

Figure 4-8 Schematic of Lanes, Ramps and Cameras

(i) Calibration of infrastructure

The infrastructure refers to the road network and its components in the simulation model, which affects the driving behaviour of simulated vehicles. The objective of the calibration of infrastructure was to ensure that the behaviour of simulated vehicle can be similar with those obtained from field observations. A number of field surveys were conducted to collect necessary data for calibrations. Firstly, a camera was mounted on the car which was driven through the selected segment of expressway. Videos from a driver's perspective on the expressway segment were recorded as references. Secondly, the road geometry, traffic signs, major landmark locations were measured on site to ensure that they can be modelled accordingly. Lastly, a GPS survey was conducted to collect location and height information of selected critical points. The GPS survey devices can obtain geographic information in terms of easting, northing and height with centimetre level accuracy (Thales Navigation, 2002). The GPS survey results were used to calibrate the alignment and elevation of the simulated road network in the traffic simulation model. Furthermore, visual database in the driving simulator is updated to ensure the traffic network in the traffic simulator and the driving simulator can be identical.

(ii) Calibration of traffic characteristics

The objective is to generate realistic traffic on the hypothesised scenarios which in drivers' perception can be a close approximation of the observed "typical" traffic conditions on an existing expressway. The drivers' perceptions on traffic conditions are closely related to levels of service they perceived, which are mainly affected by the physical characteristics of the infrastructures, the proportion of heavy vehicles, the density and the speed of traffic (Transportation Research Board, 2000). As mentioned previously, the physical characteristics of the infrastructure, such as road geometry and alignment are already carefully calibrated. Therefore, the proportion of heavy vehicles and the traffic density and speed are the major characteristics in consideration. The traffic density and speed are functions of traffic volumes (rates) and travel times, which could be directly observed from site. Therefore, traffic volumes and travel times, as well as proportion of heavy vehicles were chosen as the criteria for calibration. However, since traffic volumes and proportion of heavy vehicles are inputs for the traffic model, average travel time is therefore the actual criterion for comparison.

As reviewed in Chapter 2, there are different ways to calibrate microscopic simulation models. The selection of a calibration method depends on the applications of the traffic model, which may require different levels of accuracy. Calibration may require tremendous amount of data which are practically not available. Therefore, researchers usually choose calibration criteria which are critical to the research objective. In this study, as discussed, the average travel times are critical to the calibration objective and therefore the objective function is to minimise the travel time difference on a specific segment between simulation and field observation. Because traffic flow can be viewed as the aggregate behaviours of individual drivers of vehicles, the following vehicle specific parameters are calibrated: mean headways, mean reaction times, top speeds of specific vehicle types, aggression and awareness of drivers.

As mentioned, traffic data were collected from two stations on two overhead roads on the selected expressway segment. The locations of the two stations were indicated on Figure 4-6 as "Cam1" and "Cam2". In order to obtain typical peak and off-peak traffic patterns, the proceeding three months' traffic profile was examined to select the survey time. The average daily (Monday to Friday) traffic volume, which was collected by an EMAS surveillance camera near "Cam1" at a 15-minutes interval between January and March 2004, is presented in Figure 4-9. The x axis is the hour while the y axis is the traffic rate, which is converted into traffic volume per hour.

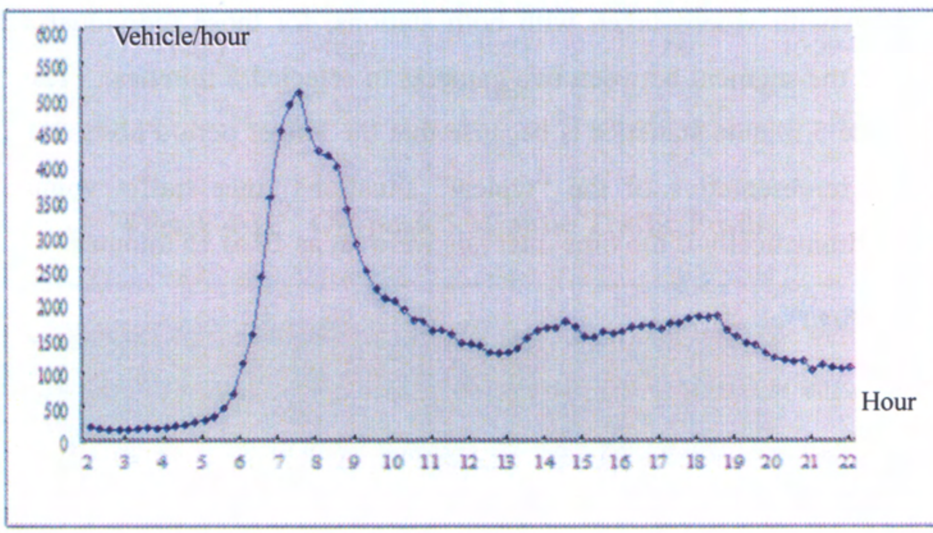

Figure 4-9 Average Daily KJE Traffic Profile

It is shown that the peak of the traffic was between 6 am and 10 am, in which the traffic flows changed dramatically. Starting from about 6 am, the traffic volume increased dramatically until its peak, which was roughly between 7:00 am to 8:00 am. After that, the traffic volume dropped dramatically until about 10:00 am. Therefore, in order to capture a typical peak and off-peak conditions, video surveillance surveys were carried out at the two stations on a typical weekday (Wednesday) from 7:00 am and ended at 10:40 am on April 21st, 2004. Wednesday was chosen as the day for the survey because Wednesday is least affected by weekend traffic and therefore considered as the most representative traffic pattern for a weekday.

After the video surveillance surveys, manual video processing was carried out in the transportation lab at NTU. 5-minute observations of the peak and off-peak periods were selected and the traffic statistics, such as total traffic volume, vehicle proportion were manually extracted from videos obtained from the first camera shown as "Cam1". The selected 5-minute observation in peak hour was around 7:30 am, which was the observed "peak" of peak hour of that day within which the saturated traffic can be observed (Figure 4-10). The selected off-peak 5-minute observation was around 10:25 am, when less fluctuation of traffic was observed (Figure 4-11). The travel times from the upstream camera to the downstream camera on each lane were also manually extracted with videos taken with both stations, for those individual vehicles entering the segment between two cameras in selected 5 minutes. The reason to choose 5 minute statistics is because that the longer period observation may be less representative of the "typical" situations since traffic volume may change dramatically if the time intervals were set as 10 to 15 minutes.

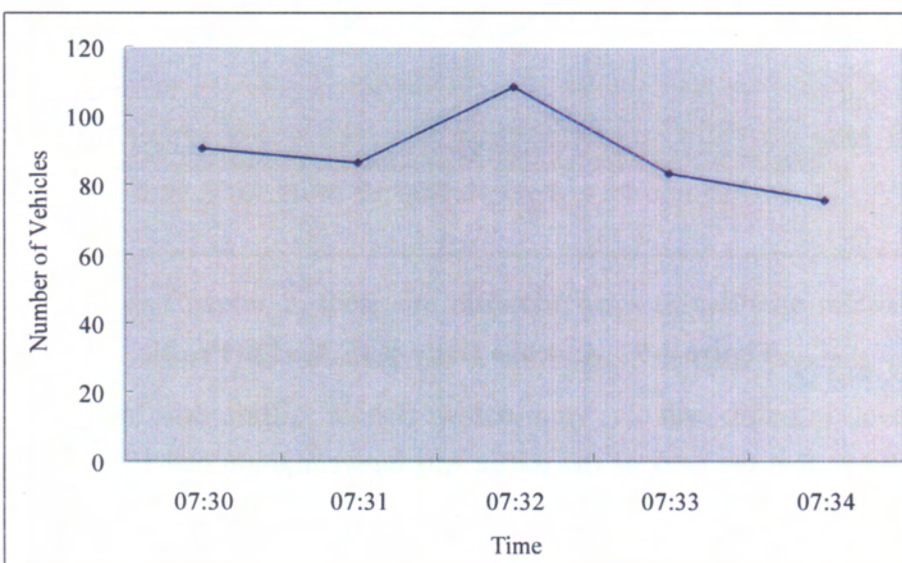

Figure 4-10 Peak 5 Minutes Traffic Profile

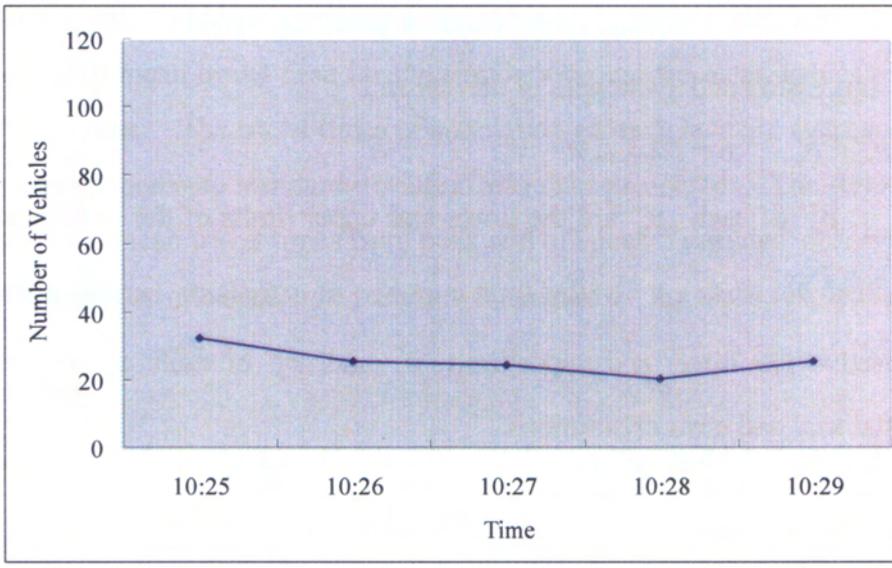

Figure 4-11 Off-peak 5 Minutes Traffic Profile

The peak and off-peak 5 minute traffic volumes, together with the vehicle type and proportion information were used to generate OD information in two traffic models for peak and off-peak periods, respectively. These two models have the same traffic corridor but different demand and vehicle characteristics parameters. An API was developed to collect individual vehicles' travel times in a 5 minutes' time after 10 minutes' warm-up period for the same segment of roadway in the field survey.

In order to allow more rigorous calibration, travel times were optimised lane by lane to minimise the travel time difference on roadway segment between two observation stations (CAM1 and CAM2) and between field observations and simulation outputs. The pooled t-tests ($\alpha = 0.05$) were used to judge whether the difference was significant. Denote t_f^1, t_f^2, t_f^3 as field travel times at slow (lane 1), middle (lane 2) and fast lane (lane 3) respectively and t_s^1, t_s^2, t_s^3 as travel times in the traffic simulator. The null hypotheses are:

$H_0 : t_f^l - t_s^l = 0$ l is the lane number and $l = 1,2,3$

The calibration is to find parameters p_n that did not reject all the null hypotheses in H_0 in instances of a simulation scenario. An instance of a scenario is a simulation run of a scenario with a random simulation seed. The

p_n refer to mean headway, mean reaction time, top speed of defined vehicle types, aggression and awareness of drivers and:

$p_n^l < p_n < p_n^u \qquad n = 1,2,3...,m$

p_n^l and p_n^u of each p_n are the lower and upper limits of the nth simulator parameter p_n while m is the total number of simulator parameters to be optimised. The lower and upper limit p_n^l and p_n^u of each p_n are defined by initial trial and error calibrations.

Scenarios of all different combinations of headways, reaction times and top speeds were created and simulated. For each scenario, ten instances with different random simulation seeds were run and the simulation outputs of all instances were stored in a database. The objective is to maximise the number of instance of a scenario in which all the null hypotheses H_0 were not rejected. Denote a Passing Rate (PR) of a scenario as:

$$PR = \frac{number\ of\ instances\ all\ the\ t-tests\ were\ passed}{total\ number\ of\ instances}$$

The objective function is to maximize the value of PR, which should have a maximum value of 1.

A computer programme was written to search the database to find out the scenario which has the highest PR value in the database. In both off-peak and peak cases, scenarios with PR values equal to 1 were found. That means, in both cases, with randomly selected simulation seed value, the travel time on each lane was not significantly different from the measured travel time in field in each of the 10 simulation instance. Furthermore, the pool t-tests were carried out to compare the overall travel times on the three lanes between field observation and each simulation instance. The results suggest that in each of 10 simulation instance, mean travel times are not significant different from those of field observations. The results also suggest that the simulation results are stable and variation between each instance taking different simulation seed value is marginal. The lane-to-lane mean travel times on the selected simulated scenario and the measured mean travel times (with standard deviations) on field are presented in Table 4-1. Note that the standard deviations of mean travel time for the simulation runs are mean values over 10 simulation runs. The travel times of simulation on each lane are averaged over 10 instances therefore standard deviation were not presented. The field travel times are the mean travel times from peak and off-peak 5 minutes' observations. The percentages of simulation results with regard to the field results are also shown.

Table 4-1 Lane-to-Lane Mean Travel Times (Seconds, SD=Standard Deviation)

	Off-peak		Peak	
	Field	Average Simulation Results of ten runs	Field	Average Simulation Results of ten runs
Slow Lane (lane 1) Mean Travel Time (sec)	30.32 (SD: 5.54)	28.89 (95.28% of field) (Mean SD:2.17)	29.25 (SD: 5.06)	28.84 (98.60% of field) (Mean SD:1.91)
Middle Lane (lane 2) Mean Travel Time (sec)	22.05 (SD: 3.58)	22.88 (103.76% of field) (Mean SD:1.43)	24.44 (SD: 1.20)	25.46 (104.17% of field) (Mean SD:0.59)
Fast Lane (lane 3) Mean Travel Time (sec)	17.87 (SD: 1.45)	18.47 (103.36% of field) (Mean SD:0.88)	22.36 (SD: 2.22)	22.17 (99.15% of field) (Mean SD:0.59)

The calibration results have shown that there were close matches of the mean travel time, in the selected simulation scenarios and the real conditions.

The 5 minute classified traffic volume of the field observations and simulation are presented in Table 4-2. The traffic volumes obtained from simulation are averaged over 10 instances of simulation.

Table 4-2 Traffic Volumes (Number of Vehicles) of Different Vehicle Type

	Off-peak		**Peak**	
	Field	**Simulation**	**Field**	**Simulation**
Car	53	51	189	185
Heavy Good Vehicle (HGV)	25	24	34	34
Motorcycle	12	11	154	163
Light Good Vehicle (LGV)	41	38	66	67
Bus	1	1	2	2
Total	**132**	**125**	**445**	**450**

The parameters obtained, in most cases the parameters obtained for peak situation, were used in the second generation system to generate traffic in the hypothesised scenarios for the new expressway which was still under construction at the time the study was carried out.

4.2.2 Calibrations of Simulation Step

The simulation step refers to the number of discrete simulation intervals that are simulated in a simulation second. In Paramics, the simulation step is adjustable through the Paramics Modeller. In the first generation driving simulator, the simulation step was the same with the frame rate, which was the number of frames the simulation can render within a second. The frame rate was dependent on the computation power of the computer used. Theoretically, the time step in Paramics and the frame rate in the driving simulator should be the same to realistically display the traffic generated in Paramics. In the first generation system, the frame rate of the driving simulator was as high as 58 frames per second (on average), the simulation step in Paramics was thus set as 58. However, in the second generation system, more advanced algorithms were developed. The algorithms can interpolate the position data of the CGF outputs from Paramics in the driving simulator according to the simulation step in Paramics and the driving simulator simulation step. For example, if the Paramics simulation step was configured as 30 while the driving simulator was running at a simulation step of 60, the driving simulation would interpolate every data set output into two data sets. With such an improvement, the distance a CGF is moving at every second is exactly the same in the driving simulator.

With all these calibrations, the traffic-driving simulator is capable of generating realistic scenarios for studies of drivers' response to VMS information. Figure 4-12 shows a screen capture of the first generation system while Figure 4-13 shows a screen capture of the second generation system. The second generation system was calibrated with a similar methodology. The resolution on the actual system is quite high and the messages on the VMS, as well as other objects, can be clearly visualised.

Figure 4-12 Screen Capture of the Prototype System

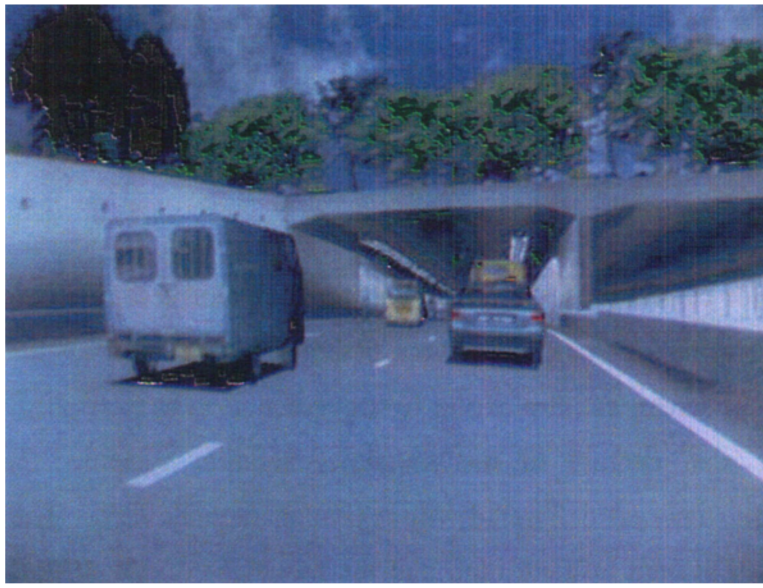

Figure 4-13 Screen Capture of the Second Generation System

4.3 Example of Data Collection

The system was fully tested and functions of each module were verified before the pilot survey was carried out with the traffic-driving simulator. In order to allow better understanding on data that could be collected by the system, data recorded in a sample scenario in the pilot survey are presented. These data include statistics on network traffic and the logged data to describe subject's driving behaviour.

4.3.1 The Sample Scenario

In the sample scenario, the operation of the ATIS in the morning peak hour was simulated. An incident was simulated during the morning peak hour. Congestion occurred and VMS were used to display information regarding the accident and traffic conditions.

A stretch of the southbound KPE was selected for this scenario. There are 4 exits and 2 entrances along this stretch of KPE as shown in Figure 4-14.

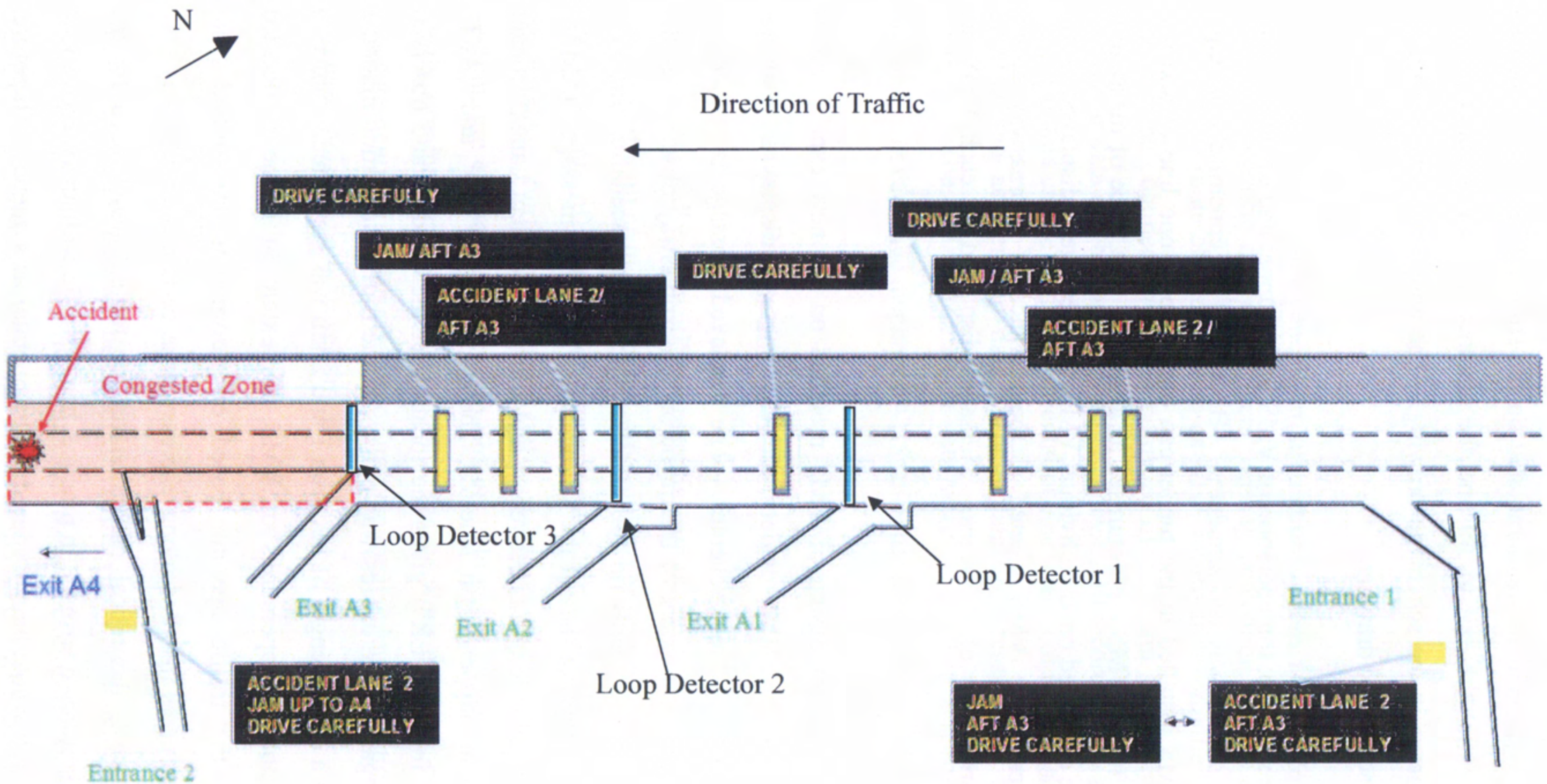

Figure 4-14 Schematic Drawing of the Sample Scenario

All the 4 exits can lead to the alternative routes which can lead to the same destination. The accident was simulated on the stretch of KPE near the exit A4, which is after the exit to A3 and the entrance 2. The location of the accident is shown in the schematic drawing. The congested zone is roughly shown in the schematic drawing.

In the sample scenario, the operation of VMS in the tunnel and on arterial road leading to the expressway was simulated. Because of the constraints on height clearance, VMS installed in the tunnel can only display one line of text and usually three tunnel VMS are organised as a group. If a piece of message is too long to be displayed on an individual VMS, the message is displayed as two toggling pages. The VMS located at the entrance of expressway allows display of three lines of messages. Messages displayed on each VMS are shown in Figure 4-14.

Although the physical design of VMS mounted on the new expressway is different from existing VMS devices, the VMS message display schemes are consistent with the current schemes. The displayed message is targeted to broadcast the physical extent of the queue on the expressway observed by the traffic surveillance cameras on the expressway. In this scenario, the three parts of the message consists of the followings. The VMS message "JAM" is used when the queue length is between 1 and 2 km. "Accident Lane 2" means that an accident happened on lane 2. The message "UP TO" and "AFT" (abbreviation for "AFTER") gives the location of the incident and observed queue with regard to the expressway exits. In the traffic simulation model, a scenario with a queue length of between 1 and 2 km was simulated. Since in the current mode of operations of VMS, the extent of queue is decided manually by the traffic operator based on information transmitted from surveillance cameras installed along expressway at certain intervals, it is very difficult to give a theoretical definition on the term "queue" used by the operator in quantitative terms. In practice, heavy traffic with an average speed less than 40 km/h would be considered by the operator as a queue. Therefore, in this study, the queue was decided manually in the similar manner as it was determined in real life. By adjusting the OD demand of the simulation model, a hypothetical scenario with the queue length between 1 and 2 km was simulated.

4.3.2 Data Collection

The developed second generation simulation system is capable of obtaining data on the traffic network, drivers' driving behaviour such as speed choice, lane choice, route choice, as well as ATIS information provided. The traffic data can be obtained on certain points or over certain sections. The driving behaviour data can be logged at a frequency of 30 records every second. The obtained data can be positions, orientation and speeds of the ownship, as well as braking and acceleration data. These data are presented in the following sections. The ATIS information data were recorded in a scenario configure file which governs the display of ATIS information in each scenario.

4.3.3 Network Data

The data on traffic network are essential for many transport studies. These data are difficult or in some cases impossible to be obtained in the field. Some special events of interest, for example, accident and congestion may not be predictable. Furthermore, some traffic statistics, such as travel times over a section, are extremely difficult to obtain. However, these statistics could be easily obtained in the traffic model. The network statistics could be point measurements on speeds, flows, or measurements along a section of road, for example, point to point travel times.

(i) Point Measurement

Point measurements could be obtained via the virtual loop detectors placed in a traffic model. In the traffic simulation model developed, three virtual loop detectors were installed at various points of the KPE traffic model. Three loop detectors near the three exits leading to three alternative routes were presented since drivers' route switching behaviour may be the most relevant to the traffic conditions observed at the decision points. The location of the three loop detectors are shown in Figure 4-14. The instantaneous speeds of all simulated vehicles passing the three loop detectors are shown in Figures 4-15 to 4-17. They are based on 10 minutes of observations as in this scenario a participant should be able to complete the scenarios in 5 to 10 minutes (the black crosses are observations for a subject driving in the traffic, which will be discussed in later sections). It is shown that traffic slow down along the expressway due to the upcoming congestion. At the expressway section near Exit A1, the traffic is smooth and vehicles can travel as fast as 90 km/h. Furthermore, it is observed that the speed are widely distributed, which suggests that traffic conditions, drivers' speeds were not constrained by other vehicles and they have more freedom to choose their speeds. However, at expressway section near Exit A2, the highest speeds drop to about 70 km/h and the speed is less widely distributed. That pattern suggests that the traffic were slowing down and the speed started to be constrained by traffic. At expressway section near Exit A3, the speed is much lower and fluctuated greatly, which suggests congestion conditions with a stop-and-go traffic.

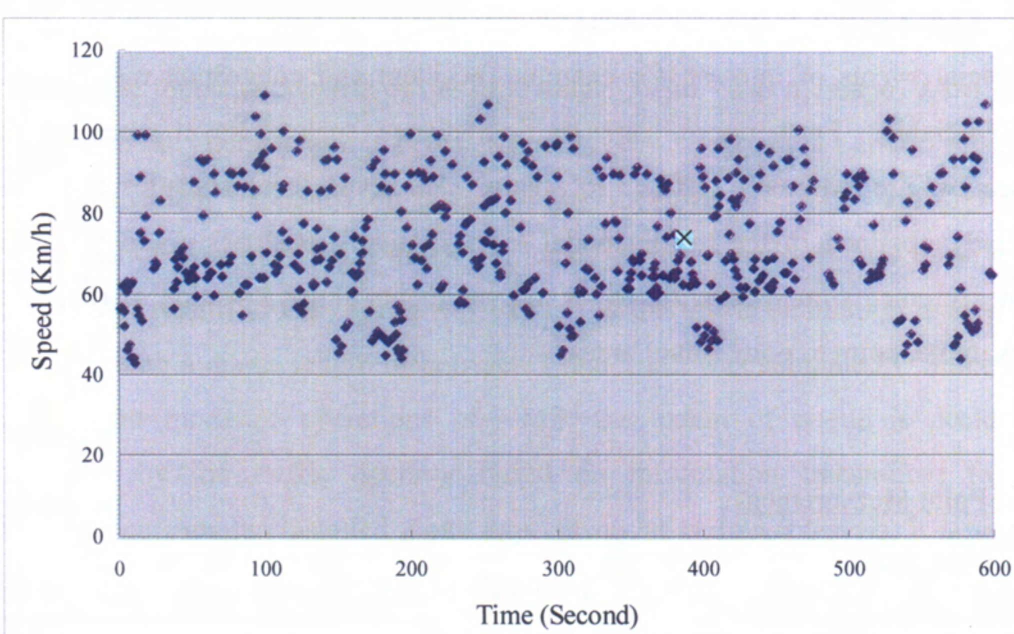

Figure 4-15 Simulation Data from Loop Detector 1 (Black X is a Respondent's Speed)

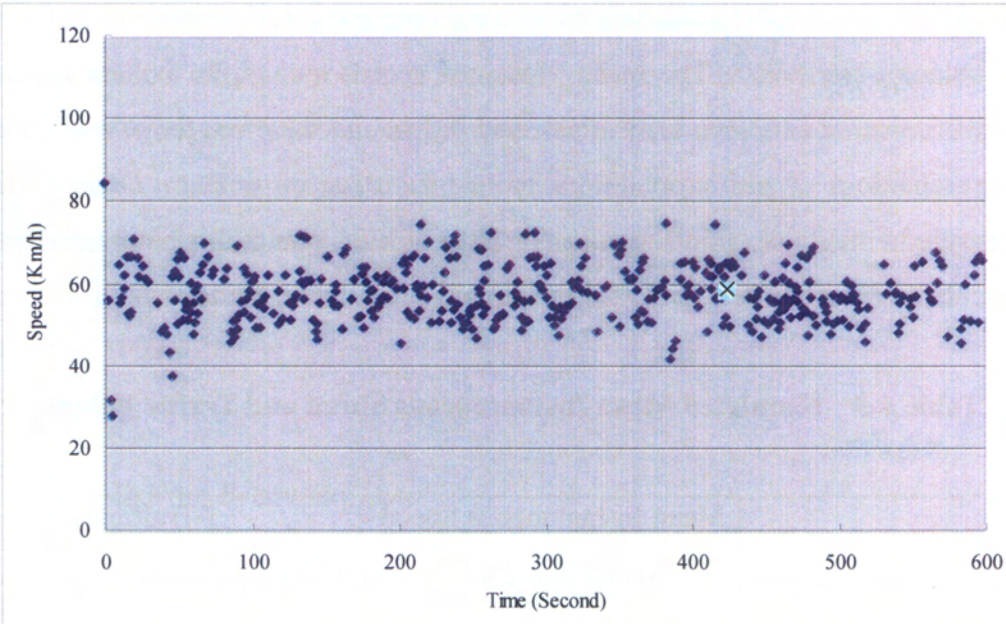

Figure 4-16 Simulation Data from Loop Detector 2 (Black X is a Respondent's Speed)

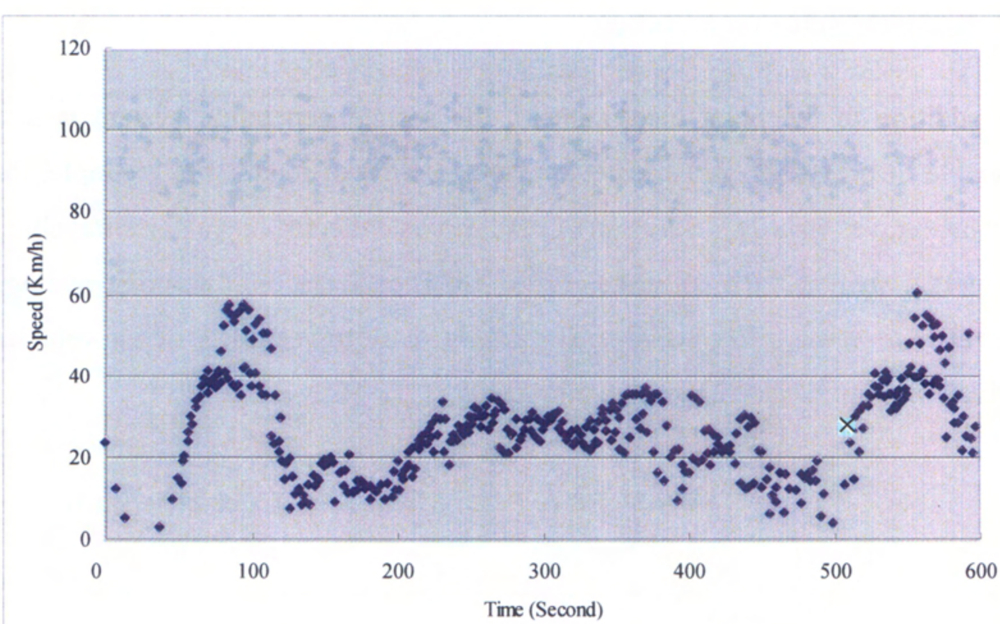

Figure 4-17 Simulation Data from Loop Detector 3 (Black X is a Respondent's Speed)

The mean instantaneous speeds and traffic volumes at the loop detectors are presented in Table 4-3. The traffic volumes are presented in terms of number of vehicles per hour. The mean values of speeds and traffic volumes were point measurements over time at selected points and therefore they were good representations of traffic conditions around the decision points. Other point measurements, for example, headways, occupancies, could also be obtained or calculated from the loop detectors in the traffic simulation model.

Table 4-3 Simulated Mean Instantaneous Speed and Traffic Volume

	Mean Instantaneous Speed (km/h) and Standard Deviation (SD)	Traffic Flow (Veh/hr)
Loop Detector 1	72.78 (SD:15.05)	2946
Loop Detector 2	58.24 (SD:6.88)	2586
Loop Detector 3	28.01 (SD:11.48)	2358

(ii) <u>Measurements over a Section</u>

In addition to the point measurement, the second generation system is also capable of providing measurements over a section of road. For example, the average travel time over a section of road can be collected by vehicles travelling over that section. To illustrate, Table 4-4 shows the point-to-point average travel time along KPE, which were averaged by travel times of all vehicles driven through the sections in 10 minutes.

Table 4-4 10 Minutes Point to Point Mean Travel Time (Seconds)

Starting Point to Exit A1	161
Exit A1 to Exit A2.	50
Exit A2 to Exit A3	86

The second generation system is capable of collecting network traffic measurements at points or over sections. These statistics could be used as variables to support various research topics on route choice or route switching study since travel times and traffic conditions in terms of speeds and flows at decision points are important variables to support development of discrete choice models on drivers' route choice or switching behaviour (Bonsall and Palmer, 1999).

4.3.4 Driving Behaviour Data

As mentioned, the traffic-driving simulator system is capable of collecting an individual driver's driving behaviour in great detail. In this section, the data collected from the participant who chose to stay on the expressway in the above sample scenario are presented. The speed profile, accelerator and brake behaviour are presented in Figures 4-18, 4-19 and 4-20, respectively.

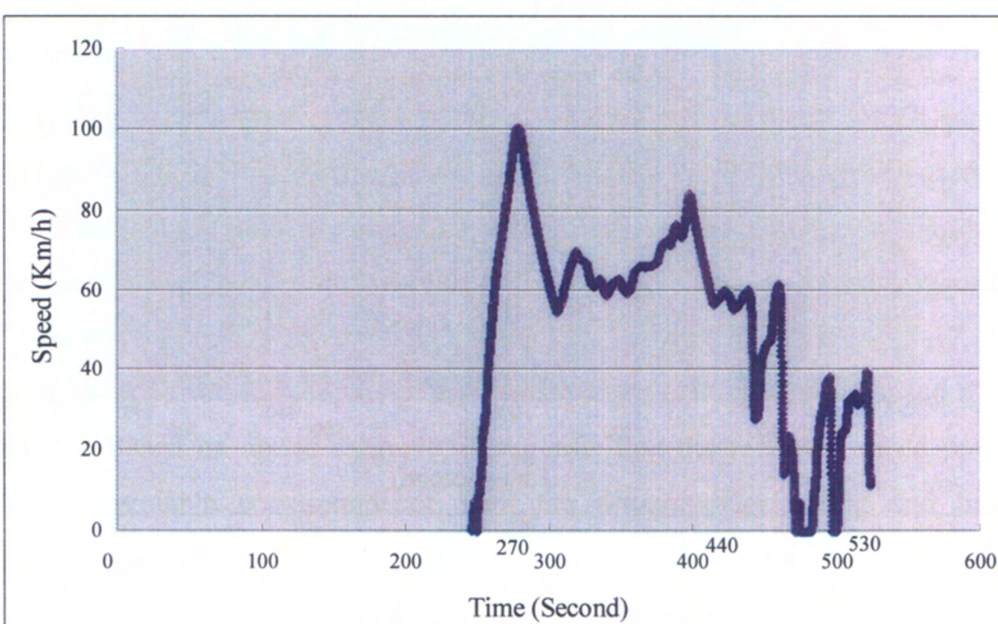

Figure 4-18 Speed Profile

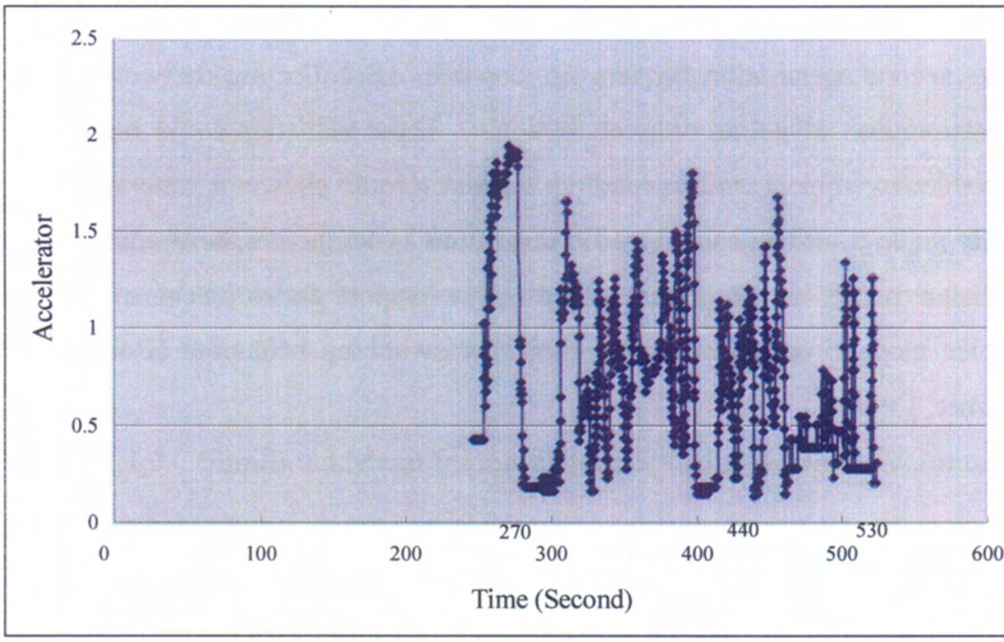

Figure 4-19 Acceleration Behaviour

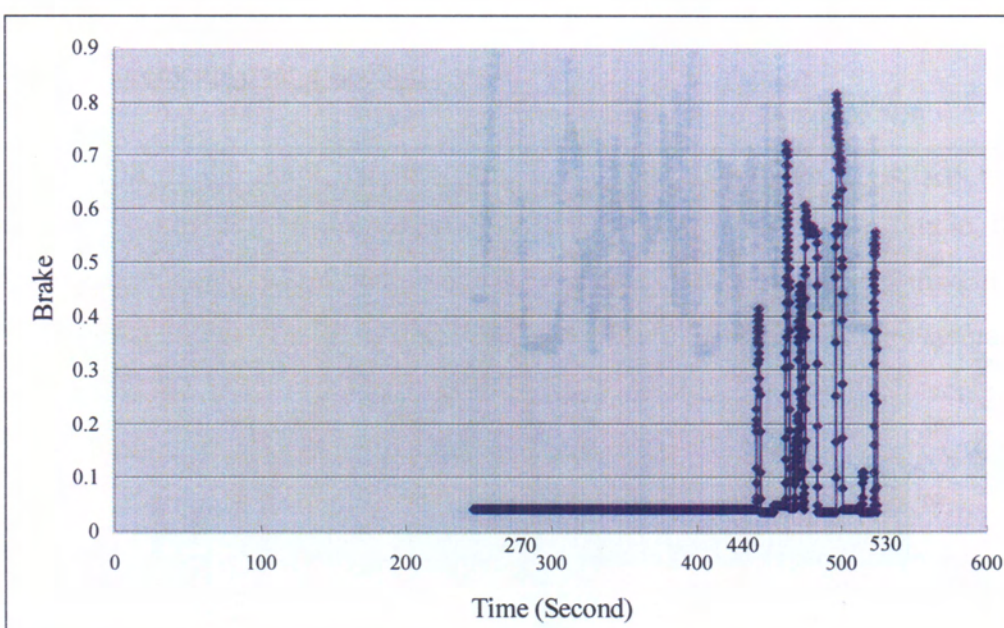

Figure 4-20 Brake Behaviour

In Figure 4-19 and Figure 4-20, the y axes are the values to indicate how much the pedals are pushed. The value range of accelerator is between 0.2 and 2.5, which are recorded value by system to indicate the status of each pedal. The lower limit indicates that a driver was not pushing the acceleration pedal while the upper limit indicates the driver was pushing the acceleration pedal to its end. Similarly the value range of brake is between 0.04 and 0.85, with the lower limit indicating no pushing of brake pedal while the upper limit indicates the brake pedal was pushed to its end. The accelerator and brake readings are different variables used in the driving simulator system and their values are not associated with any physical measurements.

The participant started his driving at the simulation time of 250th second. After the start of driving, the participant picked up his speed quickly till about 100 km/h (Figure 4-18) by continuously pressing the accelerator (Figure 4-19). After the speed hit its peak at the simulation time of 270th second, the accelerator pedal was released and speed dropped until about 60 km/h. After that, the driver controlled his speed by pushing and releasing accelerator (between 270th second and 440th second). During this time, the brake was idle until the traffic started to be congested. The point measurements of traffic can be found in Figure 4-15 and Figure 4-16, in which the participant passed the two detectors at roughly 390th and 430th second, respectively. Then the driver was driving in a queue and a stop-and-go traffic was experienced. The travelling speed varies roughly between 10 km/h and 50 km/h, which can be known by the point measurement shown in Figure 4-17. The driver used the accelerator and brake to control his own speed among a queue of simulated vehicles. Therefore, both operation of accelerator and brake were recorded (between 440th second and 530th second). As shown in Figure 4-17, the participant passed the loop detector 3 at roughly 520th second at a speed of 28 km/h. Based on above example, it suggests that the recorded speed profile have reasonable correspondence with the driver's accelerating and brake behaviour.

Other than data to record speed, acceleration and brake behaviour, the system also can collect data on positions, orientation of the vehicle controlled by a participant. These data are coordinates information which can be used to calculate drivers' lane changing behaviour, route choice behaviour, or other behaviour of interest, with respect of visual database used in the scenario. In the following chapters, the lane changing behaviour and route switching behaviour were calculated in this manner.

4.3.5 ATIS Information Data

As mentioned, ATIS information is recorded in the scenario configuration file. Type of ATIS signage, ID or the ATIS signage, position and orientation of the ATIS signage, the messages to be displayed are major information recorded. Other information, such as whether messages are displayed in toggling pages, or whether messages are flashing is also recorded in the configuration file. The file not only can be used by ATIS control interface to control the display of ATIS information, but also used in the post-scenario analysis.

4.4 Summary

The traffic-driving simulators as an integration of a microscopic traffic simulator and a driving simulator were developed at the early stage of this study with objective of using it to study driving behaviour in the presence of ATIS information. Compared with traditional simulators designed for simulation studies of ATIS, the traffic-driving simulator developed in this study is capable of generating complicated scenarios and to collect data in great detail to support studies of ATIS, as shown in the discussion of this chapter. Compared to a travel simulator, the traffic-driving simulator can support simulation of traffic of a large scale network while a more realistic driving environment can be simulated then visualised. Participants can immerse in the traffic conditions, and be exposed to ATIS information and the congestion realistically presented from the windscreen perspective. Sitting in a real car model, participants' driving behaviour can be captured in great detail. Drivers' position, speed, brake and acceleration behaviours could be traced and captured at a frequency of 30Hz. Other behaviour, such as lane changing behaviour and route choice behaviour can be obtained with the position data, with respect to the visual database used in the driving simulator model. These advantages can greatly improve the fidelity of scenarios and level of detail on data collection, as compared with a travel simulator. Compared with a conventional driving simulator, the traffic-driving simulator integrates a microscopic traffic simulator which has capabilities to simulate traffic conditions and operation of ATIS, as well as incidents at a microscopic level. This provides a cost-effective solution for a driving simulator to realistically simulate complicated traffic scenario while the statistics on the traffic are readily available. With the development of the traffic-driving simulator, a realistic driving environment could be simulated to satisfy various needs in controlled experiments. However, it should be noted that the results obtained in controlled experiments with the driving-traffic simulator is experimental at this stage, which is meant to help to understand the likely responses to ATIS information. There is no intention to use the traffic-driving simulator to replace the field study at this stage, unless the results can be validated in the future studies after the new expressway is in operation.

The traffic-driving simulator was used in the investigation of drivers' responses to different traffic schemes and the results are reported in the following chapters. Prior to the driving traffic-simulator experiments, there was a paper-based perception survey conducted. The survey was mainly targeted to study drivers' understanding on traffic messages shown on various types of VMS on an existing expressway. The results of the perception survey will be discussed in the next chapter.

CHAPTER 5. A PERCEPTION SURVEY

The perception survey was conducted to probe drivers' understanding and responses to existing traffic messages displayed on VMS mounted on an existing expressway in Singapore. Other information, such as drivers' preferences on messages shown on VMS was also investigated. Based on a conventional paper-based face-to-face interview, a large sample was collected. The survey results provided insights on drivers' perception on existing messages. These insights provide important reference for the experimental design of the following traffic-driving simulator survey. In addition, the paper-based survey was also a recruitment drive for the following wave of traffic-driving simulator survey.

5.1 General Information on the Perception Survey

The objective of the perception survey was to find drivers' understanding, responses and preferences to messages shown on various types of VMS. The primary 4 lanes Central Expressway (CTE) was used as the infrastructure for the survey since CTE was the busiest expressway in Singapore. Furthermore, CTE is nearly parallel to KPE, which serves a similar driving population as KPE. Their understanding and preferences on existing VMS and LCS were investigated and the survey findings were used to help improve the design contents of the traffic-driving simulation system described in the previous chapter.

Face-to-face interviews were carried out at selected locations, such as parking facilities and shopping malls near CTE. The targeted population was drivers who had experiences with using CTE. The survey was launched in January 2005 and completed in March, 2005. A total of 1000 completed survey forms were obtained.

5.2 Questionnaire

The survey instruments were questionnaires with show cards, which were used by interviewers to explain the scenarios to participants. A sample of the questionnaires is shown in Appendix I. Cards were printed in colour on which pictures of VMS messages, traffic and scenario information were shown. The scenario information shown on the cards includes trip purpose, time of trip, current travelling speed and speed on alternative route. The trip purpose is to work and the time of trip is the morning peak hour. Since the picture is static and respondents are not able to judge the travelling speed with the picture provided, the current travelling speed is provided on the card, together with the average speed on the alternative route. The questionnaires were written with simple words. Most questions are multiple choice questions and a few are numerical open questions. The questionnaires were divided into 4 groups and certain questions in each group are varied to allow statistical analyses to be carried out.

Before the main survey started, a pilot survey was carried out to test the design of questionnaire and obtain information regarding to the length of survey and response rate. All together there were 88 questionnaires completed by interviewers and returned in the pilot survey. On average, each interview took 12 minutes to complete. In addition, the pilot survey results were analysed. Together with interviewers' feedbacks, some minor changes were applied in the design of questionnaires and cards. In the following section, the results of the main survey are presented.

5.3 Survey Results

(a) Respondents' Profile

Table 5-1 shows the general characteristics describing the profile of the respondents. Most respondents interviewed are male (78.41%). In terms of age in years, most of them are of age 25-35 (42.5%) and 35-50 (36.6%). In terms of education, most respondents are polytechnic or equivalent (41.6%) and university (38.0%) graduates.

Table 5-1 Respondents' Profile

Socioeconomic Groups		Number of Participants	Percentage
Gender	Male	781	78.41%
	Female	215	21.59%
Age	Less than 25	157	15.76%
	25-34	431	43.27%
	35-49	353	35.44%
	50 or older	53	5.32%
	N/A	2	0.20%
Education	Secondary or below	197	19.78%
	A-level, polytechnic or equivalent	412	41.37%
	University	385	38.65%
	N/A	2	0.20%
Personal Monthly Income	Less than S$2000	248	24.90%
	S$2001-4000	438	43.98%
	S$4001-6000	219	21.99%
	S$6001-8000	48	4.82%
	More than S$8000	30	3.01%
	N/A	13	1.31%
Type of Vehicle Driven	Motorcycle	112	11.24%
	Goods vehicle	88	8.84%
	Bus	5	0.50%
	Car	791	79.42%

(b) Frequency of using CTE

Table 5-2 shows the frequency of using CTE by the survey participants. The results suggest that all respondents could be considered as regular users of CTE.

Table 5-2 Weekly Usage of CTE

Frequency	Number	Percentage
Less than 1 day (occasionally)	0	0.00%
1-2 days	301	30.22%
3-4 days	332	33.33%
5-7 days	363	36.45%

(c) Driving Habit

Two questions were asked to obtain driving habits of the targeted driving population. The first question asked whether ERP charges on CTE affect drivers' decision on using CTE. About 55% of the respondents gave the response "yes". These results imply that there is a considerable proportion of drivers whose travel behaviour was reportedly affected by ERP charges.

Another question was targeted to obtain driver tolerance on the speed on CTE. The results are shown in Table 5-3. The speeds on expressway may be a significant factor on drivers' diversion behaviour. The speeds between 20-40 km/h were the threshold that many drivers (57.24%) would start to consider diversion from expressways if alternative routes are available.

Table 5-3 Diversion Rate in Different Traffic Conditions

Tolerance on speed on CTE	Number of Diversion	Percentage	N/A
Less than 20 km/hr	822	83.54%	12
20 -40 km/hr	563	57.24%	12
40-60 km/hr	152	15.42%	12

(d) Perception and Responses to Travel Time Information on VMS

As mentioned in Chapter 1, VMS mounted on the arterial roads leading to expressways is capable of displaying a line of text information and travel times of directional traffic to the upcoming expressway exits. In addition to the travel time information, the physical extent of observed queue was reported on the VMS with displayed wording such as "Massive Jam", "Jam" and "Slow Traffic". By providing such advance traffic information, it was expected that more drivers would divert from the problematic sections of the expressway before they entered the expressway.

To study the understanding of drivers' understanding on the travel time information provided on VMS, the questionnaires are different for the four groups, as shown in Table 5-4. Groups 1 and 2 were shown with "Massive Jam" cases and groups 3 and 4 were shown with "Jam" cases. "CTE (AYE)" means that the directional traffic was towards Ayer Rajah Expressway (AYE) on CTE. In groups 1 and 3, travel time information was displayed while in groups 2 and 4, the travel time information was not displayed on the VMS. The travel time information presented on cards was similar to the actual travel times one would experience in real life. "PIE", "AYE" and "SLE" are three expressways that are linked to CTE. The travel times displayed on the VMS were estimated travel times to the exits which lead to "PIE", "AYE" and "SLE". In this scenario, drivers were told that they were travelling to downtown (towards PIE and AYE). The travel time to "SLE" was on the other direction and therefore not relevant to the scenario. If the displayed message had more texts than what can be displayed on one time on the VMS, the message would be presented as toggling messages. In addition to VMS messages, the information on destination of the trip, trip purpose, trip time, the current speed on CTE and the likely speed on the alternative route were also provided as part of scenario information.

Table 5-4 Grouping of VMS Messages

Group	**1**	**2**	**3**	**4**
VMS Message	MASSIVE JAM CTE (AYE) PIE 18 MINS AYE 27 MINS SLE 3 MINS	MASSIVE JAM CTE (AYE)	JAM CTE(AYE) PIE 10 MINS AYE 16 MINS SLE 3 MINS	JAM CTE (AYE)

(i) Perception of Travel Time Information

In order to study drivers' perception on the reliability of travel time information displayed on VMS, for groups 1 and 3 with travel time information, respondents were asked whether they felt that the travel times displayed were accurate. The results are shown in Table 5-5. In groups 1 and 3, the numbers of respondents who thought the travel time was accurate were 56.8% and 62.6%, respectively. Overall, there were almost 60% of respondents who thought the travel times were accurate.

Table 5-5 Perceptions on Reliability of Travel Time Information

Group	Sample Size	Number of Respondents Giving Positive Response	Percentage
1	250	142	56.80%
3	246	154	62.6%

(ii) Estimation of Travel Time

Followed by the previous question, in groups 1 and 3, the respondents who thought travel times were not accurate were asked to estimate the actual travel time to the exit leading to PIE. It should be noted that in the questionnaire presented in Appendix I, the lower bound of the scale used (Q4.1) in groups 3 and 4 is different from the sample questionnaire presented. The lower bound for groups 3 and 4 is 0, which is to set the displayed time (10 minutes) roughly the middle in the scale. In groups 2 and 4, respondents were also asked to estimate the actual travel time to exit leading to PIE. The results are shown in Table 5-6.

Table 5-6 Estimation of Travel Time

Group	Sample Size	Mean (Min)	Standard Deviation (Min)
1	108	19.4	5.24
2	250	17.2	4.8
3	92	12.7	4.0
4	250	11.8	3.9

The results suggested that in groups 1 and 3 those who thought that travel times were not accurate, their average estimated travel times (19.4 minutes and 12.7 minutes respectively) were slightly higher ($t=2.70$ and $P=0.004$ in the "Massive Jam" case and $t=6.54$ and $P<0.0001$ in the "Jam" case) than the travel times displayed, which were 18 minutes and 10 minutes in the "Massive Jam" case and the "Jam" case, respectively. In cases where travel times were not displayed, the average estimated times (17.2 minutes and 11.8 minutes) were slightly different ($t=-2.49$ $P=0.006$ and $t=7.25$ $P<0.0001$ for the "Massive Jam" case and the "Jam" case) from the displayed travel times in other groups, which were 18 minutes and 10 minutes in the "Massive Jam" case and the "Jam" case, respectively. In the cases of "Massive Jam" without travel time displayed, the travel time were underestimated while in cases of "Jam" without travel time displayed, the travel time were overestimated by the respondents.

These results regarding travel time reliability reflect motorists' own experience in real life situations. More motorists perceived travel time information as reliable information, as compared with motorists who did not trust travel time information. However, there is a considerable proportion of motorists who did not trust the travel time information displayed on VMS, and they are likely to think the displayed travel times are underestimated, from their own past experience. This might be attributed to the fact that motorists tend to over-estimate travel times when driving in a congested traffic conditions. However, if travel time information is not displayed, motorists tend to underestimate the travel time when the message "Massive Jam" is displayed, as compared with motorists who do not trust the information. These findings suggest that motorists' perceived travel time in congestion condition is affected by the displayed travel time information on VMS, as well as their attitudes on reliability of the travel time information on VMS.

(iii) Response to VMS Information

The responses of participants were captured in terms of whether they would choose alternative route. The results are shown in Table 5-7. It can be seen that in the "Jam" cases (Groups 3 and 4), when travel times were displayed (group 3), significantly more drivers (65.45%) would continue to enter CTE than that where there were no travel time displayed (48.0%) ($z=3.90$ $P<0.0001$). However, in the "Massive Jam" cases, with (40.16%) and without travel time (41.2%), there were no significant difference in responses of drivers ($z=0.24$ $P=0.405$). It seems that the display of travel time would not make the expressway unattractive when the reported congestion is not very severe.

Table 5-7 Diversion Response to TTD Messages

Group	Sample Size	Number of Diversion	Percentage
1	250	147	59.84%
2	250	147	58.80%
3	246	85	34.55%
4	250	130	52.00%

iv) Reasons of not diverting

For respondents who indicated that they would enter the expressway, they were asked the reasons why they did not divert. Three choices of reasons were identified. There were "Alternative route is more congested", "More convenient to use CTE" and "Unsure about the traffic conditions on alternative route". The results (Table 5-8) turned out to be that out of 487 participants who had chosen not to divert, more than half (54.03%) of them indicated the reason "More convenient to use CTE". This result revealed the intrinsic tendency of drivers to use the expressway, i.e. CTE in this case. About one third of the respondents indicated the reason "Unsure about the traffic conditions on alternative route", which suggested that the uncertainty of traffic conditions of alternative route would make the alternative less attractive. In the following investigation on other VMS types, the reasons of not diverting were not asked again because in the pilot survey, it turned out that drivers give similar answers to this question regardless of VMS types.

Table 5-8 Reasons of not Diverting to Alternative Route

Reasons of not Diverting	Percentage
Alternative route is more congested	12.18%
More convenient to use CTE	54.03%
Unsure about the traffic conditions on alternative route	30.16%
Others	5.68%

(e) Perception and Responses to VMS Information on Expressways

As discussed, VMS mounted along expressways is capable of displaying two lines of text information and a graphic symbol representing different traffic situations. By providing the advance traffic information, it was expected that drivers would divert to the alternative routes if there were traffic congestions on expressways.

The messages on VMS on expressways could be broken down into several parts. The first part is targeted to report the cause of the congestion (if any). The second part is targeted to provide message reporting the location and physical extent of the congestion on expressway. The physical extent of the congestion was reported with terms "Massive Jam", "Jam" and "Slow traffic" as observed queue lengths of "greater than 2km", "greater than 1km, but less than 2km" and "less than 1km", respectively. This definition was determined by Land Transport Authority in Singapore based on operation experience. The start and end of the queue were described through terms "AFT" (after) or "UP TO" (up to) respectively, with respect to the expressway exits. When the congestion was severe and the message "Massive Jam" was displayed, advisory information was usually displayed.

An existing VMS on CTE was selected for this question. The information on destination of the trip, trip purpose, time of the trip, current speed on CTE and likely speed on alternative route were also provided.

(i) Perceptions on Traffic Descriptives

Although the terms "Massive Jam", "Jam" and "Slow Traffic" used on VMS were decided by the physical extent of observed queues, the public were not explicitly informed the meaning of these terms. Therefore, it is likely that drivers may interpret these terms as descriptions of traffic conditions in terms of other measures, such as speed. In order to probe drivers' perceptions, drivers were asked to describe the estimated traffic conditions using both speed and queue length after viewing the cards on which different traffic descriptions were shown on the VMS. The perception of respondents on the descriptions in terms of speed is shown in Table 5-9 while the perceptions on the descriptive terms in terms of queue length is shown in Table 5-10.

Table 5-9 Perception of Descriptive Terms in Terms of Speed

Descriptive Terms	Sample size	Mean (km/h)	Std. Dev. (km/h)
Massive Jam	249	21.05	10.19
Jam	467	23.08	10.09
Slow Traffic	249	29.20	9.03

The results in Table 5-9 suggest that drivers' perceptions on the terms "Massive Jam", and "Jam" in terms of speeds were significantly different ($t=2.53$ $P=0.012$). The understanding on "Jam" and "Slow Traffic" in terms of speed was significantly different ($t=7.92$ $P<0.00001$) too. However, the difference between the "Slow Traffic" and "Jam" is greater than the difference between the "Jam" and "Massive Jam".

Table 5-10 Perception of Descriptive Terms in Terms of Queue Length

Descriptive Terms	Sample size	Mean (km)	Std. Dev. (km)
Massive Jam	250	2.07	0.84
Jam	472	2.12	0.88
Slow Traffic	250	1.98	0.9

The results in Table 5-10 suggest that drivers' understandings on terms "Massive Jam", "Jam" and "Slow Traffic" in terms of queue length were very close to each other. The estimated queue length of the message "Jam" was even longer than the message "Massive Jam". The statistical test revealed that the perceptions on the message "Massive Jam" and "Jam" was not significantly different (t=0.96 P=0.337). Further statistical tests revealed that although the perceptions on "Jam" and "Slow Traffic" in terms of speed were significantly different (t=2.14 P=0.033), the perceptions on "Massive Jam" and "Slow Traffic" in terms of queue length were not significantly different (t=1.09 P=0.274). These results further suggested that drivers had difficulties relating the traffic descriptions to the queue length, which was the criterion used by the operator.

Followed by the above two questions, drivers were asked their perceptions on descriptions of congestion. The results show that among 992 respondents who answered this question, more than half (57.19%) of them felt that the speed was a better indicator of congestion while the other 42.81% of participants preferred queue length as a better indicator of congestion. This suggested that in addition to queue length, the traffic operator may consider using speed as an alternative to decide the descriptive terms shown if it is technically feasible.

(ii) Response to VMS on expressways

There were two questions targeted to obtain drivers' route switching responses to VMS message on expressway for different groups of respondents. The numbers of diversions are shown in Table 5-11. The VMS is able to display symbols to indicate whether there is an accident which caused the congestion. The schematic drawing of CTE is presented in Figure 5-1, in which the location of VMS is shown. Drivers were asked whether they would divert from CTE via exit leading to Bukit Timah (BT) Rd to reach his destination. The messages in "Massive Jam" and "Jam" cases were messages of major interests. The messages "Slow Traffic" were usually shown with minor accident when demand was not very high, therefore, only combination of "Slow Traffic" and accident symbol were investigated. The location of queue was reported with respect to upcoming exits. For example, "UP TO ORCHARD" means the queue start at the point where the VMS is located and extends all the way to exit to Orchard Road, "AFT CAIRNHILL" means the queue started after exit to Cainhill Road.

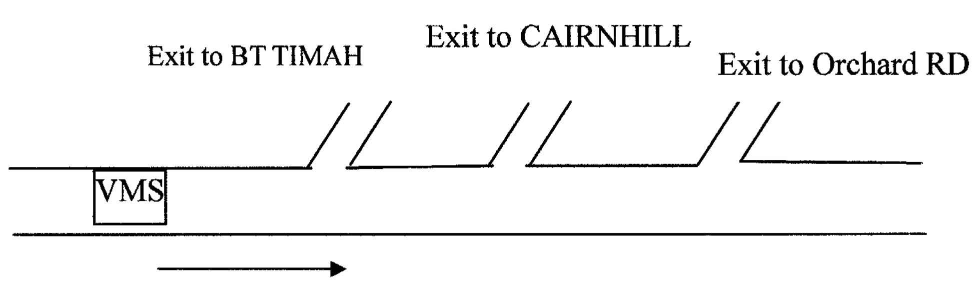

Figure 5-1 Schematic Drawing of CTE

The results suggested that when messages "Massive Jam" were displayed, around two thirds (74.4%, 67.07%, 68.02% and 68.00%) of drivers would switch from CTE. When the congestion was immediate (e.g. Up to exit to Orchard Road), there were significantly fewer drivers who would take alternative route when the congestion was reportedly caused by accident than peak hour demand ($z_0 = 1.80 > z_{0.05} = 1.645$). However, when congestion was not immediate (After exit to Cairnhill Rd), their responses were no significantly different ($-z_{0.025} = -1.96 < z_0 = 0 < z_{0.025} = 1.96$) when the reported cause of congestion was either incident or peak hour demand. Furthermore, responses to VMS messages "Massive Jam", "Jam" and "Slow Traffic" were significantly different. The "Massive Jam" case with the lowest diversion rate (67.07%) had significantly more diversions ($z_0 = 3.15 > z_{0.05} = 1.645$) than the "Jam" case with highest diversion rate (53.23%). The "Jam" case with the lowest diversion rate (52.02%) had significantly more diversions ($z_0 = 2.60 > z_{0.05} = 1.645$) than the "Slow traffic" case (40.40%).

Table 5-11 Responses to VMS

Sample Size	Traffic Information Display Messages	Number of Diversion	Percentage
250	MASSIVE JAM UP TO ORCHARD EXIT BT TIMAH	186	74.40%
249	(With Incident Symbol) MASSIVE JAM UP TO ORCHARD EXIT BT TIMAH	167	67.07%
247	MASSIVE JAM AFT CAIRNHILL EXIT BT TIMAH	168	68.02%
250	(With Incident Symbol) MASSIVE JAM AFT CAIRNHILL EXIT BT TIMAH	170	68.00%
248	JAM AFT CAIRNHILL	129	52.02%
248	(With Incident Symbol) JAM AFT CAIRNHILL	132	53.23%
250	(With Incident Symbol) SLOW TRAFFIC AFT CAIRNHILL	101	40.40%

(f) Understanding of Lane Control Sign (LCS)

LCS is one of the major signage used for tunnel traffic management in the context of incident. In normal traffic conditions, the LCS would display a green arrow symbol. When an incident happens, the LCS is capable of displaying symbols showing a flashing or static amber cross or a red cross. The amber cross symbol is a transition symbol while the red cross symbol is a sign similar to red on traffic light at junctions. This question was designed to probe drivers' understandings on amber cross or red cross symbols if they are static or flashing. The results of the questions are reported in Table 5-12.

Table 5-12 Understanding on LCS Symbols

	Flashing Amber	Static Amber	Flashing Red Cross	Static Red Cross
Proceed as normal	6.09%	2.83%	0.82%	0.61%
Proceed with caution	82.56%	30.77%	33.20%	2.83%
Change lane	9.74%	60.32%	54.10%	25.78%
Do not proceed beyond	1.42%	6.07%	11.27%	68.86%
Others	0.20%	0.00%	0.61%	1.82%
Sample Size	493	494	488	489

The results suggested that most (82.56%) respondents understand the flashing amber symbol as "Proceed with caution". For the static amber symbol, about 60% of respondents would perceive it as "Change lane" and about 30% of respondents would perceive it as "Proceed with caution". It seems that if the amber cross was static, it may result in more lane changing. For the flashing red cross symbol, more than half (54.10%) would interpret it as "Change lane" while about one third (33.2%) of participants would interpret it as "Proceed with caution". For the static red cross symbol, about two thirds of respondents (68.86%) would perceive it as "Do not proceed beyond" while about one fourth of respondents (25.78%) would perceive it as "Change lane". The static "red cross" symbol seems to be more desirable since most drivers will either change lane or stop to avoid proceeding beyond the sign. However, if the "red cross" symbol was flashing, considerable proportion of drivers may perceive it as "proceed with caution".

(g) Desired Traffic Information

This question was targeted to obtain the most important VMS information which may affect drivers' travel decisions. The results shown in Table 5-13 suggested that the descriptions on traffic conditions were the most important traffic information (31.26%) for drivers to make route choice decisions.

Table 5-13 Most Important Information Affecting Diversion Decisions (Sample size: 995)

Information Type	Percentage
Travel times (e.g. To PIE 18, To AYE 27)	23.32%
Description on incidents (e.g. ACCIDENT LN 1)	22.41%
Descriptions on traffic conditions ahead (e.g. MASSIVE JAM)	31.26%
Advisory information (e.g. EXIT AT ORCHARD)	9.35%
Speed (e.g. CAIRNHILL to ORCHARD 30 KPH)	13.47%
Others	0.20%

5.4 Summary and Conclusion

This chapter presents the results of the paper-based perception survey. Drivers' understandings on the current VMS messages were investigated. The drivers' perceptions on the travel time and descriptive messages on VMS, different symbols on LCS were investigated. In addition to their understanding, their stated responses to different VMS message types were presented.

The survey results obtained in this survey is significant to fill the gaps between VMS messages and drivers' understanding of those messages. Some of these gaps may result in wrong causes of actions, for example, wrong understanding on symbols displayed on LCS. The gaps in understanding may also contribute to less effectiveness of the information as a way to mitigate traffic congestion. For example, the survey results suggest that drivers are able to relate the descriptive terms "Massive Jam", "Jam" and "Slow Traffic" to speed while they had difficulties to relate the terms to queue length. These misinterpretations may affect drivers' route choice behaviour and result in ineffectiveness of VMS messages in diverting traffic to less congested route.

However, the limitation of the paper-based survey is obvious. The paper-based survey could not capture and present the dynamism of the scenario with a static picture. A traffic scheme may involve more than one VMS or one LCS to display messages in a sequence. In the paper-based survey, only messages on one VMS or LCS could be shown on the static picture. Drivers may have difficulties to relate the picture to actual traffic conditions. Secondly, if the research interest is the actual response, paper-based survey may not be able to capture the response in sufficient detail. For example, in study of drivers' responses to LCS, the paper-based survey only can capture "whether" a driver would change lane. Question regarding "when" and "where" to change lane cannot be answered. Finally, with the paper-based survey, if the research interests are the route switching behaviour and the results were analysed with discrete choice model or other regression model, one may have difficulty to estimate values of some independent variables, for example, in this study, travel times to destination on expressway with queue of different extent could not be estimated.

The traffic-driving simulator developed in this research can overcome the limitations of paper-based survey. In the following chapters, the results of the experiments with the traffic-driving simulator in different incident contexts will be presented. Firstly, in Chapter 6, the drivers' response to LCS and VMS information in case of accident with lane closure will be presented, followed by Chapter 7 which presents drivers' responses to fire evacuation information. The drivers' route switching behaviour in the presence of VMS information will be discussed in Chapter 8.

CHAPTER 6. DRIVERS' DRIVING BEHAVIOUR IN THE PRESENCE OF VMS AND LCS IN ACCIDENTS WITH LANE CLOSURE

As discussed in the previous chapter, although paper-based survey can obtain important information regarding to drivers' understanding on traffic messages on VMS and LCS, it is nevertheless limited to only the stated responses to these messages. The paper-based survey cannot present the dynamism of the driving scenario and cannot capture drivers' behaviour in sufficient detail. To overcome these limitations of paper-based survey, the traffic-driving simulator was developed. In this chapter, the application of the simulator system in studying drivers' behaviour in the presence of LCS and VMS information in an accident context with lane closure is presented.

As mentioned in earlier chapters, the major signage used for the tunnel incident management with lane closure is VMS and LCS. VMS signs are targeted to provide advance textual descriptions on the incident lane and segment with respect to exits and the lane of the incident. In addition, some advisory information and alert information are provided, for example, "avoid lane 1", "reduce speed" and "drive carefully". The LCS is targeted to provide immediate alert information on potential blockage ahead. In the proposed scheme, the static "green arrow" symbol, flashing "amber cross" symbol and the static "red cross" symbols will be used. As mentioned, the static "green arrow" symbol suggests usual traffic conditions. The flashing "amber cross" symbol is a transition symbol for the potential lane closure ahead. The "red cross" symbol which is similar to the red light signal at signalised intersection indicates lane closure just ahead.

The study results will be presented in the following sections of this chapter. Two scenarios were simulated in the traffic-driving simulator experiments with accident and lane closure. The drivers' responses were gauged and their lane changing behaviour and control of driving speed are presented.

6.1 Driving Scenarios

There were two scenarios simulated. Scenario 1 was the control scenario, in which all LCS signs were intentionally excluded, and only VMS were used to provide traffic information about the accident. Scenario 2 was the experimental scenario, in which the LCS signs were used together with VMS to broadcast the traffic information in accordance with the traffic management scheme. The between-scenario factor was the availability of the LCS, and other factors were exactly the same in the two scenarios. With reference of the results of previous chapters, it was decided that the yellow cross would be flashing while the red cross would be static, which is consistent with existing symbols used in CTE. Therefore, in scenario 2 the yellow cross symbols were flashing while the red cross symbols were static.

The schematic drawing of Scenario 2 is depicted in Figure 6-1. A stretch of the underground expressway was used for the study. There are two entrances and four exits in this stretch of expressway. There was one accident simulated by the traffic simulation model. A vehicle was stalled on lane 2 of the stretch of KPE leading to Exit A4. The alert zone is a straight section of tunnel between Exit A2 and A3. A series of LCS and VMS prior to reaching the incident site were simulated to display information on the accident. The text shown on the VMS can be found in Figure 6-1. As shown in Figure 6-1, from the first VMS displaying accident information to the accident site, the distance was 739 metres. The two LCS immediately upstream the accident showed the red cross symbols to indicate the closure of the lane. The distance between the first LCS showing the red cross symbol to the accident was 396 metres. Before the two LCS displaying red cross symbol, there were four other LCS displaying flashing amber cross symbols. The distance between the first LCS displaying flashing amber cross to the accident was 905 metres. The segment between the first flashing LCS to the accident site was defined as the alert zone. In order to minimise the impacts of traffic on drivers' lane changing behaviour, light traffic conditions were simulated in this scenario so drivers' lane changing behaviour would not be constrained by the ambient traffic. Furthermore, the traffic in the scenario was simulated to disregard the VMS and LCS and only changed lane at around 50 metres in front of the blockage. The traffic conditions collected at 3 virtual detectors of this scenario is shown in Table 6-1 as contextual information. The 10-minute average speed and traffic flow were measured as context information. The locations of the virtual loop detectors are shown in Figure 6-1. The reason to choose ten minutes statistics was that most respondents can complete each designed scenario between 5 to 10 minutes. The traffic flow is presented in terms of vehicles per hour.

Table 6-1 Traffic Conditions

Location	**Mean Speed (km/h) & Standard Deviation (SD)**	**Traffic Flow (veh/hr)**
Loop Detector 1	74.70 (SD: 14.23)	1590
Loop Detector 2	59.16 (SD: 6.19)	1368
Loop Detector 3	37.23 (SD: 16.55)	1260

The traffic on the expressway was light and the gaps are sufficient for participants to change lane freely. Among the different participants for Scenarios 1 and 2, the traffic simulated was identical. The only difference between Scenarios 1 and Scenario 2 is that all LCS were intentionally excluded in Scenario 1.

In order to make the scenario to be more realistic, a roadwork was also simulated on the shoulder of the tunnel. The simulation of the road work was to make the intention of the scenario less obvious to avoid potential biases introduced. There were also two LCS signs displaying flashing amber near the roadwork.

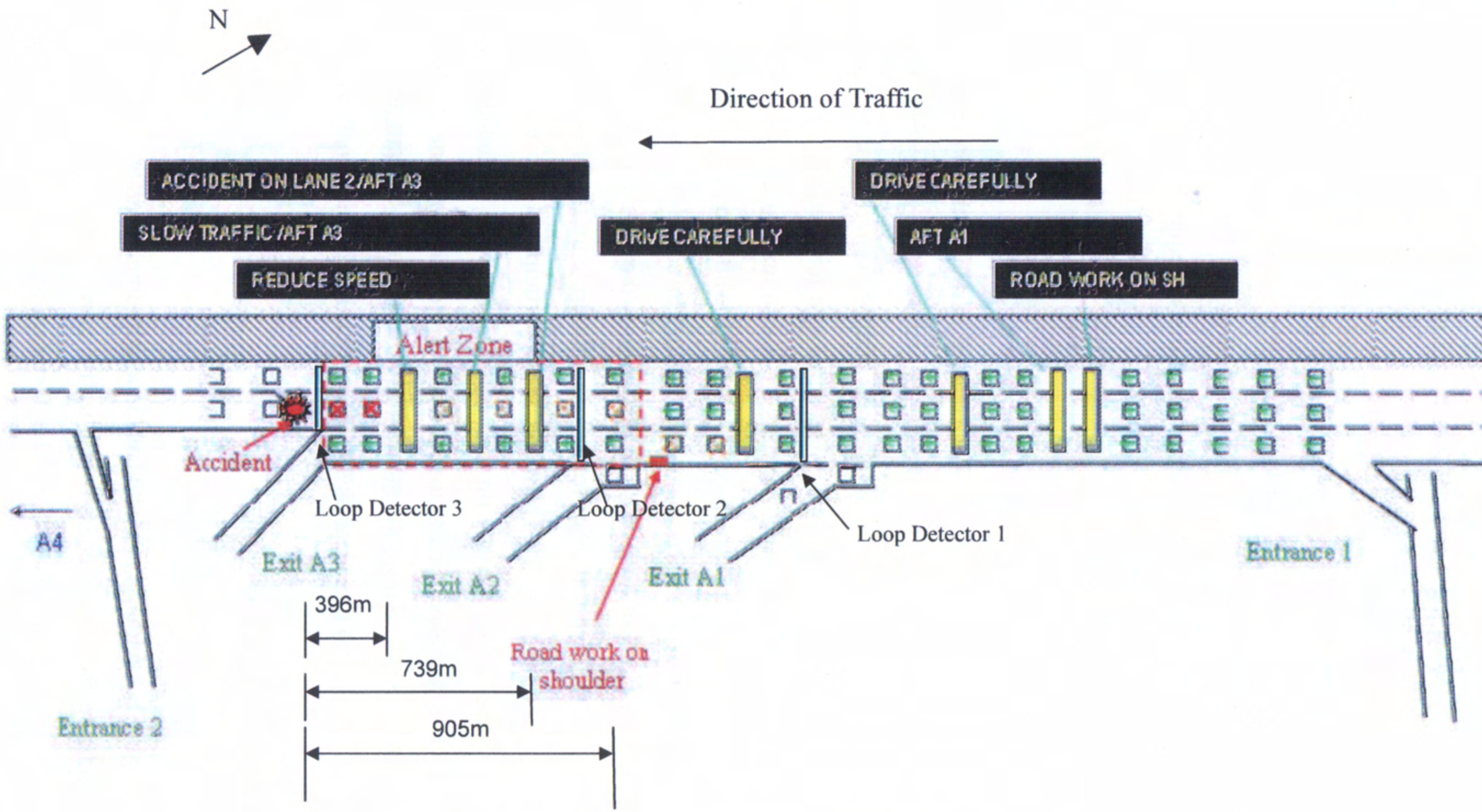

Figure 6-1 Schematic Drawing for Scenario 2

6.2 Measures

The driving behaviours of the experiment's participants were measured in a non-obtrusive manner by the traffic-driving simulator system. The measures collected include speeds, location and orientation of the car driven by subjects at each time frame. All of these data were collected at a frequency of 30 Hz.

6.3 Results

The survey results excluded the data collected from participants who reported unwell and did not complete the scenario. Altogether, there were 153 valid samples. For Scenario 1, there were 49 samples and for Scenario 2, there were 104 samples collected. The reason that the sample size for Scenario 2 is more than Scenario 1 is because Scenario 2 results were also used to develop route switching model which will be discussed in Chapter 8 while Scenario 1 results will not be used. Since the participants were asked to complete the driving task as to what they generally would do in real driving, there were possibilities that participants might divert to other routes or might drive on lane 1 or lane 3 prior to entering the alert zone. Therefore, those participants who exited to other routes or were already driving on lane 1 and lane 3 were excluded from the analysis. Only samples of participants who were driving on lane 2 when entering the alert zone were used for the analysis. There were 20 (40.8%) in Scenario 1 and 39 (37.5%) in Scenarios 2 who were excluded in the analysis.

6.3.1 Lane Changing Behaviour

The lane changing behaviour is presented as the longitudinal clearance from the accident to indicate the effectiveness of the traffic management scheme in an accident. Figures 6-2 and 6-3 show the distribution of the longitudinal clearance of individual drivers in Scenarios 1 and 2. In Scenario 1, since there was no LCS presented in the scenario, the range highlighted in yellow in Figure

6-2 is the range after which the driver has passed the first VMS showing accident information. In Figure 6-3, the area highlighted in light yellow is the area between the first LCS displaying flashing amber cross and the first VMS. The area coloured by yellow is the area between the first VMS and the first LCS displaying static red cross. The area shown in red is the area after the first LCS displaying static red cross. In both Figures 6-2 and 6-3, a line was drawn to indicate the Minimum Stopping Sight Distance (MSSD), which will be discussed in the following section.

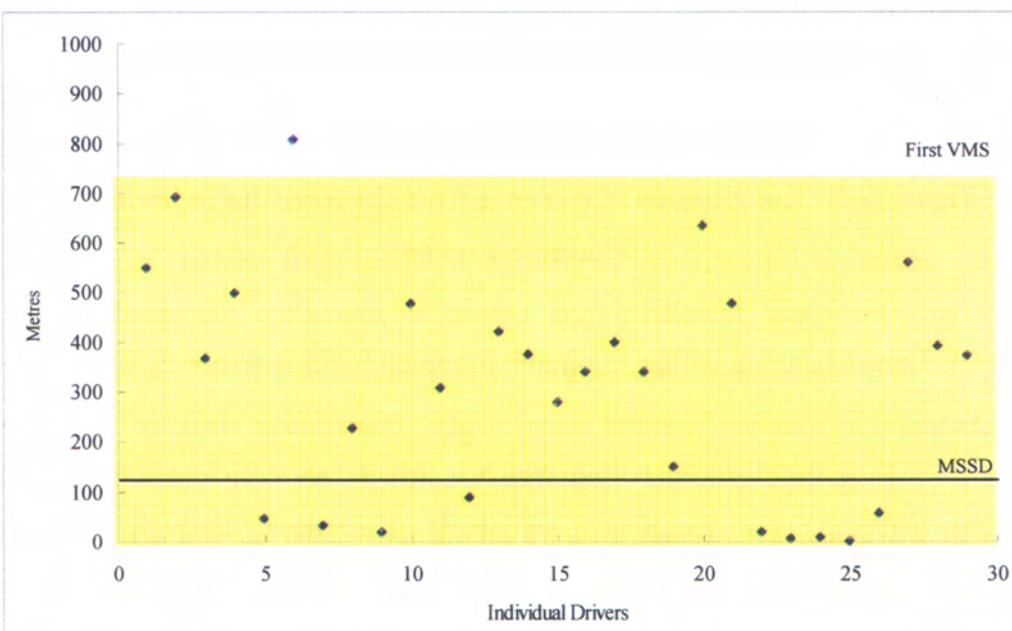

Figure 6-2 Longitudinal Clearance from the Accident in Scenario 1 (Sample size: 29)

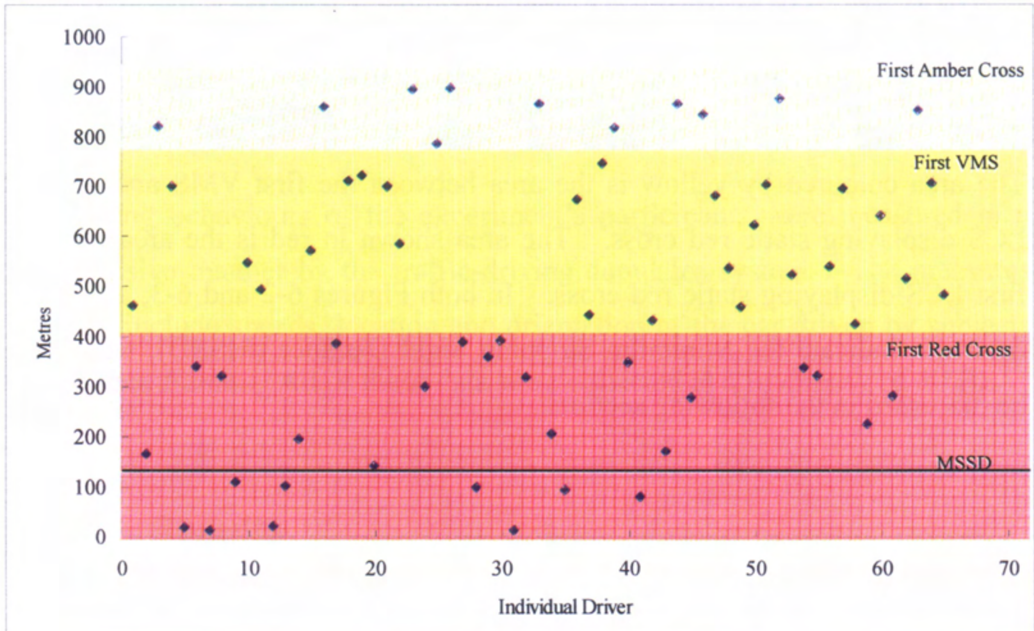

Figure 6-3 Longitudinal Clearance from the Accident in Scenario 2 (Sample size: 65)

(a) Lane Changing within Minimum Stopping Sight Distance (MSSD)

The MSSD is the distance within which a driver has sufficient time to stop his/her vehicle before reaching a stationary object along its path. For the design speed of 80 km/h of the new expressway, the design MSSD is around 120 metres. Therefore, the lane changing within 120 metres upstream of accident site is considered to be undesirable lane changing behaviour. Therefore, the expected benefit of LCS is to provide immediate guidance information to reduce the lane changing within MSSD so that safety level can be improved.

The distributions of the longitudinal clearance in the two scenarios provide some evidence on the effectiveness of LCS in this aspect. In Scenario 1 without LCS, 31% (9 out of 29) of the participants made lane changing within the MSSD, which is 120 metres upstream of the accident. However, in the scenario with LCS in operation, it can be seen that only 13.8% (9 out 65) of the participants had such a lane changing behaviour. The chi-square tests showed that in Scenario 2 with LCS, there were significantly fewer lane changes from the obstructed lane within the MSSD than Scenario 1 without LCS ($\chi^2 = 3.827$ $P = 0.05$). Therefore, the result suggested that the LCS display scheme is effective to reduce lane changing behaviour within MSSD.

(b) Longitudinal Clearance from Blockage

Table 6-2 shows the mean and 15^{th} percentile longitudinal clearance in Scenarios 1 and 2. It suggested that in the Scenario 2 with LCS, the average longitudinal clearance from blockage is about 157.2 metres longer than Scenario 1 without LCS. In addition, the statistical tests in Table 6-3, both assuming equal variance and unequal variances, showed that the differences between Scenarios 1 and 2 were significant (t=-2.70 P =0.0082 and t=-2.88 P =0.0052). This result suggests that the LCS scheme may result in early diversion of vehicles from the accident lane to the adjacent free lanes. Since merging near the bottleneck is unsafe and inefficient, early merging will therefore enhance the safety and efficiency of the tunnel expressway in the context of accident occurrence. However, in terms of variance of longitudinal clearance, there was no significant difference between Scenarios 1 and 2 (F=1.32 and P =0.4175). Thus, the result suggests that in terms of the resulting merging pattern, it may be similar in cases with LCS and in cases without LCS. In addition, the test of variance suggests the t-test assuming equal variance may be more relevant.

The 15^{th} (or 85^{th} in some cases) percentile statistics are usually used as a traffic engineering measurement for design and operation. The 15^{th} percentiles of longitudinal clearances are also shown in Table 6-2. It suggests that when the LCS is in operation, the 15^{th} percentile of longitudinal clearance (115.69) is substantially longer than that when LCS is not in operation (23.07).

Table 6-2 Summary of Statistics for Longitudinal Clearance

Scenario	Sample Size	Mean Clearance Distance (metres)	Std Dev	15th percentile
Scenario 1 (Without LCS)	29	313.44	231.18	23.07
Scenario 2 (With LCS)	65	478.07	265.96	146.24
		Difference :164.6		Difference: 123.17

Table 6-3 Test Statistics for Longitudinal Clearance

Variable	Method	Variances	DF	t Value	Pr > |t|
Clearance distance	Pooled	Equal	92	-2.70	0.0082
Clearance distance	Satterthwaite	Unequal	62.9	-2.88	0.0055

(c) Compliance to LCS Signs

In this section, only participants in Scenario 2 with LCS were analysed. The compliance was calculated with regard to the location of the first LCS displaying flashing amber cross, the first VMS with accident information and the first LCS displaying red cross that appeared to drivers. The compliance to LCS is shown in Table 6-4. There were 38 compliant participants who diverted before they proceeded beyond the red cross LCS while 27 (41.54%) participants proceeded beyond LCS displaying red cross symbol. Among these 38 participants who did not proceed beyond the LCS displaying red cross symbol, 12 (18.46%) of them diverted in the region between first LCS displaying amber cross and the VMS displaying text information, another 26 (40%) of them diverted from accident lane after they passed the VMS. It is notable that there were still a considerable proportion of non-compliant participants, even though they were not constrained by the ambient traffic. Such non-compliant behaviour could be contributed by the fact that many drivers are not familiar with operation of LCS in real life and were not aware of the operation of LCS in the experiment, as they were not explicitly told that LCS would be in operation prior to the scenario. The tunnel section in the existing CTE is short and most of the time green arrow symbols are displayed on LCS. Therefore, education on operation of LCS may be required for traffic operator prior to operation of KPE.

Table 6-4 Locations of Diversion with Respect to LCS Positions

Locations of Diversion	Number	Percentage
After passing the first LCS displaying amber cross (before VMS)	12	18.46%
After passing the first VMS (Before red cross LCS)	26	40.00%
After passing the first red cross LCS	27	41.54%

6.3.2 Effects of LCS on Vehicular Speed

The vehicular speed in the alert zone was compared in each scenario and the results are shown in Table 6-5. In Scenario 2, the average speed in the alert zone was 68.05 km/h, which is about 4.7 km/h slower than the mean speed in Scenario 1. However, the statistical test in Table 6-6, both assuming equal variance and unequal variances, showed that the difference between Scenarios 1 and 2 was only significant (t=1.75 P =0.0835 and t=1.82 P =0.0739) at a confidence level of 90%. These results suggest that LCS may have effects in reducing the vehicular speed within the alert zone. However, the effect is not very significant. In terms of variance, there was no significant difference between Scenarios 1 and 2 (F=1.22, P=0.563), which suggest the t-test assuming equal variance may be more relevant. In terms of 85th percentiles of vehicular speed, the results in Table 6-5 suggest that when the LCS is not in operation, the 85th percentile of vehicular speed (87.18 km/h) is higher than that when LCS is in operation (76.71 km/h).

Table 6-5 Summary of Statistics for Mean Vehicular Speed

Scenario	Sample Size	Mean vehicular speed (Km/h)	Std Dev	85th percentile
Scenario 1	29	72.76	11.2	87.18
Scenario 2	65	68.05	12.394	76.71
		Difference: 4.71		Difference: 10.47

Table 6-6 Test Statistics for Mean Vehicular Speed

Variable	Method	Variances	DF	t Value	Pr > |t|
Vehicular speed	Pooled	Equal	92	1.75	0.0835
Vehicular speed	Satterthwaite	Unequal	59.2	1.82	0.0739

6.4 Summary and Conclusion

The effects of LCS and VMS on drivers' driving behaviour in an incident management situation with lane closure are reported. The data were obtained using the traffic-driving simulator in typical scenarios in which the LCS and VMS were used for incident management with closure of one lane. An accident was simulated in a stretch of KPE tunnel and the LCS and VMS were used to broadcast the traffic messages regarding the incident. There were two scenarios simulated. Scenario 1 was the control scenario in which the LCS was intentionally excluded. Scenario 2 was an experimental scenario with LCS displaying messages according to the proposed traffic plan. In order to minimise potential biases, the participants were not informed about the accident prior to the run and the data were collected by the instrument in a non-obtrusive manner. Furthermore, participants were not instructed to stay on a particular lane. With all these efforts, it is expected the results can be a reasonable representation of the drivers' field driving behaviour.

170 participants completed the designed scenarios. Participants who had diverted to other routes or lanes before entering the alert zone were excluded from the final analysis. As a result, there were 29 valid samples used in Scenario 1 and 65 in Scenario 2.

Based on the collected samples, the effects of the LCS on participants' lane changing behaviour and speed choice behaviour were analysed. The analysis on the mean and the 15^{th} percentile longitudinal clearance reveals that the LCS display scheme not only was effective in reducing risky lane changing, but also induced an early merging of traffic. Therefore, there were strong indications that LCS could reduce lane changing near the bottleneck and drivers would be able to perform a smoother and safer lane changing manoeuvre. However, the analysis on variance on the longitudinal clearance did not show any significant impacts of LCS on the underlying variability. This implies that the operation of LCS may not be able to change the spread in the lane changing pattern.

The analysis on vehicular speed suggests that LCS result in slightly slower average traffic speed in the alert zone, where LCS were displaying flashing amber cross symbols or red cross symbols. The statistical tests results suggested that the decrease of the mean speed was significant only at a 90% level. However, the 85^{th} percentile speeds were rather different. Therefore, the effects of LCS to decrease vehicular speed were evident, although not very significant.

In addition to the above analysis, it should be noted that there were about 40% of drivers who did not comply and proceeded beyond the red-cross LCS. The compliance statistics provided important information for traffic operator to fine-tune the LCS display scheme. The reason for the non-compliance behaviour may be attributed to the fact many participants are not familiar with the operation of LCS and more education may be required for motorists who will drive in the new underground tunnel.

Prior to the traffic-driving simulator study, the paper-based perception survey discussed in Chapter 5 had studied drivers' understanding on the flashing and static amber cross and the red cross symbols. The results are shown in the Table 5-14. The survey results revealed that most of the drivers (82.56%) interpreted the flashing amber cross as proceed with caution. Only 9.74% of drivers interpreted the flashing amber cross as change lane. Therefore, it may not be surprising that drivers stay on their current lane even though they see the flashing amber signs. However, about 70.68% drivers interpreted the red-cross symbol as do not proceed beyond. About one fourth of drivers (26.31%) interpreted the static red-cross sign as change lane. These results suggest that drivers interpret the red-cross symbol as symbols that they should avoid the lane. However, in real life situations, drivers may need to wait for a suitable gap to filter or their inertias may prevent them to it earlier when they saw the red-cross symbol. Therefore, when they pass the red LCS, they may still be on the accident lane. Therefore, the observed inertias should be considered when the traffic scheme is planned.

Compared with the paper-base survey, the results obtained from the traffic-driving simulator are an obvious improvement. Firstly, the traffic-driving simulator is able to present the situation in a more realistic manner with the dynamism of the scenarios being well presented, as compared with a paper-based survey with static pictures shown. The operation of VMS and LCS is presented in a sequential order and the dynamism of traffic conditions is presented as well. Secondly, rather than provide a stated response, participants are actually responding to VMS and LCS information. Thirdly, data of much greater detail can be collected, compared with the paper-based survey. These advantages make the traffic-driving simulator a more attractive instrument to study drivers' responses to ATIS information.

CHAPTER 7. DRIVERS' DRIVING BEHAVIOUR IN THE PRESENCE OF ATIS IN FIRE EVACUATION OF ROAD TUNNEL

As mentioned in Chapter 1, since a long section of the new expressway is an underground road tunnel, there will be signage and equipment to be introduced as public announcement system in cases of emergency evacuation. VMS, LCS and Radio Re-Broadcast & Break-in (RBBI) are the major signage and public announcement equipment to be used to disseminate visual and audio information to guide drivers to evacuate from the road tunnel in cases of fire, as it will be the major type of emergency that requires evacuation from the expressway tunnel. Depending on the actual location of the fire and the availability of exit slip roads, drivers will either be guided to take the immediate slip road to leave the tunnel or abort their vehicles to escape using the emergency exits on the side walls of the tunnel. As in findings discussed in previous chapters, how drivers would respond to the evacuation information on VMS, LCS and RBBI is of significant importance to the effectiveness of the evacuation. This is of utmost important as any slight delays in evacuating people trapped inside a tunnel could potentially become a huge disaster. Therefore, studies on drivers' responses to VMS, LCS and RBBI during fire evacuation are essential to fine-tune the emergency evacuation plans to maintain the safe and efficient operation of the new expressway and other road tunnels to be built in the near future.

A study of this kind is impossible to be investigated through field surveys or observations, especially when the tunnel is still under construction as in this study. This could be a common problem for the evacuation design of tunnel expressways, or any other similar types of infrastructure, as the evacuation plans and designs need to be drawn well in advance of the actual completion of the tunnels. The importance of a thoroughly safe evacuation plan, and the tremendous repercussion for the lack of it, has warranted the type of problems to be studied in a well-designed simulator such as the one invented in this study as discussed in the previous chapters. The traffic-driving simulator developed is capable of duplicating a very realistic driving environment with both ambient traffic and traffic scheme in the context of a fire evacuation simulated. The high fidelity of the traffic-driving simulator greatly enhanced the realism of the survey environment. The study was a pioneer investigation on the responses of individual driver on the evacuation plan in a controlled experiment using a driving simulator.

In addition to the utilisation of the advanced instrument, there were other experiment controls to minimise the potential biases that may be introduced. Firstly, a between-subject experimental design was adopted to avoid potential learning effect. Secondly, participants were not explicitly told the purpose of the scenario during the pre-briefing. The scenarios with fire evacuation were mixed with other scenarios serving other purposes. Participants were instructed to complete a journey as they have done in other scenarios. This helps to test participant's nature responses and avoid some potential biases. With all the above efforts, participants would be able to respond to the traffic scheme spontaneously and their responses were collected by the system in a non-obtrusive way.

7.1 Study Purpose

Fire evacuation is something most drivers would hardly think of when driving through a tunnel. In fact, fire is not an event that one would encounter normally. When it does happen, drivers may be clueless and confused by the sudden circumstances and find difficulties to make a decision in responding to the message broadcasted, especially during the early stage when the information was first broadcasted to the drivers who were within the immediate vicinity upstream of the fire. Therefore, in this study, a few scenarios were simulated to study the responses of drivers who were in this situation. The results would provide not only scientific information on drivers' responses to road tunnel fire evacuation information, but also would have important implications on the design or fine-tuning of the fire evacuation plan for road tunnel fire protection in general.

7.2 Participants

In total, 60 participants were asked to drive in the designed fire evacuation scenarios. In total, there were 47 (78.33%) male and 13 (21.67%) female participants. In terms of age, there were 12 (20%) participants less than 25 years old and 38 (63.33%) participants between 25 to 35 years and 10 (16.67%) participants aged over 35. The selection of the participants for each scenario was on a random basis.

7.3 Driving Scenarios

The design of the fire evacuation scenarios was based on hypothetical fire scenarios, which happened on a typical weekday afternoon before peak hour. A truck caught fire inside the underground expressway. One minute later, the Control Centre detected the fire. Another minute passed, the emergency evacuation plan was launched. All the LCS and VMS started to display the guidance information. At the same time, the RBBI started to broadcast the guidance information. Drivers who were immediately upstream of the fire experienced the updated information on signage regarding the fire while they were still driving.

In the fire evacuation of a road tunnel, drivers were either guided to take nearby slip road to leave the road tunnel or to abandon their vehicles to evacuate via the emergency exits on the side walls of the tunnel. Therefore, the first concern was to study how drivers would respond to the above two evacuation schemes. Another concern was the effect of audio information broadcasted by the RBBI, which was different from site-specific visual information displayed by VMS and LCS. The RBBI is a public announcement system to be used at the KPE tunnels, which is also the first time for its use in Singapore.

However, the current design of RBBI is not able to provide segment-specific broadcasting. Once the RBBI is launched, the same announcement will be broadcasted throughout the whole directional traffic via radio and drivers on the same direction will receive the same announcement, regardless their actual positions. This technical constraint on the RBBI has been a concern in the formation of the evacuation plan. Therefore, based on the two concerns that need to be studied, a 2×2 factorial experimental design was used and the two between-subject factors were the evacuation methods and the availability of RBBI.

There were four scenarios designed to simulate the initial stage of the fire since it was reported to be the most crucial period for individual decisions (Bryan, 2002). The scenarios "Fire 1" and "Fire 2" (Figure 7-1) were targeted to study a typical situation in which drivers were guided to take the exit slip road and leave the tunnel before they saw the fire scene. The scenarios "Fire 3" and "Fire 4" (Figure 7-2) were targeted to study a typical situation in which the tunnel sections were blocked by the fire and nearby exit slip road was not accessible to vehicles (Figure 7-3). Drivers were instructed to leave their vehicles and escape via the emergency exits on the side walls of the tunnel before they saw the actual fire. In order to further differentiate the effects of the RBBI broadcast, it was intentionally excluded in scenarios Fire 1 and Fire 3.

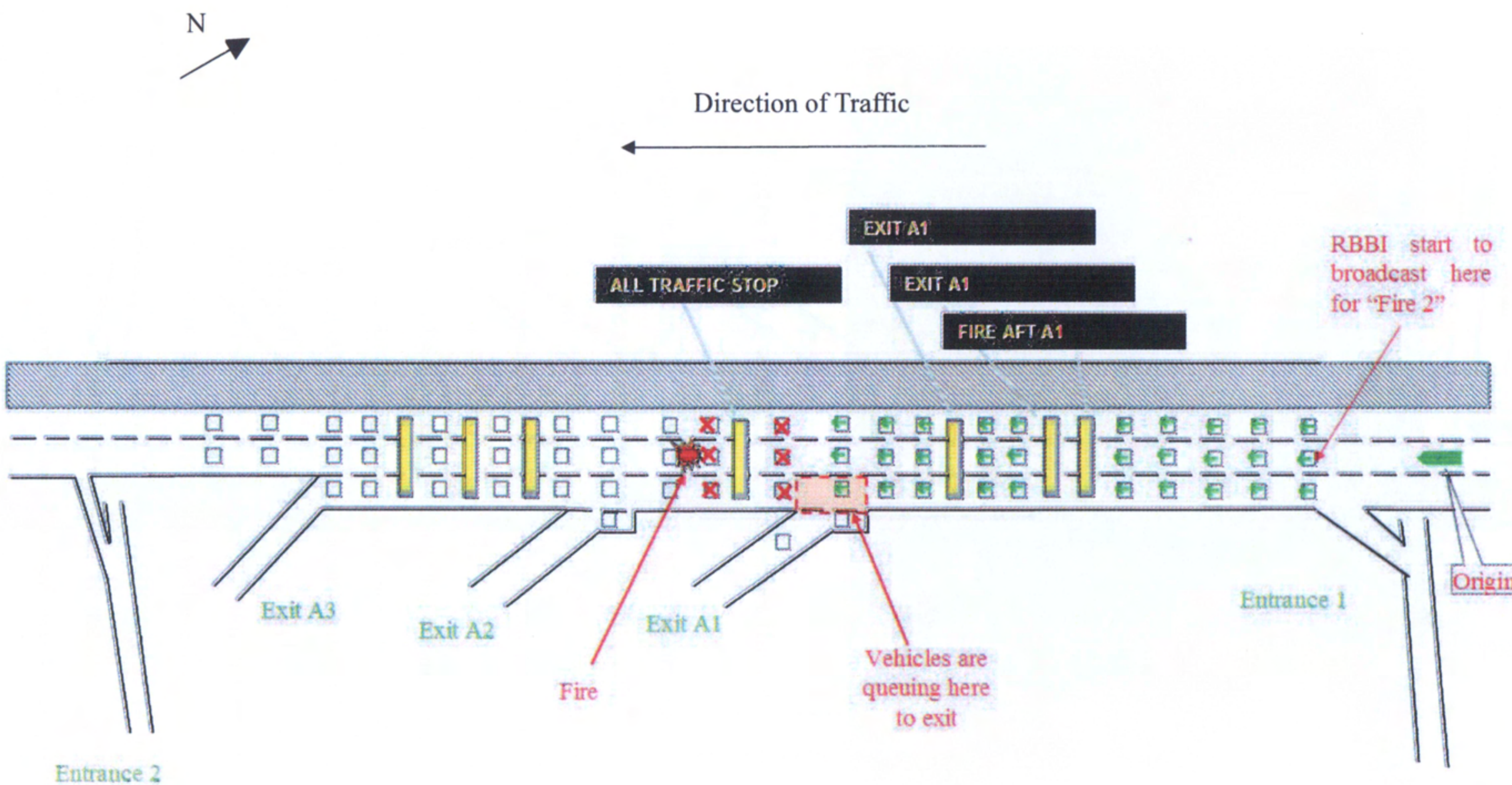

Figure 7-1 Schematic Drawing for the Scenarios Fire 1 and 2

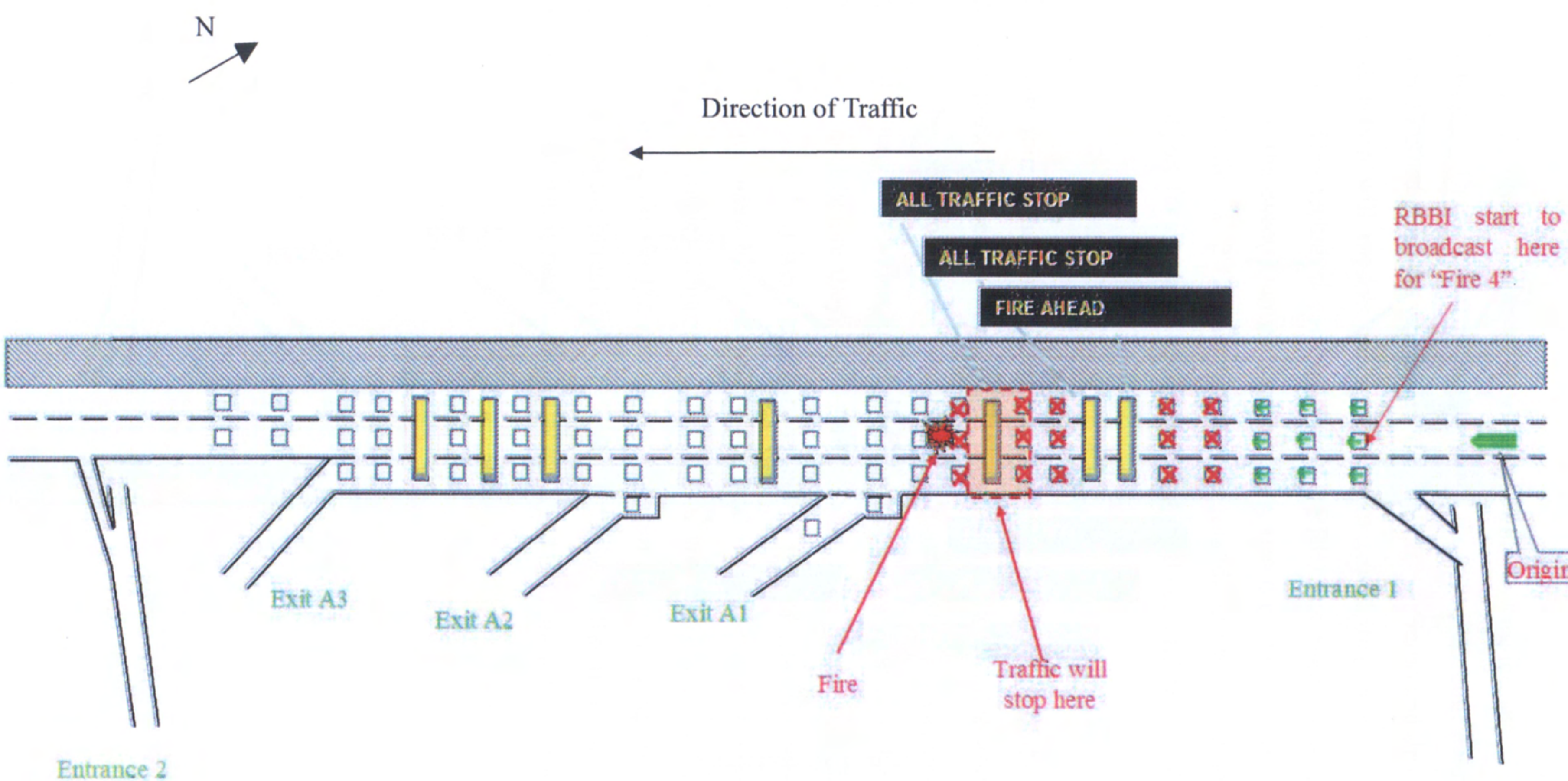

Figure 7-2 Schematic Drawing for the Scenarios Fire 3 and 4

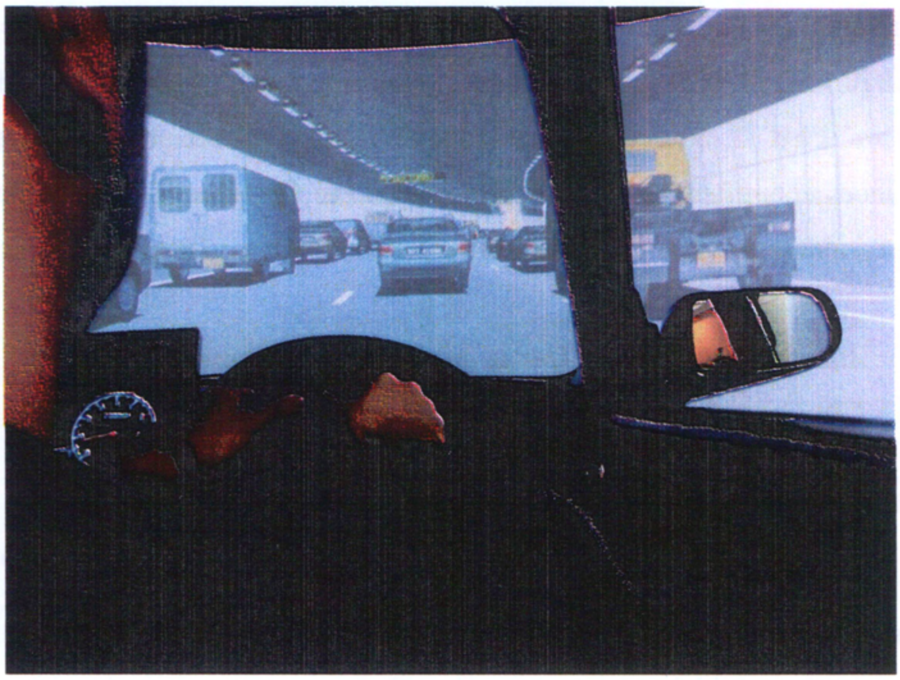

Figure 7-3 A Queue of Vehicles before the Fire

The traffic conditions including LCS and VMS information displayed for the scenarios Fire 1 and Fire 2 are shown in Figure 7-1. The truck fire was placed at the main tunnel section, between the exits A1 and A2. As shown in Figure 7-1, the VMS and LCS were updated to broadcast information regarding the fire and drivers were guided to leave the tunnel via the Exit A1. The VMS gave messages asking drivers to take the nearest slip road leading to Exit A1 and leave the tunnel. The green arrow symbols were displayed on the LCS at the tunnel sections before the Exit A1 to indicate the accessibility of the nearby slip road. However, on the tunnel sections after the Exit A1, red cross symbols were displayed on the LCS to indicate that drivers cannot proceed beyond that point if they failed to exit at the slip road. Light traffic conditions were simulated at the tunnel section to avoid external effects due to heavy traffic conditions. A queue of vehicles could be seen before the exit slip road to Exit A1. This was because the capacity of the slip road was much less than the capacity of the main tunnel and could not sustain the demand from the main tunnel even when the traffic on the main tunnel was light. Furthermore, a driver could not see the actual fire and smoke near the Exit A1. He/she could only see the actual fire and smoke if he/she continued to proceed on the tunnel, beyond the Exit A1. In the scenario Fire 1, in order to differentiate the effects of RBBI, the RBBI announcements were intentionally excluded. In the scenario Fire 2, the RBBI was simulated to start broadcasting the announcements after the drivers have passed the Entrance 1. The following repeated message was announced via the RBBI:

> *Attention, all drivers. This is an emergency announcement from LTA Control Centre. There is a fire in the tunnel. I repeat, there is a fire in the tunnel. Tunnel is closing. Please leave via the nearest exit. Look out for pedestrians.*

In the Scenarios "Fire 3" and "Fire 4", drivers were guided to stop immediately and abort their vehicles to escape using the emergency exits since the main tunnel was blocked and the nearest exit slip road was not accessible. The traffic conditions, LCS and VMS information for the scenarios "Fire 3" and "Fire 4" are depicted in Figure 7-2. The truck fire was simulated before the tunnel Exit A1. As shown in Figure 7-2, the VMS and LCS were updated to broadcast information regarding the fire. Textual messages were displayed on the VMS to guide drivers to stop immediately and the LCS was displaying the red cross symbol for the same purpose. When the drivers first saw the LCS displaying the red cross symbol and the first VMS displaying message regarding the fire, the actual fire and smoke was still not visible to them. To focus the effects due to fire, a light traffic on the KPE tunnel was simulated. Similarly with scenarios "Fire 1" and "Fire 2", the RBBI announcements were intentionally excluded in the scenario "Fire 3" and the RBBI was simulated to start broadcasting the announcements after drivers have passed the Entrance 1 in the scenario "Fire 4". The following repeated message was announced via the RBBI:

> *Attention all drivers, this is an emergency announcement from LTA Control Centre. There is a fire in the tunnel. The exit ahead is blocked. Turn off engine and leave your vehicle*

immediately. Please walk to the nearest emergency exit in the direction you came from.

The broadcasting of RBBI was released slightly earlier than the first update of LCS and the complete announcement took about 25 seconds. Therefore, after the complete announcement, a driver might still see one or two rows of LCS displaying the green arrow symbol before they saw the red cross symbol.

7.4 Results

The data capturing participants' driving behaviour were logged by the traffic-driving simulator during the survey. The participants' responses were analysed with the logged data and the results are reported below.

7.4.1 Responses to Guidance Information to Leave from Slip Road

The scenarios "Fire 1" and "Fire 2" were designed to study participants' responses to guidance information targeted to guide drivers to take the impending slip road. The primary considerations on scenarios "Fire 1" and "Fire 2" are whether the drivers would follow the guidance information and take the immediate exit slip road before the actual fire was seen.

(a) Result of Scenario "Fire 1"

In the scenario "Fire 1", only VMS and LCS were broadcasted to provide the guidance information. It turned out that 6 (40%) out of 15 participants chose to use the Exit A1. The other 9 (60%) participants did not take the Exit A1 and continued to drive on the tunnel towards the fire location. For those who did not take the Exit A1, they were asked to provide their reasons. Table 7.1 gives a summary of their responses.

Table 7-1 Reasons of not Exiting at A1

Reasons	Number of drivers
Never refer to the VMS in the real life.	1
VMS information were just recommendation, not compulsory	1
Confused, did not know what to do	1
Did not notice the sign	2
Misunderstood the information	2
No reason was given	2

(b) Result of Scenario "Fire 2"

In the "Fire 2" scenario, RBBI was used to broadcast the emergency announcement. All details in this scenario were exactly the same as the "Fire 1" scenario except that RBBI was broadcasted after drivers had passed the Entrance 1. It turned out that with RBBI broadcasting, drivers' responses were very different from the first scenario. All 14 participants assigned in the scenario Fire 2 chose to exit at the Exit A1.

(c) Effect of RBBI

The effects of RBBI can be determined by comparing the results of scenarios "Fire 1" and "Fire 2" (Table 7-2) with Fisher's exact test.

Table 7-2 Differences in Response for Scenario "Fire 1" and "Fire 2"

Scenario	Between subject factor	Sample Size	Number of Participant Took Exit A1
Fire 1	Without RBBI	15	6 (40%)
Fire 2	With RBBI	14	14 (100%)

Fisher's exact test (Fisher, 1922) is used to analyse the difference in responses for scenarios "Fire 1" and "Fire 2". Fisher's exact test is an alternative to the

Chi-square test in the analysis of categorical data, when sample sizes are small. The test is used to examine the significance of the association between two variables in a 2 x 2 contingency table. Consider a 2x2 contingency table shown in Table 7-3, with the cell frequencies represented by a, b, c, d, and the marginal totals represented by a+b, c+d, a+c, b+d, and n.

Table 7-3 A 2*2 Contingency Table

	B1	B2	Totals
A1	a	b	a+b
A2	c	d	c+d
Totals	a+c	b+d	n

Fisher showed that the probability of obtaining any such set of values was given by the hypergeometric distribution:

$$p = \binom{a+b}{a}\binom{c+d}{c} \Big/ \binom{n}{a+c}$$

$$= \frac{(a+b)!(c+d)!(a+c)!(b+d)!}{n!a!b!c!d!}$$

where the symbol "!" indicates the factorial operator.

The Fisher's exact test revealed that the response in terms of exiting from the slip road in scenarios "Fire 1" and "Fire 2" were significantly different. There are significantly more (P=0.0005) drivers who followed the instructions and took the exit slip road in scenario Fire 2 with RBBI.

7.4.2 Responses to Guidance Information to Leave from the Emergency Doors

The scenarios "Fire 3" and "Fire 4" were designed to study participants' responses to guidance information targeted to guide drivers to leave their car and evacuate the tunnel via the emergency exits on the side walls. The primary considerations on scenarios "Fire 3" and "Fire 4" are whether the guidance information is effective to make drivers stop and leave their car even when the actual fire has not been seen.

(a) Result of Scenario "Fire 3"

In this scenario, only the LCS and VMS were simulated to be updated once the drivers had passed the third LCS after Entrance 1. The participants were able to see a few rows of LCS displaying the green arrow before they saw a row of LCS displaying the static red cross. There was no RBBI broadcasting in this scenario. Altogether, there were 16 drivers who were randomly selected to participate in this scenario. It turned out that all of them continued to drive on regardless of whether the LCS was displaying the static red cross symbol and VMS instructing drivers to stop immediately. All of them did not stop until they saw the actual fire scene and the formation of the queue of vehicles. Drivers were further asked what their next actions would be after they stopped. The results are tabulated in Table 7-4. The results suggest that most drivers would stay in their cars and wait.

Table 7-4 Participants' Stated Action after the Vehicles Stopped

Drivers' Intended Actions	Number of drivers
Stay and wait	13
Leave the car immediately	3

(b) Result of "Fire 4" Scenario

The scenario "Fire 4" was exactly the same as the scenario "Fire 3", except that the RBBI was simulated to broadcast the announcement after the drivers passed Entrance 1. It turned out that only 1 out of the 15 participants proceeded until the actual fire was seen. The other 14 participants stopped before seeing the actual fire. The stopping positions of the 14 participants are reported in Table 7-5 with regard to the location of the different signage. 10 out of 14 participants stopped their cars immediately when they saw the LCS displaying red cross symbol while another 4 participants stopped their cars after they saw the LCS displaying red cross symbol and the VMS displaying the "All Traffic Stop" message.

A follow-up question was asked on their next actions after they stopped. Fourteen participants stated they would leave their cars and use the emergency exits to escape immediately. Only 1 driver who stopped after seeing the VMS message said he would stay in the car and observe for a while and decide whether to leave the car.

Table 7-5 The Stopping Position with Regard to LCS and VMS

The final position drivers stopped	Number of drivers
After the LCS displaying red cross, before seeing the VMS displaying "All Traffic Stop"	10
After the LCS displaying red cross and the VMS displaying the "All Traffic Stop" message	4

(c) Effect of RBBI

The effect of RBBI can be determined by comparing the results of scenarios "Fire 3" and "Fire 4" (Table 7-6). The Fisher's exact test revealed that the responses in terms of stopping before seeing the actual fire in scenarios "Fire 3" and "Fire 4" were significantly different ($P<0.0001$). In terms of actions after stopping the car, the Fisher's exact test also revealed that the responses were significantly different ($P<0.0001$).

Table 7-6 Difference of Response in Scenarios Fire 3 and Fire 4

Scenario	Between subject factor	Sample Size	Number of participants proceed until seeing the actual fire
Fire 3	Without RBBI	16	16 (100%)
Fire 4	With RBBI	15	1 (6.67%)

7.4.3 Comparisons of Compliance to Emergency Evacuation Plans

The effects of the two emergency evacuation plans were compared in terms of compliance of drivers to the guidance information. In the cases without RBBI, as in the scenario 1, a smaller number of participants complied with the guidance information provided by signage while in the scenario 3 none of the 16 participants complied with the guidance information provided by signage. The Fisher's exact test suggested that the compliance of drivers in scenarios 1 and scenario 3 are significantly different (P= 0.0068). However, in the cases with RBBI, as in the scenario “Fire 2” and the scenario “Fire 4”, there are no significant difference in drivers’ compliance to the guidance information (P= 0.5172) as almost all of them followed the instructions.

7.5 Summary and Conclusion

This research also investigated the drivers’ responses to the evacuation plan in the initial stage of a road tunnel fire. Making use of the traffic-driving simulator developed in this study, participants were asked to drive in the scenarios within which they were positioned at immediately upstream of the tunnel fire. Four scenarios were simulated to study drivers’ responses in two evacuation schemes. RBBI were intentionally excluded in 2 scenarios so the effects of RBBI could be differentiated.

In the scenarios “Fire 1” and “Fire 2”, drivers were guided to take immediate exit and leave the tunnel. In the scenario without RBBI, there were considerable number of drivers who did not take the slip road, even though there were other vehicles already queuing to take the exit slip road. These results implied that visual message by signage may not be sufficient to provide compelling information to define and evaluate the fire incident if no other cues of fire was perceived by the drivers. The results of post-scenario questionnaire for those participants who did not take the exit slip road further support the implication. Drivers might overlook or misunderstand visual messages provided by signage if there were no other cues provided. However, in the scenario "Fire 2" with the audible messages by RBBI, all participants followed the instruction and took the nearby slip road. This result suggests that the audible messages are more indicative and may provide very helpful information to help drivers to define the fire and evaluate the threat. Therefore, proper actions of egress would be prompted in time with the audible message by RBBI.

Similar phenomena were observed in the scenarios "Fire 3" and "Fire 4", in which drivers were guided to stop immediately and give up their car and escape via emergency doors. In the scenario "Fire 3" without RBBI, it turned out that all participants proceeded until they saw the fire scene, despite the red cross symbol being displayed on LCS and the warning message on VMS. This again suggests that the visual messages on signage may not be sufficient to let the drivers realise the impending threat due to the fire. Therefore, drivers may need further cues to validate the fire and evaluate the threat. That could explain why drivers still proceed until the fire was visible to them.

However, in the scenario "Fire 4", when the RBBI announcement was broadcasted, the audible messages turned out to be very effective. Almost all drivers stopped and gave up their car before they saw the actual fire and the queue of vehicles. That implies that the audible messages would be very helpful for the drivers to evaluate the threat and make prompt decision. However, it should be noted that in this scenario, for those who stopped before seeing the actual fire, they did not stop immediately after they heard the RBBI announcement. Out of the 14 participants who had stopped before seeing the actual fire, 10 proceeded until they saw the LCS displaying the red cross symbol while another 4 proceeded even further until they saw the VMS messages reporting the fire ahead. These results suggest that even with announcement, drivers may still need to validate the site-specific information on the signage. If the audible and visual information are conflicting, drivers may require further confirmation on the fire incident.

The last point to address is that when the responses to the two evacuation plan were compared, it turned out that it would be more difficult to ask drivers to stop rather than to ask drivers to exit via the slip road, in cases where only visual guidance information was provided. However, when the audible RBBI information was provided, there were no significant differences in the drivers' responses to the two evacuation plans. These results again suggested the effectiveness of the audible messages by RBBI.

As a conclusion of the study results discussed in this chapter, it was found that visual information alone may not be sufficient to guide drivers to evacuate in case of fire incident. When only visual information are presented, some undesirable responses were observed, which is consistent with some responses observed in real tunnel fire (Rhodes, 2007). These responses include: drivers continued to drive until the fire and smoke were seen; drivers stayed in their car; few drivers used the emergency exits. The audio information broadcasted by the RBBI was found to be very effective to guide drivers to evacuate from the tunnel and above undesirable behaviour was not longer observed when the audio information was presented. However, the RBBI information has to be consistent with the visual information provided by signage. The research results thus provide some important scientific evidence for the fine-tuning of the fire evacuation plans in the tunnel and other tunnels in general.

The traffic-driving simulator was found to the best way in such studies. The traffic-driving simulator is capable of simulating complicated scenario in extreme conditions which can never be tested in field studies. In addition to capability to simulate complicated scenario, the traffic-driving simulator is capable of simulating visual information as well as audio information in a real time driving environment. Such level of fidelity can hardly be achieved by paper-based surveys or travel simulators. In the case of evaluating evacuation strategies, traffic-driving simulator approach may be the most suitable approach due to the complexity of the interactions and the hypothetical scenarios needed in the design.

CHAPTER 8. DRIVERS' ROUTE SWITCHING BEHAVIOUR IN THE PRESENCE OF VMS MESSAGE IN ROAD CONGESTION

Traffic congestion on the expressway is usually caused by the imbalance between demand and capacity, which is either caused by the decrease in supply due an incident that happened on the expressway or an increase in demand during the peak hour. The advance of IT technologies made extensive monitoring of traffic conditions on expressways possible and the incident that affects the capacity of an expressway could always be promptly detected and removed. However, as an expressway demand management tool in congestion, the full potential of VMS have not been fully realised since the drivers' switching behaviour in the presence of VMS messages were not fully understood. In particular, the question regarding the factors affecting the drivers' behaviour in the presence of VMS remains unanswered. The knowledge on factors affecting drivers' switching behaviour in the presence of VMS messages, not only can be used as reference which provide some insights to improve current VMS display scheme, but also beneficial to design and operation of similar system in general.

Therefore, this chapter is targeted to study drivers' route switching to VMS messages in some hypothesised scenarios, (Figure 8-1) in which congestion and operation of VMS was simulated with the traffic-driving simulator developed in this study. Based on the data obtained from the survey, behaviour models will be developed to differentiate the effects of VMS messages and other factors on drivers' route switching behaviour.

Figure 8-1 VMS Message in Traffic Congestion

8.1 The Traffic-Driving Simulator Survey

The design of the traffic-driving simulator survey was briefly discussed in Chapter 3. In this chapter, the details of the traffic-driving simulator survey will be further discussed to allow readers to have a better understanding on how data were collected to support model development, and more importantly, how the traffic-driving simulator can be utilised to facilitate this type of study.

Scenarios simulated in this study were based on two sections of the KPE expressway. The segment of KPE shown in Figure 8-2 is the southern portion. Initially in the pilot survey, all the scenarios were simulated on this segment. However, as mentioned in Chapter 3, as a measure to minimize the chance of simulation sickness by reducing exposure time, a shorter section on the northern portion, as shown in Figure 8-3, was eventually used in the main survey.

There were a number of scenarios simulated to allow a systematic study of driving behaviour at different traffic conditions with different VMS presented. In the following sections, eight of the major scenarios will be presented, as examples of scenarios developed. Scenarios 1 to 4 used the southern portion of KPE, while Scenarios 5 to 8 used the northern portion as the infrastructure to test drivers' responses to the various VMS messages. In all the eight scenarios, drivers were travelling south bound.

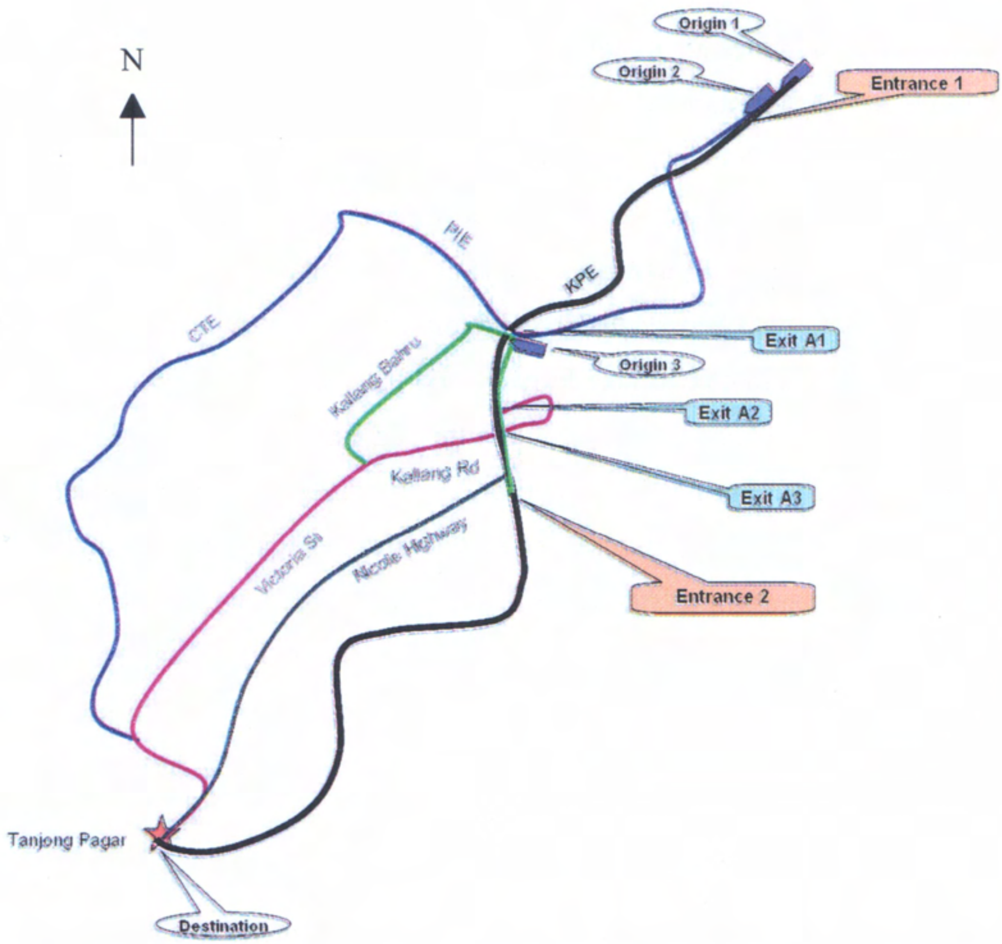

Figure 8-2 Road Map for the Southern Portion of KPE (Scenarios 1 to 4)

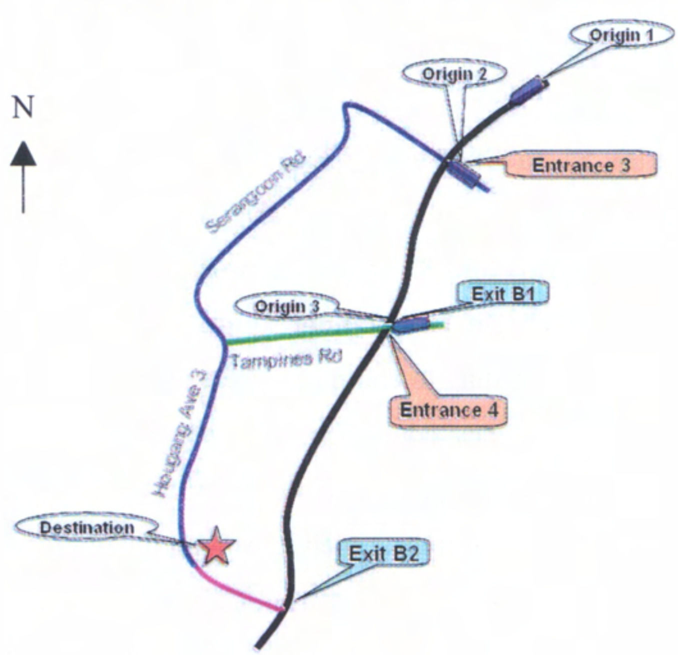

Figure 8-3 Road Map for the Northern Portion of KPE (Scenarios 5 to 8)

The origins and destinations in scenarios S1 to S4 are marked in Figure 8-2, in which a map showing all the available routes can be found. Subjects were randomly selected to start from different origins while they were asked to drive to the same destination. Origin 1 was on the expressway, assuming subjects already entered it from an earlier entrance while origins 2 and 3 started from arterial roads leading to entrances 1 and 2. For subjects who started from Origin 1, they could choose either to stay on the expressway and drive all the way to the destination, or to take Exit A1 and use the blue alternative route to the destination. Otherwise, they could either choose to take Exit A2 and use the purple alternative route, or to use Exit A3 via the red alternative route to the destination. In order to reduce the time of subject at the traffic-driving simulator, the scenario was stopped once the subject chose to exit from any slip road because that would be the final decision. For subjects who started from Origin 2, they could choose to use the blue alternative route or to enter the expressway. Once they entered the expressway, they could choose to continue their trips, as subjects who started from Origin 1. For subject who started from origin 3, they could choose to either enter KPE via the light blue slip road or take the green alternative route and join the purple alternative route leading to their destination. For subjects who started from origins 2 or 3, the scenario was stopped once the subject had chosen not to enter the new expressway and to use the alternative route.

Similar to scenarios S1 to S4, the origins and destinations of the runs for scenarios N1 to N4 are marked in Figure 8-3, in which a map shows all the available routes in scenarios 5 to 8. Subjects were randomly selected to start from origins 1, 2 or 3. Origin 1 started on expressway while origins 2 and 3 started from arterial roads leading to entrances of the expressway. For subjects who started from Origin 1, they could choose to stay on the expressway and drive all the way to destination. Alternatively, they could choose to take Exit B1 and use the green alternative route which joins with the blue route leading to the destination. For subjects who started from Origin 2, they could choose to enter the expressway or use the blue alternative route to their destination. For subjects who started from Origin 3, they could choose to either enter KPE or take the same alternative route as subjects who started from origin 1.

In all scenarios, the switching behaviour is considered as a consecutive binary choice between the expressway and respective alternative routes, as the subjects can make such decisions whenever they passed by an exit on their ways to the destination. A simulation run would stop once a driver decides to switch to an alternative route or if there is no further choice to be made. Therefore, the number of choices made is different for different runs made by a subject in different scenario. Those who chose to use an earlier exit had less choices made.

The schematic drawings of the scenarios S1 to S4 and N1 to N4 are shown in the Figures 8-4 to 8-11, respectively. The extent of queue was reflected by the VMS messages displayed, through the use of terms Massive Jam, Jam and slow traffic, as discussed in previous chapters. The details of the messages and the physical extent of the queue are roughly presented in each figure depicting each scenario. If there was not sufficient space to display the messages on a VMS, they were displayed in two pages.

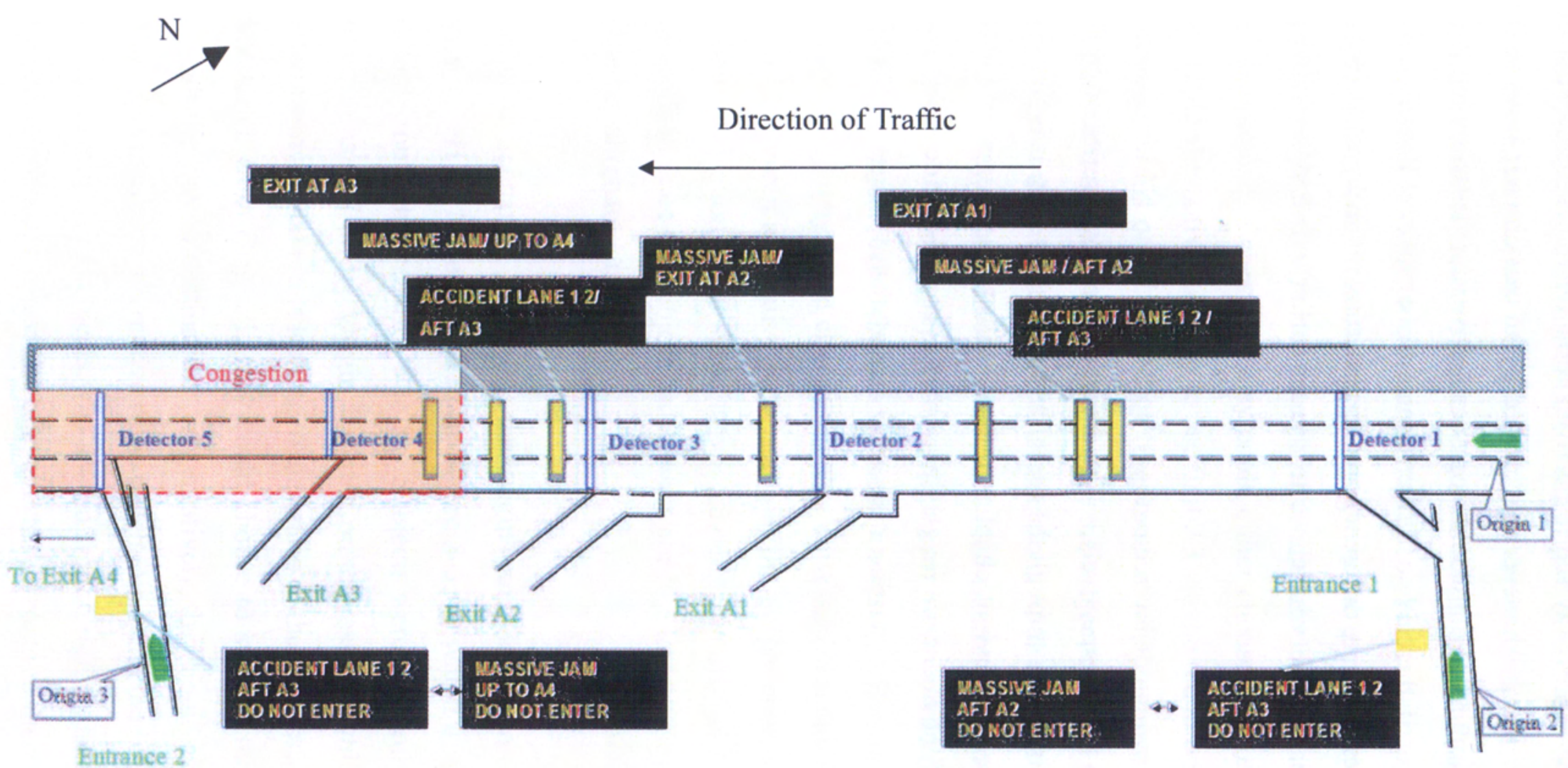

Figure 8-4 Schematic Drawing for the Scenarios S1

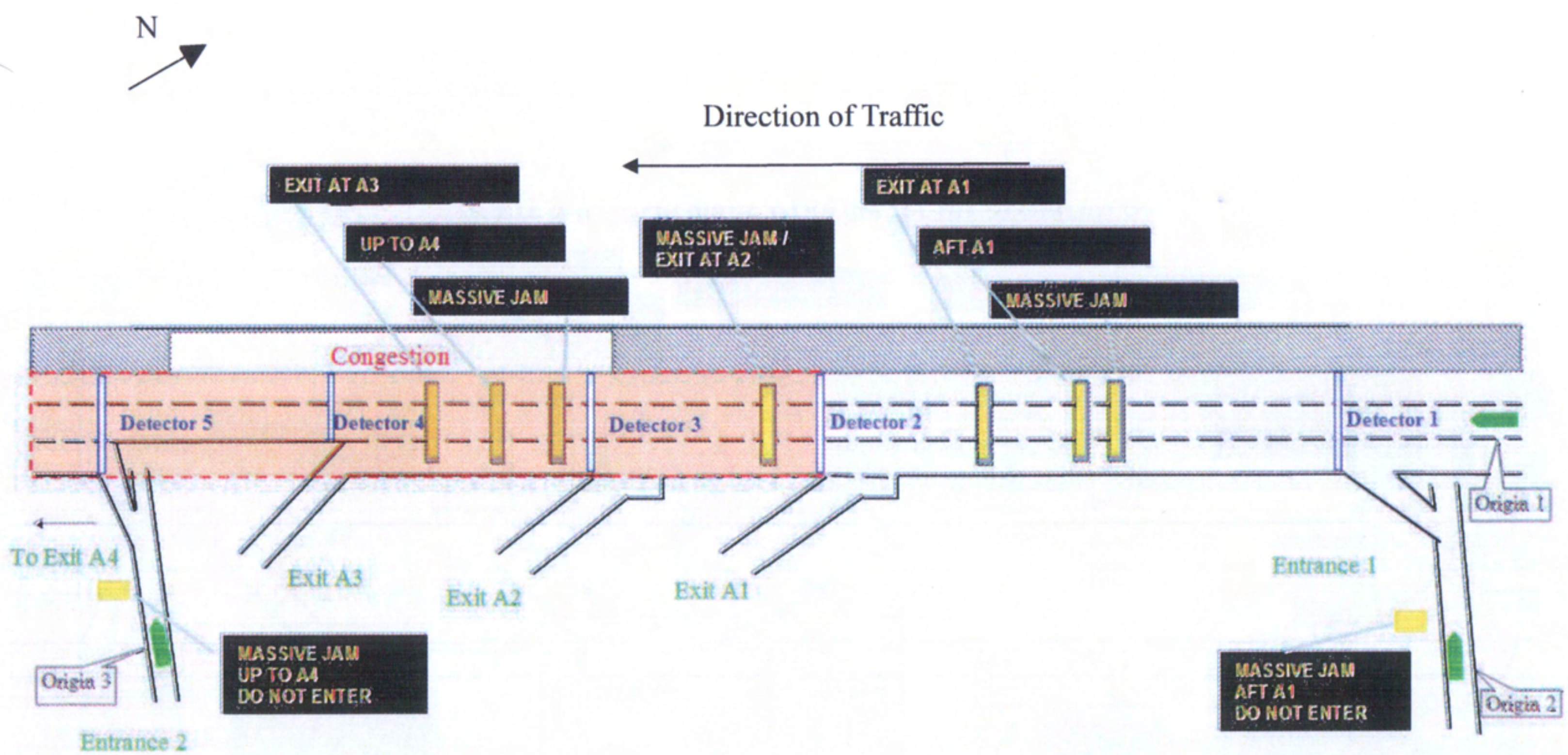

Figure 8-5 Schematic Drawing for the Scenarios S2

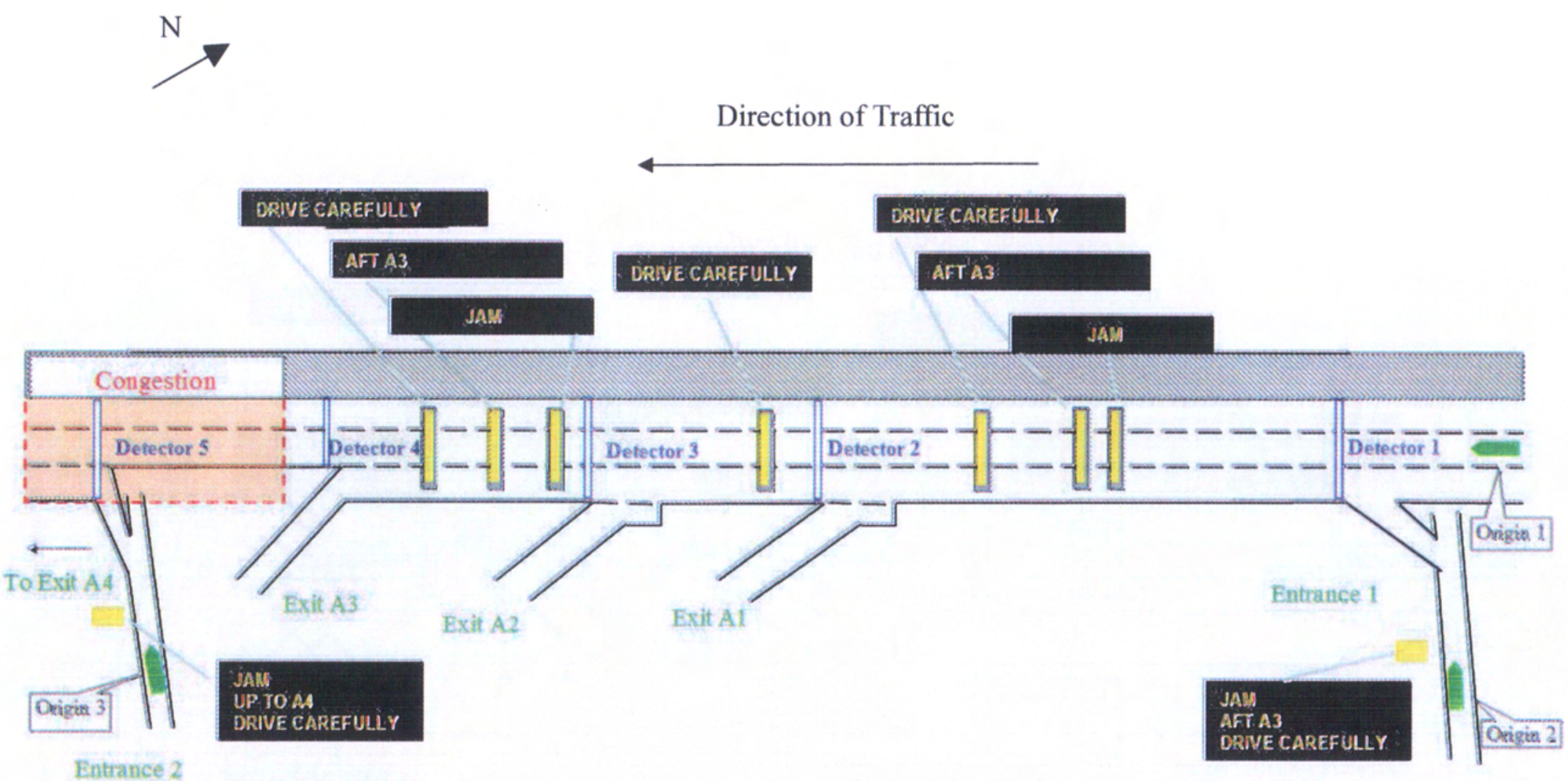

Figure 8-6 Schematic Drawing for the Scenarios S3

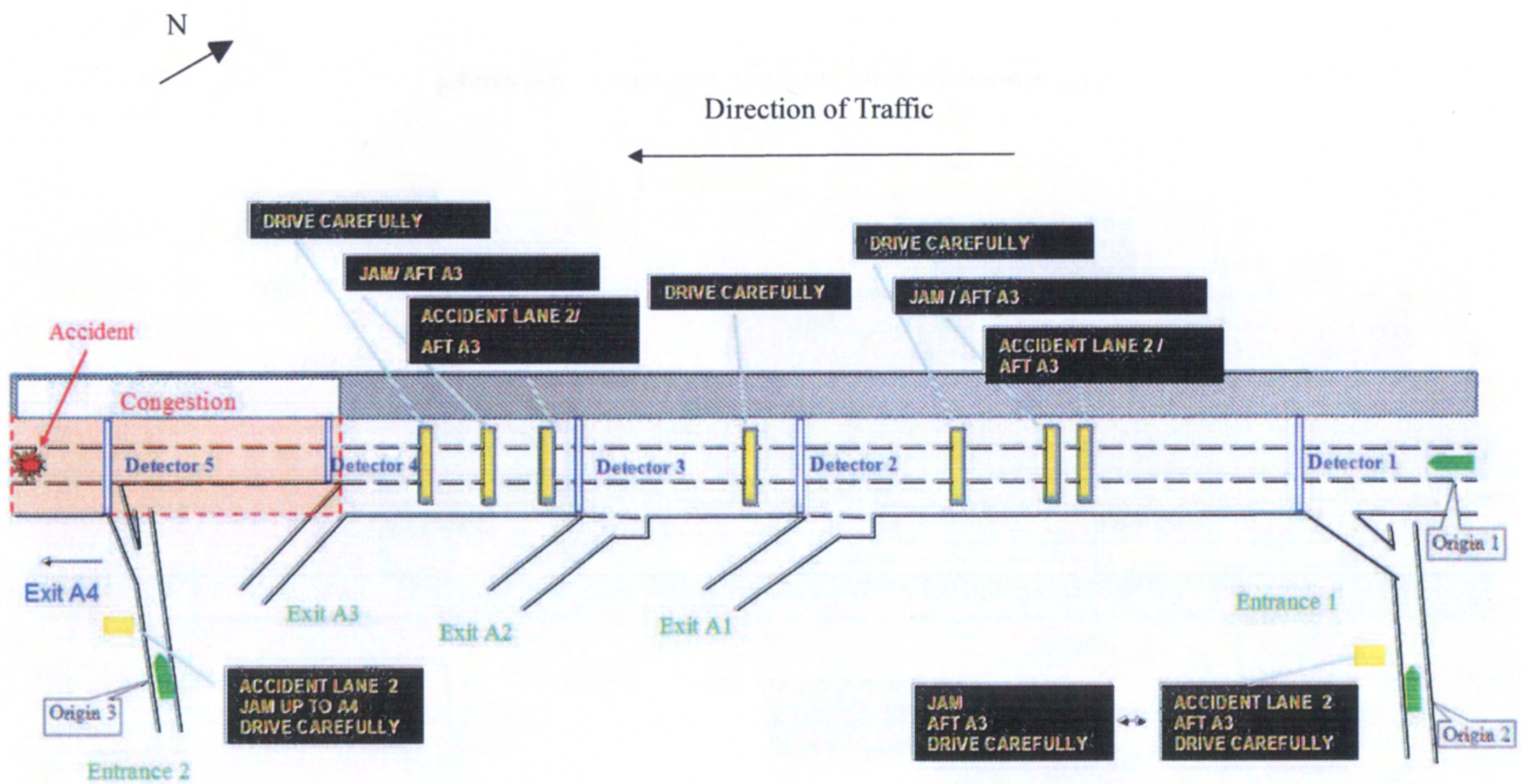

Figure 8-7 Schematic Drawing for the Scenarios S4

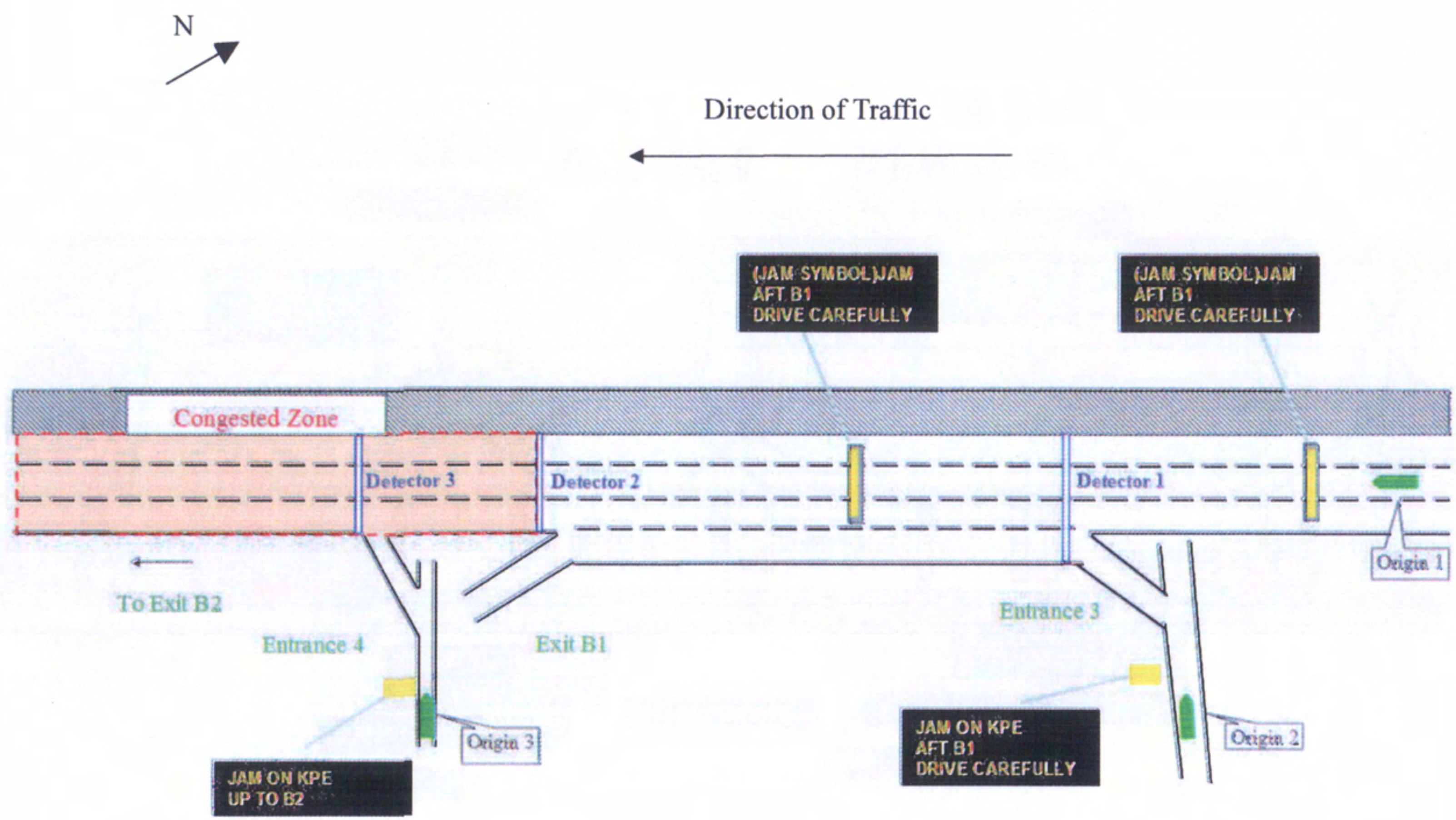

Figure 8-8 Schematic Drawing for the Scenario N1

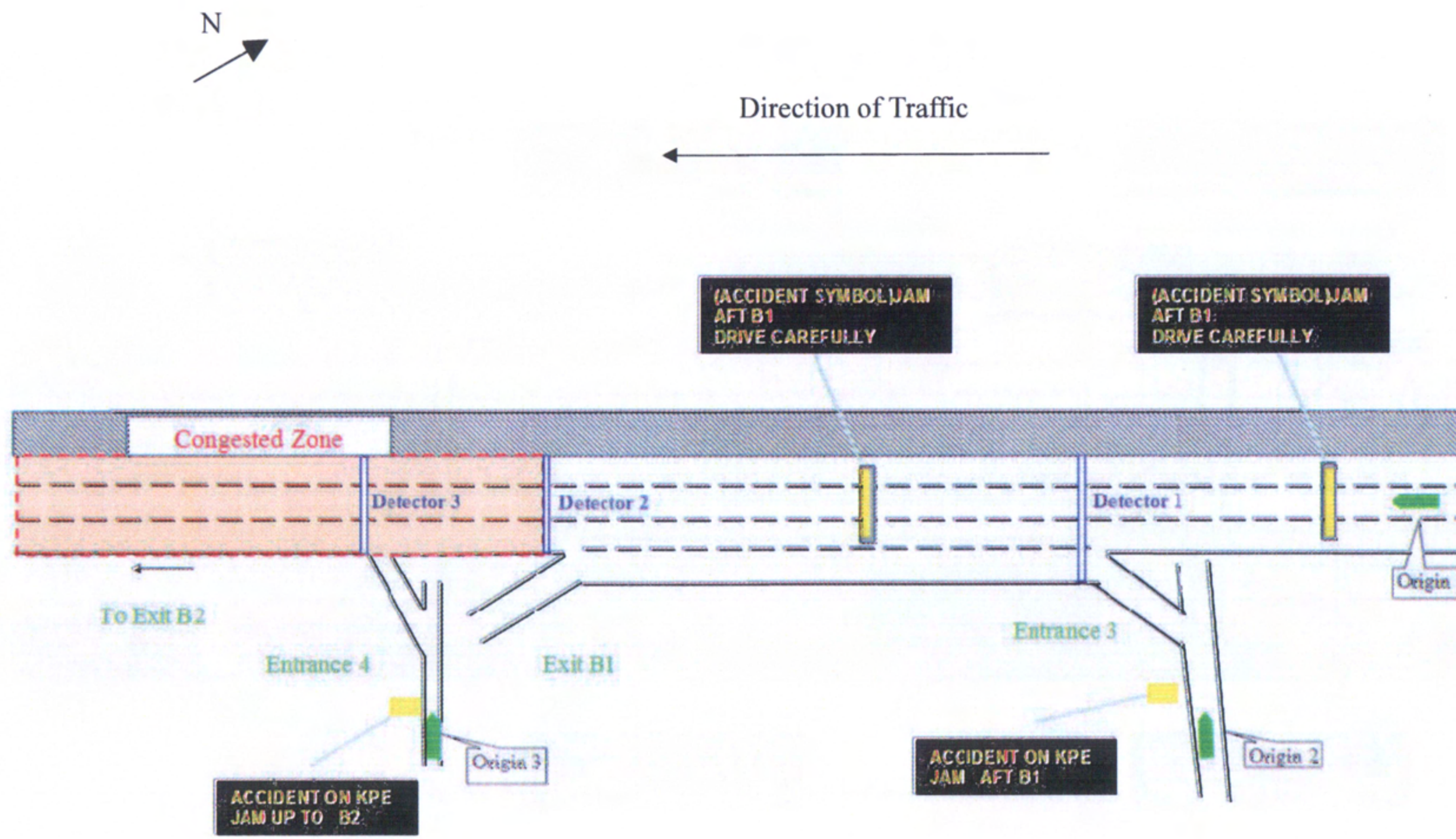

Figure 8-9 Schematic Drawing for the Scenario N2

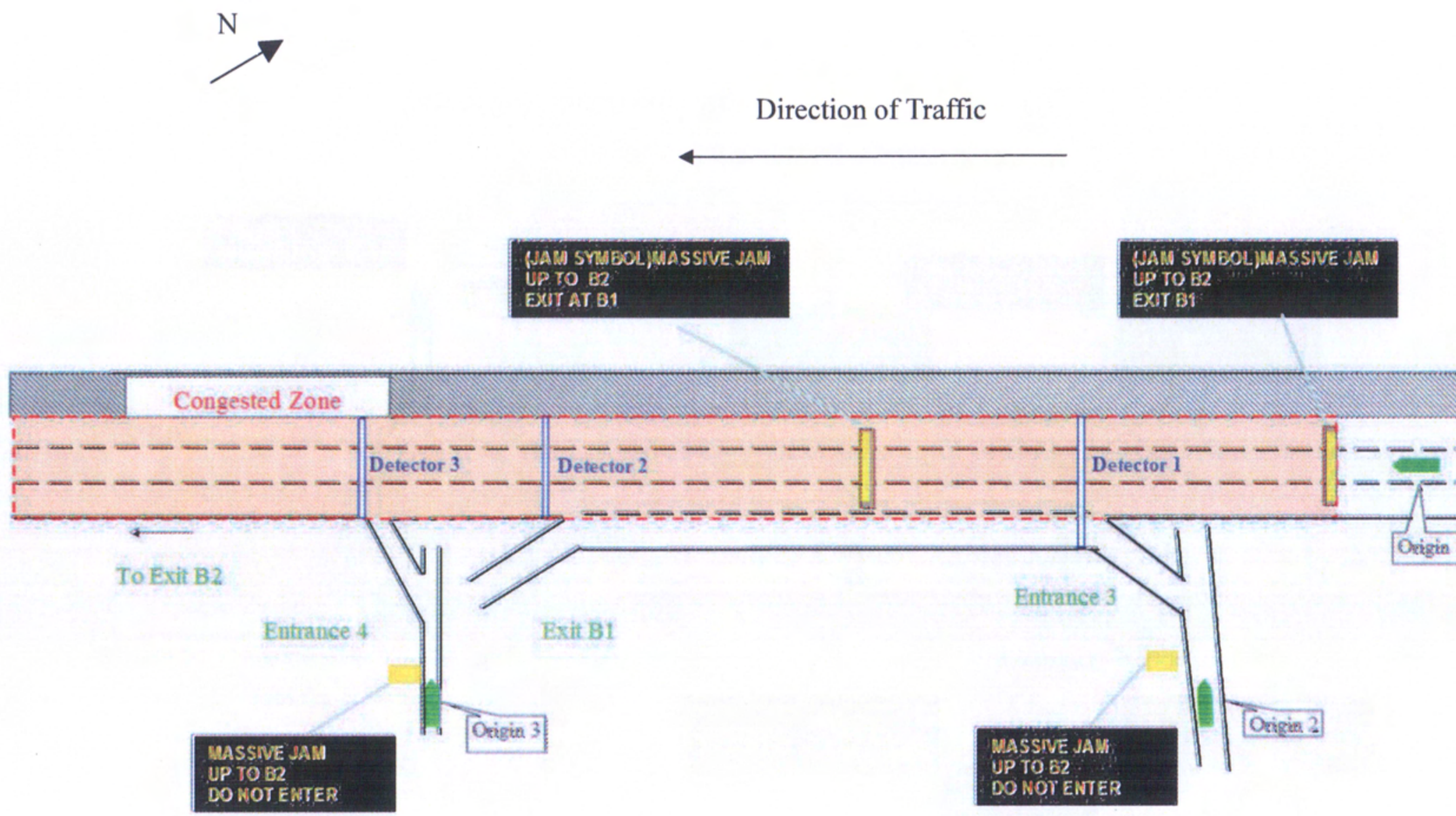

Figure 8-10 Schematic Drawing for the Scenario N3

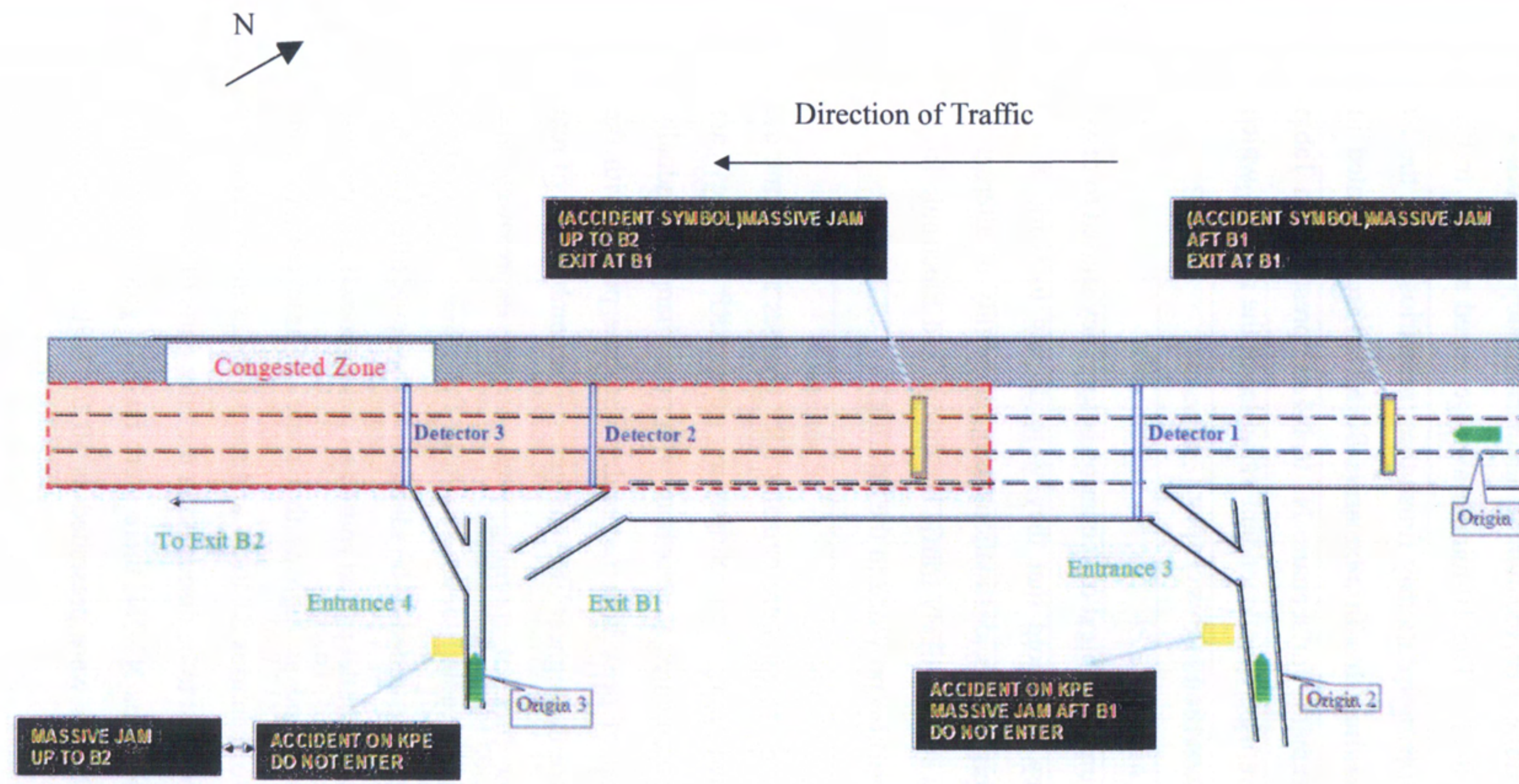

Figure 8-11 Schematic Drawing for the Scenario N4

Traffic conditions in each scenario were collected with virtual loop detectors placed on the main expressway section and near (after) each exit or entrance in the traffic simulation model. The location of the virtual loop detectors are shown in Figures 8-4 to 8-11. The 10-minute average speed and the traffic flow were measured since participants may finish these scenarios within the 10 minutes given. The measurements for scenarios S1 to S4 are presented in Table 8-1 and the measurements for scenario N1 to N4 are presented in Table 8-2. These statistics were used as independent variables in the models, which will be discussed in a later section of this chapter.

Participants were briefed on the context of scenarios before they started to drive in each scenario and they were told that they were driving to work in the morning peak hour. Their origins, destinations, the availability of alternative routes and their attributes such as likely traffic conditions and Electronic Road Pricing (ERP) charges were also provided in the briefing.

ERP charges in Scenarios S1 to S4 were existing ERP charges at the time the experiments were carried out. In Singapore, the ERP charges are cordon-based and only implemented at peak hour with rates changing gradually according to the spreading of peak hour demand. The time period with the highest demand would have the highest ERP charges. The combination of real ERP charges at different time of morning peak, on the expressway and alternative route each exit is leading to, are shown in Table 8-3. The charges on the new expressway were assumed to be identical to the route after Exit A1 since the new expressway is parallel to that route and it is expected that the new expressway will attract demand as high as that route. These combinations were randomly assigned to scenarios S1 to S4 and were used as an independent variable for model development to be discussed in the later parts of this chapter. In the KPE section in scenarios N1-N4, there were no ERP gantries installed and therefore the ERP charges were presented as $0 for KPE and alternative routes.

Table 8-1 Point Measurements of Traffic Conditions of Scenarios S1-S4

	Locations on KPE Expressway	Mean Speed (km/h) & Standard Deviation (SD)	Traffic Flow (Veh/hr)
Scenario S1	Detector 1	76.4 (SD:7.09)	2754
	Detector 2	72.43 (SD:13.76)	2394
	Detector 3	59.06 (SD:6.27)	2106
	Detector 4	45.31 (SD:14.02)	1584
	Detector 5	48.38 (SD:13.87)	1122
Scenario S2	Detector 1	67.99 (SD:6.48)	3598
	Detector 2	70.58 (SD:13.26)	4200
	Detector 3	55.77 (SD:5.67)	4032
	Detector 4	40.22 (SD:11.43)	3588
	Detector 5	25.06 (SD:12.89)	3630
Scenario S3	Detector 1	65.86 (SD:6.92)	3200
	Detector 2	72.78 (SD:15.05)	2946
	Detector 3	58.24 (SD:6.88)	2586
	Detector 4	28.01 (SD:11.48)	2358
	Detector 5	43.17 (SD:14.06)	3564
Scenario S4	Detector 1	75.27 (SD:6.30)	1557
	Detector 2	71.23 (SD:12.88)	3816
	Detector 3	57.58 (SD:6.18)	3498
	Detector 4	36.61 (SD:12.62)	3150
	Detector 5	36.73 (SD:13.35)	3054

Table 8-2 Point Measurements of Traffic Conditions of Scenarios N1-N4

	Locations on Expressway	Mean Speed (Km/h) & Standard Deviation (SD)	Traffic Flow (Veh/hr)
Scenario N1	Detector 1	54.97 (SD:14:59)	4704
	Detector 2	34.95 (SD:10.73)	3534
	Detector 3	39.67 (SD:7.32)	4579
Scenario N2	Detector 1	65.22 (SD:8.09)	4092
	Detector 2	39.49 (SD: 13.29)	2838
	Detector 3	40.83 (SD:9.27)	3504
Scenario N3	Detector 1	30.38 (SD:12.55)	4680
	Detector 2	35.02 (SD: 11.63)	3696
	Detector 3	41.42 (SD:10.08)	4920
Scenario N4	Detector 1	64.0 (SD:7.17)	4074
	Detector 2	31.07 (SD: 14.73)	2364
	Detector 3	36.67 (SD:7.87)	3246

Table 8-3 ERP Charges on Alternative Routes via Different Exits

	Exit A1	Exit A2	Exit A3	KPE
07:30 - 07:35	$0.80	$0.00	$0.50	$0.80
07:35 - 08:00	$1.50	$0.00	$0.50	$1.50
08:00 - 08:05	$1.50	$0.00	$1.50	$1.50
08:05 - 08:30	$1.50	$0.00	$2.50	$1.50
08:30 - 08:35	$2.30	$0.50	$2.50	$2.30
08:35 - 08:55	$3.00	$0.50	$2.50	$3.00
08:55 - 09:00	$2.00	$0.50	$2.50	$2.00
09:00 - 09:25	$1.00	$0.50	$2.00	$1.00
09:25 - 09:30	$0.50	$0.50	$1.50	$0.50

Although statistically it would be more desirable to allow more variations of ERP charges in different scenarios, some combinations of ERP charges may be too far away from drivers' expectation from their past experience. Since ERP charges were not the main objective of this study, they were presented to participants as contextual information targeted at making the scenarios more realistic and closer to drivers' expectation.

The traffic conditions in terms of average speeds on alternative routes were presented to the participants. The speeds are assumed speeds which varied from 30 km/h to 70 km/h, depending on road types and existing traffic conditions of the alternative routes. Participants were told that it was the most likely average speed on alternative route after KPE is open to traffic. As mentioned, the two maps in Figures 8-2 and 8-3 were extracted from a complicated urban traffic network and for readers' convenience, only available routes to destination were identified. Each of the alternative routes is part of a complicated urban network and the traffic conditions on alternative routes depend on demand from not only the new expressway, but also many other roads connected to them. Therefore, it was assumed that average speeds on each alternative route were not necessarily correlated to traffic conditions on KPE. Therefore, the variations on average speed on alternative routes are independent from the traffic conditions on the expressway in the experimental design.

Table 8-4 presents the mean of average speeds of major alternative routes. In scenarios S1 to S4 the major alternative routes are the alternative after Exit A1, A2 and A3. The alternative route after A1 is an expressway and alternative route after A3 is a semi-expressway. Therefore, the average speed is higher than alternative at A2, which is a downtown carriageway. In scenarios N1 to N4 the major alternative routes are the one after Entrance 3 (the blue route in Figure 8-3) and the alternative route after Exit B1 (the green route joined with the blue route, in Figure 8-3). Both alternative routes have wide carriageway with smooth traffic and it was assumed that the average traffic is the same on these two major alternative routes.

However, the average speed on the expressway was not presented to subjects during the briefing since drivers could obtain traffic condition information based on their own driving experience on the expressway and VMS messages regarding traffic conditions for upcoming stretch of the expressway. However, the average travel time to destination via expressway in each scenario was calculated by the traffic simulation model and used to support model development. The visual scenes and the driving experience itself may represent a complicated factor associated with subjects' decisions during simulation runs. In this study, the average travel times are treated as a surrogate variable to capture, or reflect, the traffic conditions visually perceived by the subjects during their driving runs.

Table 8-4 Means and Standard Deviations (SD) of Average Speeds on Alternative Routes Linked to Different Exits

	Means and SD Average Speeds (km/h)
Exit A1	61.16 (SD: 6.80)
Exit A2	37.44 (SD:6.23)
Exit A3	58.39 (SD:6.07)
Exit B1	58.23 (SD:6.27)

The way the scenario information was presented during the simulation run is based on the fact that drivers in real life have access to real time traffic information via VMS while they are on expressways. In most travel behaviour studies, the travel time on all alternative routes were presented explicitly in their SP survey. These SP studies were usually highly conceptual and based on the assumption that travellers had access to perfect real time travel time information through ITS. The objectives of those studies were to find out the trade-off between travel time and other attributes, such as cost and different traffic information provided. For example, Jou et al. (2005) used the bounded rationality framework to investigate the trade-off between travel time, cost and real time information in travel route switching behaviour. However, in this study, the objective is to find out the factors influencing drivers' route switching behaviour with the provision of traffic information, given that VMS have been in operations for many years. In such condition, drivers were assumed to have access to traffic information on an expressway via VMS and such information is presented in textual terms rather than numerical travel time. For other alternative routes, no real time information regarding the traffic conditions on alternative route was available. On these roads, drivers were assumed to have past experiences and knowledge about the traffic conditions, such as speeds. Therefore, although the calculated travel time based on simulation results on the expressway and the assumed average speed on alternative route were used as independent variables for model development, the travel time information on expressway and alternative route was not presented to the subjects explicitly. As a matter of fact, perfect travel time information is not usually available to drivers. Therefore, during the simulation run, on the alternative route, only average speeds were given and they were interpreted as the most likely average speed after the new expressway is open to traffic. On the expressway itself, only VMS information was given because subjects had used VMS for many years on expressways and they had experience on traffic conditions for the upcoming stretch of expressway if certain messages were shown.

A short questionnaire was also used to collect data regarding to participants' socio-economic characteristics. In addition, their familiarity with the alternative route was collected after the briefing. These data were used as independent variables to support model development as well.

8.2 Results

In total there were effective sample collected from 170 participants, of whom 136 (80%) are male and 34 (20%) are female. In terms of age, there were 131

(77%) participants aged 35 and less (with 38 participants less than 25 years old and 93 participants between 25 to 35 years old) and 39 (23%) participants aged over 35. All participants were educated and 134 (79%) of them had tertiary education.

The drivers' diversion behaviour in each scenario was recorded in a non-obtrusive manner. The aggregated results as the number of diversion and percentages of diversion at each decision are summarised in Tables 8-5 and 8-6 for the scenarios S1 to S4 and for the scenarios N1 to N4, respectively.

Table 8-5 Aggregated Diversion at Each Decision Point for Scenarios S1 to S4

Scenario	Traffic conditions	Incident attribute	Entrance 1	Exit A1	Exit A2	Exit A3	Entrance 2
S1	Massive Jam	Accident	6 (33.3%)	15 (25.5%)	19 (22.2%)	27 (77.1%)	14 (77.78%)
S2	Massive Jam	peak hour	3 (21.4%)	15 (41.7%)	8 (38.1%)	8 (61.5%)	5 (45.5%)
S3	Jam	Accident	2 (16.7%)	4 (11.1%)	5 (15.2%)	20 (74.1%)	6 (46.2%)
S4	Jam	peak hour	4 (23.5%)	11 (18.3%)	11 (22.4%)	22 (57.9%)	14 (73.7%)
SA	Slow Traffic	Accident	N/A	2 (4.26%)	1 (2.22%)	18 (40.91%)	N/A

As shown in Table 8-5, the results obtained from the scenarios S1 to S4 suggest Exit A3 is an attractive alternative route, with high diversion rates in all cases. Much lower diversion rates were observed at other exits leading to other alternative routes, except scenario 2, in which the queue extended to Exit A1 and higher diversion rate was observed at Exit A1 and Exit A2. The scenario SA is the scenario reported in Chapter 6. About half of the samples were randomly selected to pool into the data to study the route switching behaviour on expressway. Since that scenario is mainly designed for study of lane changing behaviour in presence of LCS, drivers' were not asked to start their run at entrance of expressway.

The results of scenarios N1 to N4 are presented in the Table 8-6. Some scenarios in which the VMS message "SLOW TRAFFIC" was shown are not reported due to its relatively smaller sample size. The results suggested that in cases where drivers were already on KPE and that the traffic information was "Massive Jam", the observed diversion were higher than when the message "Jam" was shown.

The statistics shown in Tables 8-5 and 8-6 are targeted to give readers an impression on the magnitude of diversion rates in each scenario. The factors affecting the diversion results, however, are not conclusive based the descriptive statistics since there may be different factors contributing to the observed diversions.

Table 8-6 Aggregated Diversion at Each Decision Point for Scenarios N1 to N4

Scenario	Traffic conditions	Incident attribute	Entrance B1	Exit B1	Entrance B2
N1	Jam	Peak hour	9 (60.0%)	14 (41.2%)	15 (71.4%)
N2	Jam	Accident	4 (57.1%)	13 (54.2%)	16 (76.2%)
N3	Massive Jam	Peak hour	7 (58.3%)	15 (60%)	18 (90.0%)
N4	Massive Jam	Accident	10 (83.3%)	16 (64.0%)	21 (91.3%)

The main purpose for the above section is to provide background on the data collection before the models are presented. The values and percentages presented in Table 8-5 and 8-6 provide sense of actual magnitude of diversion. There are some unique features of this study which distinguishes it from other conventional SP studies. Firstly, the traffic network used is a complicated urban network rather than simple parallel suburban roads. Secondly, the participants are experienced users of VMS and they are familiar with the existing VMS message scheme. Thirdly, the data were collected with a traffic-driving simulator and this is perhaps the first time a full-scale driving simulator is used for route switching study. Lastly, unlike many studies that the travel times on alternative route were presented, in this study the travel times were not presented explicitly. In the following section, the modelling of the drivers' switching behaviour in response to VMS will be presented. The research focus is more on the diversion responses to the traffic information schemes rather than the human factor aspects of displaying these messages. Therefore, the impacts on how the messages were displayed, for example, in different fonts or different colours, in different pages, are not within the scope of this research.

8.3 Modelling of Drivers' Route Switching Behaviour in Response to VMS Messages

The route switching behaviour in response to VMS messages is a dynamic process. A usual optimal route may turn out to be less than optimal as a result of incidents and spreading of congestion. In the experimental studies, drivers were exposed to a number of decision points (Exits) while driving towards their destinations via the expressway. Therefore, a driver makes a series of binary choices between the expressway and the alternative route to the destination at consecutive decision points according to the observed traffic conditions and traffic information provided. The number of decisions made by different individual is a variable since the later decision will not be available to drivers who make a decision to switch to alternative route at early decision points.

In order to capture drivers' switching behaviour along the expressway in the presence of VMS messages and traffic conditions, the utility maximisation decision rule is assumed in this study to formulate binary probit models. The data sets collected in this study contain observations on multiple binary choices observed for each individual in a run and therefore the data sets may be considered as panel data. The random effects probit models (Hsiao, 1986) are used since they allow modelling of panel data sets so potential correlation of a sequence of choices can be tested. Further, take a probit form, the random effects probit model assumes heterogeneity among different drivers.

The model is given as follows:

$$Y_{it}^{*} = \beta x_{it} + \varepsilon_{it}, \qquad i = 1,\ldots,N, \quad t = 1,\ldots,T, \tag{8-1}$$

The i indexes individuals and t indexes time period. N is the number of individuals and T is a variable to indicate the number of consecutive decisions made for each of the individual. For example, for a driver switching to alternative route at the first decision point, they are not available to subsequent decisions along KPE and the variable T is equal to 1, while variable T for drivers switching at the second and third decision points are 2 and 3, respectively. k is the number of attributes and the x_{it} is a $1 \times k$ vector of exogenous variables and β is a $k \times 1$ vector of coefficients. The disturbances ε_{it} are generated by μ_i and v_{it}:

$$\varepsilon_{it} = \mu_i + v_{it} \tag{8-2}$$

μ_i is the unobserved heterogeneity error and assume to be normally distributed with zero mean and variances σ_μ, that is, $\mu_i \sim N(0,\sigma_\mu^2)$; v_{it} is the stochastic term in the model and $v_{it} \sim N(0,\sigma_v^2)$. μ_i and v_{it} are mutually independent and $\varepsilon_{it} \sim N(0,\sigma^2)$

Y_{it}^{*} is an unobserved latent variable. One can define an observed random variable which can describe Y_{it}^{*} in the following manner:

$Y_{it} = 1$ if $Y_{it}^* > 0$ and 0 otherwise (8-3)

Let $\sigma^2 = \sigma_\mu^2 + \sigma_v^2$ and ρ is the correlation between successive disturbances for the same individual, $\rho = corr(v_{it}, v_{it-1}) = \sigma_\mu^2 / \sigma^2$ and impose the normalisation $\sigma^2 = 1$.

The $Y_i = \lfloor Y_{i1}, Y_{i2,\ldots,} Y_{iT} \rfloor$ is the observed sequence for individual i

and let $\tilde{\mu}_i = \mu_i / \sigma_\mu$,

$$P(Y_i) = \int_{-\infty}^{\infty} \prod_{t=1}^{T_i} \Phi\left\{\left[(X_{it}\beta / \sigma_v) + \tilde{\mu}\left(\frac{\rho}{1-\rho}\right)^{1/2}\right][2Y_{it} - 1]\right\} * f(\tilde{\mu}_i) d\mu_i \quad (8\text{-}4)$$

The likelihood function for the observed sample of Y_{it}'s is:

$$L = \prod_{i=1}^{N} P(Y_i) \quad (8\text{-}5)$$

Which can be maximised with respect to β / σ_v^2 and ρ, to obtain consistent and asymptotically efficient estimators.

In the applications of random effects probit models in this study, the x_{it} is a $1 \times k$ vector of exogenous variables, which refer to attributes associated with the KPE and the alternative route, for example, VMS information, distances, ERP charges and travel times. Table 8-7 listed all the independent variables used for the probit models.

Table 8-7 Summary of Independent Variables

Independent Variables	Description
Gender	A binary variable, "1" if female and "0" if male.
Age	"1" if age is less than 25 "2" if age is between 25 to 34 years old "3" if age is more than 35
Edu	A binary variable to indicate education level, "1" if participant is a university graduate and otherwise "0".
Unfam	A binary variable, indicating unfamiliarity with alternative route. Unfamiliarity = 1 if a participant is unfamiliar with the alternative route, otherwise equals to "0"
Distance (Km)	The difference of distance to destination at each decision point between the expressway and alternative routes. The distance difference is presented with variables DIS_GAIN and DIS_LOST. If the value of KPE is lower than alternative route, the variable DIS_GAIN equals the difference and DIS_LOST equals to 0. If the value of KPE is higher than alternative route, the variable DIS_LOST equals the difference and DIS_Gain equals to 0. if the difference equals to 0, both DIS_GAIN and DIS_LOST equals to 0.
ERP (Singapore dollar, which equals to 1.5 US dollar)	The difference of ERP charges at each decision point between the expressway and the alternative route. The ERP difference is presented with variables ERP_GAIN and ERP_LOST. The definition of ERP_GAIN and ERP_LOST are similar with variables DIS_GAIN and DIS_LOST.

Travel Time: (Seconds)	The difference of average travel time at each decision point between the expressway and alternative route to destination. The average travel times on the expressway are estimated with the simulation model and the average travel times on alternative routes are estimated with the measured distances and the assumed average speed on the alternative routes. The travel time difference is presented with variables TT_GAIN and TT_LOST. The definition of TT_GAIN and TT_LOST are similar with variables DIS_GAIN and DIS_LOST.
Pace (Minutes/km)	Pace is the reciprocal of speed and is used to indicate the traffic conditions on KPE at decision points. Pace were average values collected by the traffic simulation models at 10 minutes intervals
Flow (Veh/h)	Traffic flow at decision point on KPE in the traffic simulation model.
VMSMJAM	A binary variable to indicate whether the VMS message "MASSIVE JAM" and advisory information is displayed. Yes =1 and No =0 (As mentioned, advisory information was only displayed when the message "MASSIVE JAM" was displayed.)
VMSJAM	A binary variable to indicate whether the VMS message "JAM" is displayed. Yes =1 and No =0
VMSSLOW	A binary variable to indicate whether the VMS message "SLOW TRAFFIC" is displayed. Yes =1 and No =0
VMSACCID	A binary variable to indicate whether VMS message regarding accident is displayed on VMS. If the

	congestion is caused by an accident, the accident is reported on VMS, VMSACCID = 1. If the congestion is caused by peak hour demand and no accident is reported as the reason for the congestion, VMSACCID = 0.
VMSUPTO	A binary variable to indicate whether information "UP TO" is displayed on VMS "UP TO" = 1 and "AFT(after)" = 0
ATENTER	A binary variable to indicate whether the switching decision is made at expressway or entrance of expressway ATENTER = 1 if the decision is made at entrance of expressway, otherwise ATENTER=0

The following independent variables: Pace, Flow, VMSMJAM, VMSJAM, VMSSLOW, VMSACCID, VMSUPTO are specific to the expressway KPE. As discussed, the ERP is contextual information and therefore is based on real charges. The Distances were measured using a digital map system. The travel time, as mentioned before, were estimated differently on the expressway and on the alternative route. As discussed in Chapter 4, the traffic simulation model was calibrated and therefore the travel time over expressway sections should be a close approximation of the real travel times. The potential errors in the estimation of travel time can be captured by the error term of the discrete choice model, as reviewed in Chapter 2. The travel time on the alternative route was estimated based on an assumed average speed and measured distances. The travel time on alternative route was not shared with participants. As mentioned, since the traffic network is part of a complicated urban traffic network, therefore, it is not necessary that the traffic on expressway is correlated with traffic on the alternative routes. Therefore, the traffic conditions on the expressway and the alternative route are assumed to be independent.

Based on the collected data, a model was developed to capture factor affecting drivers' route switching behaviour and established to test the potential correlation of the decision made at a series of switching points. A statistical analytical package named LIMDEP (Greene, 2000) was used to estimate the probit models. In LIMDEP, the random effects model is estimated with Butler and Moffitt's derivations (Butler and Moffitt, 1982). The algorithm is the Davidon Fletcher Powell (DFP) algorithm (Fletcher and Powell,1963) and the BHHH estimator (Berndt, et al., 1974) is used for the asymptotic covariance matrix. The details of estimation of random effects model is presented in Appendix III.

Taking a straightforward binary form, the probit models provided good insights on data collected. The estimated coefficients of statistical significant attributes are shown in Table 8-8. The descriptive statistics and correlation matrix of independent variables are shown in Table 1 and Table 2 of Appendix IV, respectively. Marginal effects of each statistical significant attributes are also shown in Table 8-8. The marginal effects are changes in probabilities induced by 1 unit change in each attribute, which give a sense of actual magnitude of impacts of attributes on the probability of diversion. This is especially helpful to understand impacts of different VMS messages since they are dummy variables and the marginal effects of them are differences of diversion probabilities between with presence of the messages and without presence of the messages. Estimates of the marginal effects are computed at the overall means of the data sets.

Table 8-8 Estimation Results for Complete Data Sets

Variables	Coefficients (t value in parenthesis)	Marginal effects (t value in parenthesis)
CONSTANT	-1.424 (-4.63)	-0.372 (-4.61)
VMSMJAM	1.531 (9.40)	0.400 (9.69)
VMSJAM	1.069 (6.87)	0.280 (7.13)
VMSSLOW	0.802 (4.34)	0.210 (4.28)
VMSACCID	-0.261 (-2.63)	-0.068 (-2.58)
PACE	0.416 (2.04)	0.109 (1.95)
TT_LOST	0.005 (2.20)	0.001 (2.08)
TT_GAIN	-0.002 (-4.78)	-0.0004 (-4.80)
DIS_GAIN	-0.243 (-3.79)	-0.06 (-3.76)
ATENTER	0.649 (6.45)	0.170 (6.18)
UNFAM	-0.299 (-2.71)	-0.078 (-2.78)
ρ	<0.001	
Number of observations	1298	
L(0)	-846.82	
L(β)	-626.63	
1-(L(β)/L(0))	0.26	

The estimated ρ is less than 0.001, which suggests that no discernible evidence of correlation for successive decisions is found and the estimate of ρ is negligible. In that case, the model is exactly the same as a base binary probit model without considering the correlation of successive decisions.

CONSTANT is negative, which implies that overall there is a natural tendency for drivers to use KPE and not to switch to alternative route.

VMSMJAM, VMSJAM, VMSSLOW are positive and significant. It suggests that the VMS messages "Massive JAM" or "JAM" and "SLOW TRAFFIC" could affect drivers' route switching behaviour. It is noted that the absolute value of the coefficient of "VMSMJAM" is greater than "VMSJAM" and value of "VMSJAM" is greater than "VMSSLOW", which suggests that message reporting a more extensive congestion would result in higher diversion rate. As reported in Chapter 5, drivers have difficulties to relate the message to the actual queue lengths and they may interpret these messages as speeds rather than queue lengths. However, even though drivers may interpret the messages in a different way defined by the transport operator, drivers more or less can relate the messages provided with the severity of congestion based on their past experience. Therefore, in terms of route switching, when messages describing different extent of congestion are provided, drivers can differentiate the difference and their responses are different. The marginal effects indicate that when these messages are shown, the difference in probability of diversion could be up to 40%, as compared with the same condition without these messages being shown. These results suggest that VMS messages showing extent of congestion would be effective measures to divert traffic from expressways.

VMSACCID is negative and significant, which suggest that when the congestion is caused by an accident and the message reporting the accident is displayed, drivers were more likely to use the expressway rather than alternative route. The possible explanation is that accident on expressways usually was detected and cleared promptly in Singapore. Therefore, the congestion caused by accident cleared much faster than congestion caused by peak demand. In many cases, by the time drivers reached the location of the accident, the accident was already cleared. Therefore, such past experience may be the reason that drivers' are more likely to use expressway if the congestion was caused by accident rather than peak demand. However, the marginal effect of VMSACCID is only -6.8%, which suggests that although the message reporting the accident is statistically significant, the impacts are moderate, as compared with messages indicating traffic queues.

PACE is positive and significant. As mentioned, PACE is the reciprocal of speed and is used to indicate the traffic conditions on the expressway at decision points. This positive sign suggests that the higher the unit travel time on the expressway at decision points, the more likely drivers would switch to alternative route. This result suggests that other than VMS messages, drivers also rely on their own observation at decision points to make route switching decisions.

TT_GAIN is negative and TT_ LOST is positive and both variables are significant. This result implies that if the alternative route takes longer travel time to destination than KPE, the less likely a driver would divert from expressway. In case that the alternative route takes shorter time than the expressway, the more likely a driver would divert to the alternative route.

DIS_GAIN is negative, which implies that if an alternative route is longer than the expressway, the less likely a motorist would switch to the alternative route.

ATENTER is positive, which suggests that at entrances of the expressway, drivers are 17% more likely to switch to alternative route. The possible reason is that at entrance traffic conditions on expressway is not visible to drivers and the uncertainties on traffic conditions make the expressway less attractive.

UNFAM is negative, which suggests that if drivers are unfamiliar with the alternative route, it is less likely they will switch to alternative route.

Above are the independent variables which are statistically significant. However, there are variables which are not significant and there are less evidences to support that these variables have impacts on drivers' route switching behaviour. Those variables are:

GENDER, Age, EDU are not significant (t=0.822, t=-0.933 and t=0.50 respectively), as shown in Tables 3 to 5 in Appendix IV. Although there is no evidence to support that drivers of different gender, age and education level have different route choice switching behaviour in this study, given the proportion of respondents represented (see Section 8.2), the impacts of these socio-economic variables are inconclusive at this stage of the study.

ERP_GAIN and ERP_LOST are not significant (t=0.37 and t=-1.29), as shown in Table 6 and Table 7 in Appendix IV. As discussed before, the ERP charges are contextual information and real charges are used. The ERP charges thus may not be statistically desirable for estimation of discrete choice models. Therefore, although the ERP charges are not significant in this study, it is not conclusive on whether ERP charges have impacts on drivers' route switching behaviour.

DIS_LOST is not significant (0.41), as shown in Table 8 in Appendix IV. This result suggests that if alternative route is shorter than the expressway, it is not necessarily that a driver is more likely to switch to alternative route.

FLOW is not significant (-0.75), as shown in Table 9 in Appendix IV. This result suggests that the flow rate at decision points on expressway may not affect drivers' route switching behaviour. The possible explanation is that the flow rate may not be a good representation of level of congestion, as a low flow rate could happen at a free flow condition with lower demand or a congested condition with constraint of capacity in an incident context, which may result in different diversions.

VMSUPTO is a special case. As mentioned, the VMS message "UP TO" is only displayed when drivers is within the congestion and PACE is high. Therefore the variable VMSUPTO is highly correlated with the variable PACE (0.72, if 1 is considered as perfect correlation). Therefore, as shown in Table 10 in Appendix IV, the variable PACE becomes insignificant when VMSUPTO is introduced. Therefore, the impacts of VMSUPTO is not conclusive in this study

The modelling results reveal that the following factors affect drivers' route choice in road congestions: VMS messages, traffic conditions on decision points, attributes on alternative routes as compared with the expressway and the location of the driver. These results have significant implications on operations of ATIS in an urban area. The messages reporting magnitude of congestion are the most effective messages and displaying them at VMS on arterial roads leading to expressways are more effective than displaying them VMS on expressways.

8.4 Summary

In this chapter, the traffic-driving simulator was used to investigate drivers' route switching behaviour in the presence of VMS information in road congestion. A number of complicated scenarios were simulated and drivers' route switching behaviour was systematically studied.

The traffic-driving simulator proved to be an excellent data collection tool in the study of drivers' route switching behaviour. The traffic-driving simulator allow scenario to be realistically presented in a windshield perspective in real time. Such level of fidelity was never offered in past similar studies.

The results were presented with descriptive statistics and further analysed with discrete choice models. The modelling results reveal that the following factors affect drivers' route choice in road congestions: VMS messages, traffic conditions on decision points, attributes on alternative routes as compared with the expressway and the location of the driver. These results are consistent with some of past studies (Wardman et al., 1997; Bonsall and Palmer, 1999). However, it is inconclusive whether other factors, such as ERP and drivers' characteristics would significantly affect driver route switching behaviour in road congestion because the lack of variations of these factors. It is expected that in future studies, samples comprising other socio-economic groups could be collected to address this issue.

The consistency of results with past studies suggests that the traffic-driving simulator is able to capture the effects of some factors affecting drivers' route switching behaviour.

CHAPTER 9. CONCLUSION

In this study, a traffic-driving simulator has been developed and tested through calibrations and applications in different studies on drivers' behaviour in the presence of ATIS information. The traffic-driving simulator was an integration of a traffic simulator and a driving simulation. Through calibration, the system is able to realistically present complicated scenarios in which ATIS is in operation in different incident contexts. Drivers are allowed to drive in such an environment and their driving behaviours are captured in great detail. The applications of the traffic-driving simulator in this study have shown that the traffic-driving simulator can provide a critical observation basis for studies of driving behaviour in the presence of ATIS in incident context. Firstly, the traffic-driving simulator can be used to study drivers' behaviour in extreme conditions which may never be investigated, or reproduced, in the field. As demonstrated in this study, the system can be used to study the drivers' responses to emergency evacuation. Secondly, the traffic-driving simulator can capture drivers' behaviour in great detail. As presented in the study of drivers' behaviour with the use of LCS in a lane closure context, drivers' lane changing behaviour and speed choice behaviour were captured in great detail. Thirdly, the traffic-driving simulator can allow optimal experimental control and data collection at different levels. As shown in the study of drivers' route switching behaviour in road congestion, the variations of certain variables were controlled in scenarios presented. The network statistics, such as traffic conditions at decision points and travel times over on the expressways, were then collected. With all the effects, the data collected can be a rich pool of information source to support the development of discrete choice models, as illustrated in the modelling results.

The following sections discuss the contributions from this research, outline the empirical findings, highlight the significant findings, as well as the limitations of this study and identify directions for future research.

9.1 Contributions

The major contributions from the study can be classified as methodological and substantive. The methodological contribution refers to the development of the traffic-driving simulator and the applications of the traffic-driving simulator in different studies, which were carried out with SP survey techniques in many cases. The substantive contribution refers to the examination of driving behaviour in the presence of ATIS in different incident contexts.

The development of the traffic-driving simulator significantly contributes to the data collection to support different travel and driving behaviour studies. The simulator can replicate an actual driving environment in which the dynamism of traffic conditions and traffic information broadcast schemes can be realistically presented in a real time environment. This greatly enhances the realism of scenarios which cannot be presented by traditional travel or driving simulator. Some attributes, such as speeds at decision points, are presented in a natural way rather than an artificial measure in numerical numbers. In addition, the traffic-driving simulator can allow data collection at different levels of attributes. A subject's driving behaviour, for example, the route choice, lane choice, etc. can be collected in a non-obtrusive manner. Traffic network statistics, such as traffic flow and travel time are readily available as well. Finally, the traffic-driving simulator allows optimal control of experiments. For example, experimental variables can be varied in designed scenarios and repeated experiments. With all of these advantages, the system is able to collect data which cannot be systematically collected by traditional data collection methods, such as SP surveys, field experiments, conventional travel or driving simulators. Therefore, some research issues, such as behavioural responses to ATIS in this study, which previously could not be systematically investigated due to limitations in data collection, can be investigated with the traffic-driving simulator.

The applications of the system in studies of drivers' driving behaviour with presence of ATIS in different incident contexts also have some methodological contributions. Firstly, all the experiments are conducted in a real time environment, which means that the simulation time is equivalent to the actual time in real life. Such an experiment control was not achieved by many studies, especially in the study of drivers' route choice or route switching behaviour. Presenting the scenarios in real time allows drivers to experience the actual delay in the scenarios and their decisions are made in real time as well. Such enhanced realism greatly improves the realism of survey scenarios in studies of route switching behaviour and respondents do not have to imagine the scenarios.

In addition to the methodological contribution, this research investigates the following substantive issues that have not been systematically investigated in previous studies. Firstly, drivers' actual driving behaviour in the presence of LCS and VMS in an accident context with lane closure has not been studied before. In the previous research, only the understanding to LCS signs and the corresponding aggregated effects were investigated. The understanding of LCS may not be a good representation of actual behaviour since what drivers have said may not be what they would do. Aggregated effects of LCS were critically dependent on individual responses to LCS which was based on assumptions in these studies. The traffic-driving simulator is capable of capturing actual behavioural responses in the presence of LCS in a controlled experimental environment. Secondly, drivers' responses to emergency evacuation plans in a road tunnel were not examined in studies reported in the public domain. A lot of studies focused on the fire evacuation in buildings. However, drivers' responses to emergency evacuation in a road tunnel fire received less attention. This research is a pioneer study which tries to fill the gap. Thirdly, although there were a lot of research efforts on investigation of drivers' route switching behaviour, few of them were carried out on a full scale driving simulator which offers a windscreen perspective and a real time driving environment. The most advanced studies so far reported, in the form of a travel simulator, can only offer a presentation of map and static pictures of traffic at decision points (Bonsall, 2004). The effects of ambient traffic therefore could not be fully captured. Furthermore, the travel simulator surveys were not carried out to investigate the behaviour in real time. The investigation in this study therefore is a significant improvement. Furthermore, the population surveyed in this study was experienced users of ATIS and their responses are expected to be a good reflection of their actual behaviour in daily commute.

9.2 Significant Findings

The data collected in different experiments was analysed with statistical tests and discrete choice models. The empirical results have shown that there are reasonable relationships between drivers' driving behaviour and the attributes of scenarios, such as ATIS information being provided and traffic conditions. This further shows that the traffic-driving simulator is able to capture drivers' responses to the ATIS information in different contexts. The empirical findings in this research are significant to provide behavioural inputs into the design and operation of an ATIS system, which will be discussed as follows.

9.2.1 Lane Changing Behaviour in a Road Accident with Lane Closure

The analysis on the mean longitudinal clearance reveals that the LCS display scheme is effective not only in inducing an early diversion of traffic, but also in reducing hazardous lane changing. LCS is effective in reducing lane changing near bottlenecks and drivers are able to perform a smoother and safer lane changing manoeuvre. However, it should be noted that there were about 40% of drivers who did not comply and proceeded beyond the red cross LCS. This finding has significant implications on the design and operation of LCS schemes to accident management. Although in general the LCS is effective, the compliance level suggests that in the design of such system, a greater buffer for lane changing might be needed because not all drivers comply with the instructions by LCS. On the other hand, the operator may need to provide more education to drivers on the proper actions when seeing different LCS symbols.

9.2.2 Driving Behaviour in the presence of ATIS in Emergency Evacuation

The study results indicate that when only visual messages were shown in the emergency evacuation scenarios, some undesirable responses occurred. This was observed in a simulated tunnel fire scenario, where drivers continued to drive until the fire and smoke was seen. It was observed in the experiment that drivers stayed in their cars, and fewer drivers used the emergency exits. These results suggest that visual messages by signage may not be sufficient to provide compelling information to define the threat of a fire incident, if no other cue of fire is received by the drivers. Drivers may overlook or misunderstand the visual messages provided by the signage. However, when audio messages were broadcasted by radio, together with the visual information provided by signage, all participants followed the instruction to either take the exit slip road or to abort their cars and escape from the emergency doors. This result suggests that the audio messages are more indicative and may provide indicative information to help drivers to define the fire and evaluate the threat. Therefore, proper actions of egress would be prompted in time with the audio message.

However, there is some evidence to indicate that when audio information is not consistent with the site-specific visual information, drivers would not follow the instructions by the audio information until the consistent visual information is seen. These results suggest that even with a radio announcement, drivers may still need the site-specific information on the signage as guidance. If the audible and visual information are conflicting, drivers may ignore the instruction by audio information until they receive confirmation via site specific visual information.

The last point to address is that when the responses to the two evacuation plans are compared, it turns out that it would be more difficult to ask drivers to stop and abort their cars, than to ask them to take the slip road and leave the tunnel, in cases when only visual guidance information was provided. However, when the audio RBBI information was provided, there were no significant differences in the drivers' responses to the two evacuation plans. These results again suggest the importance of the audio messages.

The empirical evidence provided in this study provides essential behavioural inputs for road tunnel evacuation planning. To provide information to effectively evacuate drivers' from a road tunnel, the provision of audio information with the site-specific visual information is essential. However, the audio information must be consistent with the visual information. Otherwise, the evacuation plan may become less effective because drivers' may ignore the audio information until they receive the confirmation from the visual information.

9.2.3 Drivers' Route Switching Behaviours in the presence of ATIS Information in Road Congestion

The modelling results reveal that the following factors affecting drivers' route choice in road congestion: VMS messages, traffic conditions on decision points, attributes on alternative routes as compared with the expressway and the location of the driver. These results have significant implications on operations of ATIS in an urban area.

The VMS messages describing the extent of congestion are found to be significant to affect drivers' route switching behaviour. The message reporting a more extensive congestion would result in higher diversion rate. These results imply that through years of operation, even though drivers may interpret the messages in a different way as understood by the transport operator, drivers more or less can relate the messages provided with the severity of congestion based on their past experience. Therefore, in terms of route switching, when a message describing different extents of congestion is provided, drivers can differentiate the difference and their responses are different.

The VMS message describing the cause of congestion is found to be a significant factor affecting drivers' route switching behaviour as well. If the reported cause of the congestion was accident rather than the peak hour demand, there was less diversion observed. This result reflects a fact that in Singapore accidents on expressway were usually cleared in a short time with the vehicle recovery crew arriving within 8 to 15 minutes (One Monitoring, 2007) and in many cases when drivers reached the reported accident location, the accident has already been cleared. Such an experience may be the reason that drivers are less likely to divert when the congestion was reported to be caused by an accident.

Above results on effects of VMS messages imply that drivers' route switching behaviour is affected by their own experience on using VMS. Therefore, providing reliable information is essential to operation of VMS. Otherwise, drivers may lose confidence on the information provided on VMS, which would become less effective.

Other than VMS messages, the speeds on expressway at the decision points are found to be a significant factor affecting drivers' route switching behaviour. These results imply that drivers would make their route switching decision not only based on the VMS information provided, but also their own observation at decision points. However, it should be noted that there is no evidence to support that traffic flow rate at decision point is a significant factor. Therefore, by providing static pictures showing the density of traffic on decision points, as it was done in SP surveys and travel simulator surveys, may not be sufficient to capture the dynamism of the scenarios and drivers' responses may be less realistic.

The attributes of alternative roads, such as travel time, distance on alternative route, as opposed to travel time and distance on KPE, drivers' unfamiliarity on alternative route, are found to be significant factors affecting drivers' route switching behaviour. These results suggest that drivers' route switching behaviour is not only related to traffic conditions and VMS messages on the expressway, but also related to the attributes of the alternative route. Therefore, forecasting impacts of VMS should be site-specific since at each decision point the alternative route available may not be the same.

The locations of drivers are found to be a significant factor affecting the route switching behaviour. If a driver makes his or her switching decision at entrances of expressways, it is more likely that he or she would divert to an alternative route, compared with a similar condition on expressways. This result suggests that it is much easier to divert drivers before they enter expressways. Therefore VMS at the entrance of expressways are more effective and should be more effectively utilised.

9.3 Limitation and Future Extensions

Through the applications, the system developed in this study has been shown to be an effective way to collect data to study drivers' driving behaviour, especially in the presence of ATIS. The data collected can help designer and operator of ATIS understand the likely responses of drivers to ATIS information provided in different incident contexts. However, there are some limitations of the systems and future studies may be required to address these limitations.

9.3.1 Limitations

Firstly, the simulation sickness is a limitation in applications of the system in a driving behaviour study. Simulation sickness is a side effect that makes the simulation less attractive in applications in many areas. Simulation sickness can not be totally removed but may be reduced by the design of simulation system or experiment procedures. Future research on development of the traffic-driving simulator and experiment procedures for the purposes of reducing simulation sickness are therefore required. Furthermore, simulation sickness may be a potential factor that might affect drivers' driving behaviour in such a system. However, in this study, since those scenarios in which drivers' reported simulation sickness was removed, the effects of simulation sickness were not investigated. In the future applications of the system, the experimenter may measure drivers' simulation and investigate the impacts of the simulation sickness on their driving performance.

Secondly, the samples used in traffic-driving simulator survey were opportunity samples comprising subjects who were available, which turned out to be mostly young, male and tertiary educated respondents. In Singapore, car ownership is restricted and there were considerable difficulties to invite experienced drivers to the laboratory to participate in the driving survey. The control on subject selection was therefore quite limiting in this study. Another possible limitation is that the subjects participating in this study may be the group which was least affected by simulation sickness. The reader should therefore be mindful of the limitations in sample selection when generalising the study results to the Singapore population.

Thirdly, the research results should be validated and with field observation after KPE is open to traffic. In the current study, the research objectives are to understand the likely behaviour in different hypothetical situations. Traffic simulated on the KPE was based on observations of traffic conditions on one of the existing expressways. As discussed, although the KPE is used as the infrastructure for investigations, it is expected that the results can be generalised into other existing expressways, especially for the study of route switching behaviour with VMS messages. If that is the rationale behind the assumption, it seems that using an existing expressway may produce convincing results. However, the advantage to use KPE rather than existing expressway as the infrastructure is that the new information devices and schemes that are used for road tunnel accident management and emergency evacuation can be investigated with the same model that is developed. Based on such assumptions of traffic conditions on KPE, there might be potential estimation error on the traffic statistics, such as travel times. Even though the errors can be captured to a certain extent by the use of discrete choice models, it may be more prudent that the model results be validated with field observations before they are practically used.

Fourthly, as reviewed in the second chapter, it is extremely difficult for a driving simulator to achieve absolute validity while relative validity is warranted. However, relative validity is sufficient for most study objectives, which is the case in this study. One of the objectives of this study is to understand the likely responses of drivers in different incident contexts, absolute validity is therefore not necessary for this study. For example, in the study of driver route switching behaviour, only the sign and relative magnitudes of the estimated coefficients matters. Therefore, despite the limitation, the traffic-driving simulator is a good observation basis for objectives of this study. In the future works, it may be promising to combine the driving simulator results with field observation. Such effort will combine the flexibility of the traffic-driving simulator with reliability of observations. The model developed with the combined data therefore can be used in traffic assignment models or micro-simulation models to study the aggregated impacts of ATIS on network traffic. The results will have far-reaching implication on the design and operation of ATIS to optimise the efficiency of current traffic system.

Finally, although the traffic-driving simulator is shown to be a good basis for observation for the scope of this study, the applications of the system in other studies should be carefully decided based the study objectives and required accuracy. The traffic-driving simulator is not a panacea for all the traffic problems and it is only an alternative of field studies. In some traffic engineering domain, especially safety, which requires accurate measurement to decide critical design parameters, the application of a driving simulator is not recommended. At the current stage of development, a driving simulator is only suitable for those studies targeted to understanding the likely driving behaviour, in cases where field studies are not feasible to carry out.

9.3.2 Future Extensions

This research is of an early stage of investigation on drivers' responses to ATIS with the traffic-driving simulator. It took tremendous effort to develop the simulator system and use the system to collect all the data presented in this thesis. As discussed above, there were considerable difficulties to invite experienced drivers to the laboratory to participate in the driving survey. Therefore, the scope at this stage was to establish the traffic-driving simulator and use the system to study drivers' responses to ATIS in a new expressway for some of the most important aspects. Data collected with the traffic-driving simulator were presented and interpreted as they were in a descriptive manner before any advanced data analysis can be carried out in the future. There will be some interesting and promising extensions, based on traffic-driving system developed as a data collection instrument and data collected in this study.

Firstly, more driving experiments or surveys can be carried out to extend the current study to different circumstances or a different group of subjects. For example, for the study on effects of LCS, more congested scenarios can be simulated and tested. The results can be compared with the free flow scenarios tested in the study and the effects of congestion can be known. More female and older drivers can be invited to participate so impacts of ATIS on different gender and age can be conclusive.

Secondly, the data modelling was somehow limited by non-availability of analytical tools. A random effects binary probit model may be a wonderful specification to process. However, the estimation package LIMDEP may not be the best tool to estimate such a model. The likelihood specification in the random effects binary probit model pre-conditions the number of decision points, which should be undefined and random. This is a statistical issue not easily addressed in the LIMDEP, and may require a hierarchical model for conditioning, and coding of maximisation of likelihood at a different level. Such a methodological challenge will be a promising extension of this study.

Finally, another promising area of extension of this study is to study the impacts of ATIS in a micro-simulation context with incorporation of results obtained in this study. With such an extension, the implications of the operation of ATIS on expressways or other traffic network could be known. For example, what will be the evolvement of traffic given different traffic conditions, incident and operation on ATIS? Given different symbol or messages on ATIS devices, or given different locations of ATIS devices, what are the differences in the impacts? Answers to these questions can help to determine the optimal strategy of ATIS implementation and operation and the benefits of ATIS to improve the efficiency and safety of roads could be fully realised.

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APPENDIX I. SAMPLE QUESTIONNAIRE AND CARDS USED IN THE PERCEPTION SURVEY

QUESTIONNAIRE

Instructions: Please answer each question by ticking the box or scale provided. Texts in Arial font are instructions.

Part I. Driving Habit

Q 1. On the average, how many days in a week do you drive on CTE?

1.☐ Less than 1 day (occasionally). **Thank you, please stop here**

2.☐ 1-2 days

3.☐ 3-4 days

4.☐ 5-7 days

Q 2. Do ERP charges affect your decision on whether to use CTE?

1.☐ Yes 2.☐ No

Part II. Understanding of and response to VMS signs

The following questions are based on the following scenarios. Each question describes a unique circumstance and is independent from each other:

On a typical week day, you drive to work in the morning rush hour. Your usual route is through CTE. However, you have an alternative route, on which the usual speed is about 30 km/hr.

Q 3. If you were already on CTE travelling to work, under the following traffic condition, would you choose to take alternative route?

3.1 Your speed on CTE is less than 20 km/hr 1.☐ Yes 2.☐ No

3.2 Your speed on CTE is 20 -40 km/hr 1.☐ Yes 2.☐ No

3.3 Your speed on CTE is 40-60 km/hr 1.☐ Yes 2.☐ No

Questions 4-6 are based on existing VMS signs

Q4.1 If you were about to enter the slip road leading to CTE, (Please read card 1,), do you think the travel time to PIE is accurate?

1.☐ Yes 2.☐ No, please specify estimated time by ticking at the following line

10 12 14 16 18 20 22 24 26 28 Mins

Q4.2 What would you do if you were about to enter the slip road?

1☐ Continue to enter CTE 2☐ Take alternative route (Go to Q5)

Q4.3 Please indicate the most important reason that you do not want to take the alternative route:

1☐ Alternative route is more congested
2☐ More convenient to use CTE
3☐ Unsure about the traffic condition on alternative route
4☐ Others, please specify______________________________

Q5 If you were driving along CTE (Please read card 2), under this condition, what would you do?

1☐ Stay on CTE 2☐ Take alternative route

Q6 If you were driving along CTE, (Please read card 3), by reading the VMS message, can you describe your estimated traffic condition after CAIRNHILL exit using speed and length of the congestion area?

Q6.1 Please tick at the following line to indicate your estimated speed of traffic after CAIRNHILL exit.

0 5 10 15 20 25 30 35 40 45 Km/hr

Q6.2 Please tick at the following line to indicate your estimated length of the congested area after CAIRNHILL exit.

0 0.5 1 1.5 2 2.5 3 3.5 4 4.5 Km

Q6.3 What do you feel is a better description of the traffic condition?

1 ☐ Speed
2 ☐ Length of congested area

Q6.4 What would you do if you were driving on CTE?

1☐ Stay on CTE 2☐ Take alternative route

Questions 7-9 are for VMS designs to be installed.

Q7. If you were driving along CTE and you saw these signs (Please read card 4), what would you do?

1☐ Stay on CTE 2☐ Take alternative route

Q8 If you were about to enter the slip road leading to CTE and you saw this sign (Please read card 5), what would you do?

1☐ Stay on CTE 2☐ Take alternative route

Q9. In the new Kallang-Paya-Lebar (KPE) Tunnel, if the following lane use sign symbols are used (Please read card 6), please indicate your understanding on the meanings of the following symbols used on the sign?

9.1. Flashing Amber	9.2. Static Amber	9.3. Static Red Cross
1☐proceed as normal	1☐proceed as normal	1☐proceed as normal
2☐proceed with caution	2☐proceed with caution	2☐proceed with caution
3☐change lane	3☐change lane	3☐change lane
4☐do not proceed beyond	4☐do not proceed beyond	4☐do not proceed beyond
5☐others, please specify__________	5☐others, please specify__________	5☐others, please specify__________

Q9.4 With regards to the safety features and traffic equipment for the new KPE, what means of information channel would you prefer to receive such information?

1☐ Internet
2☐ Newspapers
3☐ Television
4☐ Pamphlets
5☐ Articles in magazines
6☐ Radio
7☐ Others, please specify ______________

Q10. In case of congestions, what traffic information do you think is the most important for you to make a decision on whether to use CTE? (If you have more than 1 choice, please indicate your ranking of the importance in the boxes)

1☐ Travel times (e.g. To PIE 18, To AYE 27)
2☐ Description on incidents (e.g. ACCIDENT LN 1)
3☐ Descriptions on traffic condition ahead (e.g. Massive Jam, After Orchard)
4☐ Advisory information (e.g. Exit at Orchard)
5☐ Speed (e.g. CAIRNHILL to ORCHARD 30 KPH)
6☐ Others, Please Specify ______________________

Part III driver data

Q11. Your gender:

1☐ Male
2☐ Female

Q12. Your age:

1☐ less than 25
2☐ 25-35
3☐ 35-50
4☐ 50 or older.

Q13. Your education level:

1☐ Secondary or below
2☐ A level, poly or equivalent
3☐ University

Q14. Your personal monthly incomes:

1☐ Less than S$2000
2☐ S$2001-4000
3☐ S$4001-6000
4☐ S$6001-8000
5☐ More than S$8000

Q15 The type of your vehicle:

1☐ Motorcycle, please specify class
  a☐Class 2a (200cc and less)
  b☐Class 2b (201cc-400cc)
  c☐Class 2 (greater than 400cc)
2☐ Goods vehicle
3☐ Bus
4☐ Car

Part V. Recruitment form for Wave 2 survey

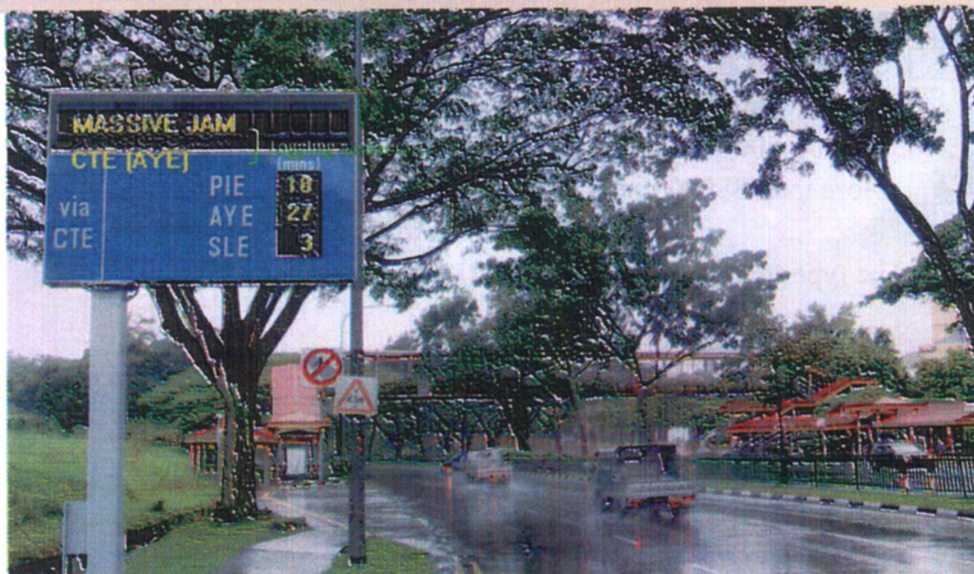
Thank you for your cooperation. We'll be conducting a follow-up survey in a few months time. We would like to invite you to participate in the follow-up survey, in which you'll have the chance of experiencing a state-of-the-art driving simulation system at the NTU campus. The purpose of the survey is to find out your understanding and response to some of the new systems to be used in the Kallang-Paya-Lebar Expressway.

Q16. Would you like to participate in the follow-up survey?
1☐Yes
2☐No
If yes, please leave you contact: (name, e-mail, phone number, these information will be strictly confidential)

Name ______________________________
Email: ______________________________
Phone numbers:
Home: ______________________________
Office: ______________________________
Mobile: ______________________________
Address: ______________________________
____
Postal Code: ______________________________

CARD 1

You are on Ang Mo Kio Avenue 5 and driving towards CTE for work during morning rush hours. Your speed now is 50 km/hr.



Your destination is CBD.
You have an alternative road on which the usual speed is 30 km/hr.

CARD 2

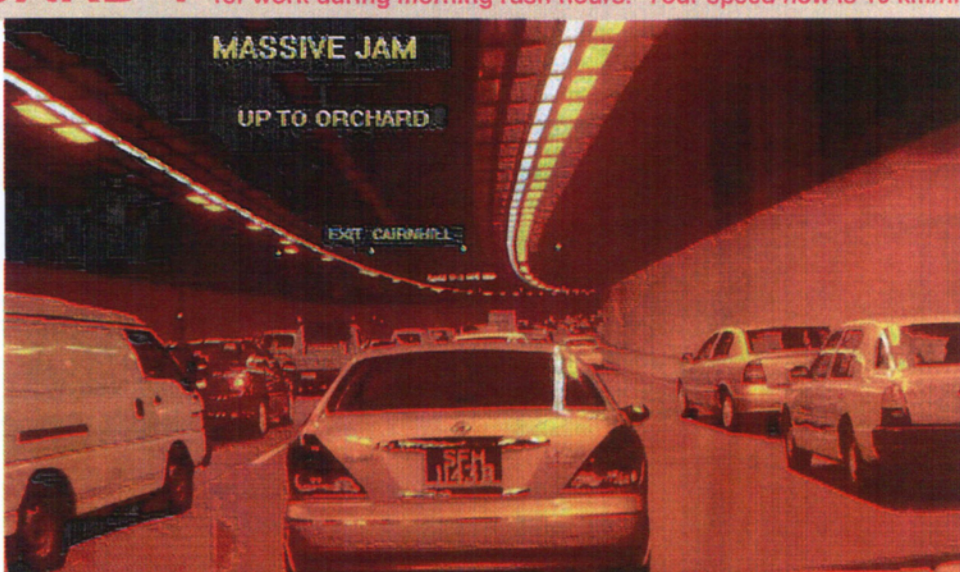
You are on CTE towards AYE (approaching exit 6 to Bukit Timah Rd.) for work during morning rush hours. Your speed now is 10 km/hr.

Your destination is CBD.
You have an alternative road on which the usual speed is 30 km/hr.

CARD 3 You are on CTE towards AYE (approaching exit 6 to Bukit Timah Rd.) for work during morning rush hours. Your speed now is 50 km/hr.

Your destination is CBD.
You have an alternative road on which the usual speed is 30 km/hr.

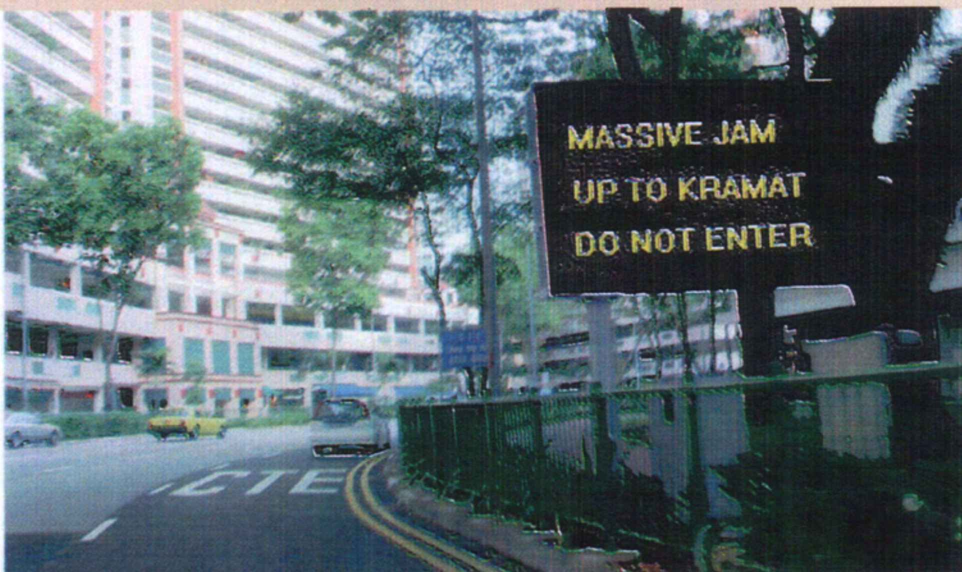
CARD 4 You are Kampong Java Tunnel and driving towards AYE for work during morning rush hours. Your speed now is 10 km/hr.



Your destination is CBD.
You have an alternative road on which the usual speed is 30 km/hr.

CARD 5

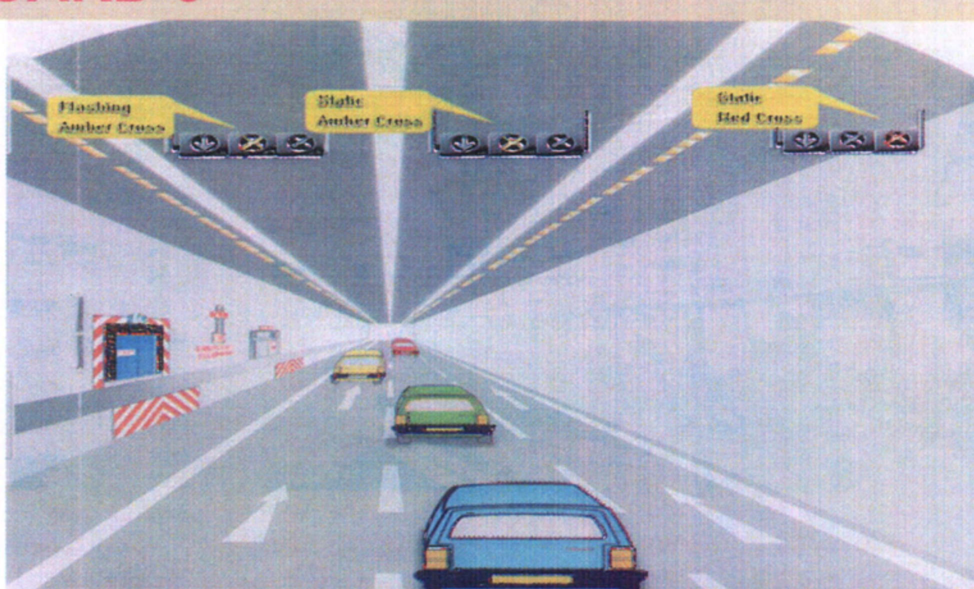
You are on Upper Cross Street and driving towards CTE for work during morning rush hours. Your speed now is 50 km/hr.



Your destination is Ang Mo Kio.
You have an alternative road on which the usual speed is 30 km/hr.

CARD 6

Lane Use Signs inside tunnels



APPENDIX II. STATISTICS FOR DRIVERS' RESPONSES TO LCS

The appendix targeted to present the details on statistics used in Chapter 6, as drivers responses to LCS in terms longtitudinal clearance and speed changes. The results were extracted from each driver' logged data with a computer programme developed. The difference of means in the group with presence of LCS and withouth presence of LCS were compared with the SAS TTEST procedure. The original SAS outputs for longtitudinal clearance are presented as follows.

The TTEST Procedure

Statistics

Variable	wlcs	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
distance	0	29	225.5	313.44	401.38	183.46	231.18	312.66	42.93
distance	1	65	412.17	478.07	543.98	226.8	265.96	321.58	32.988
distance	Diff (1-2)		-278.1	-164.6	-51.15	223.64	255.87	299.04	57.139

T-Tests

Variable	Method	Variances	DF	t Value	Pr > |t|
distance	Pooled	Equal	92	-2.88	0.0049
distance	Satterthwaite	Unequal	61.5	-3.04	0.0035

Equality of Variances

Variable	Method	Num DF	Den DF	F Value	Pr > F
distance	Folded F	64	28	1.32	0.4175

The variable "distance" is the longtitudinal clearance and the unit used is meter. The variable "wlcs" is a binary variable to indicate presence of LCS. The value "0" indicate the group without presence of LCS while "1" indicates the group with presence of LCS. "N" is the number of valid observations used in calculating the t-test. "Lower CL Mean" and "Upper CL Mean" are the lower and upper bounds of the confidence interval for the mean. "Lower CL Std Dev" and "Upper CL Std Dev" are the lower and upper bound of the confidence interval for the standard deviation. "Std Dev" and "Std Err" are standard deviation and standard error respectively. "DF" is the degrees of freedom. "Method" in the t-tests statistics is the method for computing the standard error of the difference of the means. The method of computing this value is based on the assumption regarding the variances of the two groups. If we assume that the two populations have the same variance, then the first method, called pooled variance estimator, is used. Otherwise, when the variances are not assumed to be equal, the Satterthwaite's method is used. Variances is the pooled estimator of variance, which is a weighted average of the two sample variances, with more weight given to the larger sample and is defined to be

$$S^2 = ((n_1 - 1) * s_1 + (n_2 - 1) * s_2)/(n_1 + n_2 - 2),$$

where s_1 and s_2 are the sample variances and n_1 and n_2 are the sample sizes for the two groups. The standard error of the mean of the difference is the pooled variance adjusted by the sample sizes. It is defined to be the square root of the product of pooled variance and $(1/n_1 + 1/n_2)$. Satterthwaite is an alternative to the pooled-variance t test and is used when the assumption that the two populations have equal variances seems unreasonable. It provides a t statistic that asymptotically (that is, as the sample sizes become large) approaches a *t* distribution, allowing for an approximate *t* test to be calculated when the population variances are not equal.

"Num DF" and "Den DF" are the degrees of freedom of the numerator and the degrees of freedom of the denominator of the *F* distribution. In SAS convention, the numerator corresponds to the sample with larger variance and the denominator corresponds to the sample with smaller variance.

"F Value" is the test statistic of the two-sample F test, which is a ratio of sample variances, as $F = s_{12} / s_{22}$ where it is completely arbitrary which sample is labeled sample 1 and which is labeled sample 2. SAS's convention is to put the larger sample variance in the numerator and the smaller one in the denominator. This is called the folded F-statistic, which will always be greater than 1.

Similarly, the original SAS output for speed are for presented as follows. The variable "speed" is the longtitudinal clearance and the unit used is km/h. The variable "wlcs" is a binary variable to indicate the presence of LCS.

The TTEST Procedure

Statistics

Variable	wlcs	N	Lower CL Mean	Mean	Upper CL Mean	Lower CL Std Dev	Std Dev	Upper CL Std Dev	Std Err
speed	0	29	68.499	72.759	77.019	8.8878	11.2	15.147	2.0797
speed	1	65	64.982	68.053	71.124	10.569	12.394	14.986	1.5373
speed	Diff (1-2)		-0.635	4.7059	10.047	10.526	12.043	14.075	2.6894

T-Tests

Variable	Method	Variances	DF	t Value	Pr > |t|
speed	Pooled	Equal	92	1.75	0.0835
speed	Satterthwaite	Unequal	59.2	1.82	0.0739

Equality of Variances

Variable	Method	Num DF	Den DF	F Value	Pr > F
speed	Folded F	64	28	1.22	0.5631

APPENDIX III. RANDOM EFFECTS PROBIT MODEL ESTIMATION METHODS USED IN LIMDEP

In Limdep, the random effects model is estimated according to Butler and Moffitt's (1982) derivations. The algorithm is The algorithm is the Davidon Fletcher Powell (DFP) algorithm, and the BHHH estimator is used for the asymptotic covariance matrix. The log-likelihood for the random effects model is derived in Butler and Moffitt and the likelihood function is:

$$L = \prod_i L_i \quad ,$$

then $\ln L = \sum_i \ln L_i$.

The terms L_i are $$L_i = \int_{-\infty}^{\infty} \frac{1}{(2\pi)^{1/2}} e^{-\varepsilon/2} \prod_t \Phi(r_{it} Z_{it}) d\varepsilon_i ,$$

Where $$r_{it} = 2y_{it} - 1$$

And $$z_{it} = \beta' x_{it} + [\rho/(1-\rho)^{1/2} \varepsilon_i].$$

Let $$h_i = \varepsilon_1 / \sqrt{2}$$

Then, $$L_i = \int_{-\infty}^{\infty} \frac{1}{\sqrt{\pi}} e^{-V} \prod_t \Phi(r_{it} w_{it}) dv_i ,$$

Where $$w_{it} = \beta' x_{it} + [2\rho/(1-\rho)]^{1/2} h_i .$$

Now, let $$w_{it} = \beta' x_{it} + \theta h_i ,$$

Where $\theta = [2\rho/(1-\rho)]^{1/2}$.

The log-likelihood function is maximised over β and θ to obtain the estimates. The vector of derivatives is

$$\partial L_i / \partial \alpha = \int \frac{1}{\sqrt{\pi}} e^{-V} \left[\sum_t r_{it}\lambda_{it}\right]\left[\prod_t \Phi(r_{it}w_{it}\right][Z_{it}]dv_i$$

Where $\alpha = [\beta, \theta]$,

$Z_{it} = [x_{it}, h_i]$,

And $\lambda_{it} = \phi(r_{it}w_{it}) / \Phi(r_{it}w_{it})$.

Once β and θ are computed, the transformation back to the original parameter is $\rho = \theta^2/(2+\theta^2)$.

The integrals are of the form

$$F_i = 1/\sqrt{\pi}\int_{-\infty}^{\infty} e^{-Z^2} f(z)dz,$$

Which can be evaluated by using Hermite integration. An eight point quadrature (Abramovitz and Stegun, 1972) is used in LIMDEP, which is suggested by Butler and Moffitt (1982).

The estimated covariance matrix for the estimates is the BHHH estimator,

$$H = [\sum_i g_i g_i']^{-1}.$$

APPENDIX IV. DESCRIPTIVE STATISTICS, CORRELATION MATRIX OF INDEPENDENT VARIABLES AND MODELLING RESULTS FOR THE RANDOM EFFECTS PROBIT MODEL

Table 1 Descriptive Statistics of all Independent Variables

Independent Variables	Mean	Std.Dev.	Minimum	Maximum
GENDER	0.180277	0.384566	0	1
AGE	2.0208	0.715743	1	4
EDU	2.0963	1.04891	0	3
UNFAM	0.184129	0.387739	0	1
DIS_LOST	0.329045	0.365822	0	1
DIS_GAIN	0.807991	1.08933	0	2.77273
ERP_LOST	0.398998	0.682488	0	2.3
ERP_GAIN	0.026547	0.146834	0	1
TT_LOST	6.71497	22.9588	0	168.259
TT_GAIN	144.683	138.076	0	588.786
PACE	1.19909	0.393729	0.707664	2.14209
FLOW	2467.65	1056.73	1260	4704
VMSMJAM	0.284284	0.451246	0	1
VMSJAM	0.302003	0.459304	0	1
VMSSLOW	0.165639	0.3719	0	1
VMSINCID	0.454545	0.498122	0	1
VMSUPTO	0.253467	0.435164	0	1
ATENTER	0.234977	0.424148	0	1

Table 2 Correlation Matrix of Independent Variables

	GENDER	EDU	AGE	VMSMJAM	VMSJAM	VMSSLOW	VMSACCID	VMSUPTO	FLOW	TT_LOST	TT_GAIN	DIS_LOST	DIS_GAIN	ERP_LOST	ERP_GAIN	UNFAM	PACE
GENDER	1.00																
EDU	0.04	1.00															
AGE	-0.02	-0.04	1.00														
VMSMJAM	-0.05	-0.13	-0.04	1.00													
VMSJAM	-0.03	-0.11	0.01	-0.45	1.00												
VMSSLOW	0.10	-0.04	0.06	-0.27	-0.28	1.00											
VMSACCID	-0.01	-0.11	0.02	0.30	-0.06	0.30	1.00										
VMSUPTO	0.02	-0.22	0.01	0.14	0.24	-0.10	0.08	1.00									
FLOW	-0.02	-0.33	-0.03	0.23	0.48	-0.27	-0.19	0.18	1.00								
TT_LOST	-0.05	-0.02	-0.02	0.19	-0.01	-0.05	0.29	0.36	-0.01	1.00							
TT_GAIN	0.06	-0.06	0.07	0.08	-0.05	-0.15	-0.15	-0.34	0.00	-0.32	1.00						
DIS_LOST	0.00	0.22	0.01	-0.10	-0.03	0.44	0.27	0.35	-0.35	0.09	-0.23	1.00					
DIS_GAIN	-0.02	-0.03	-0.02	0.05	0.00	-0.19	-0.09	-0.44	0.16	-0.17	-0.03	-0.66	1.00				
ERP_LOST	-0.06	0.06	-0.08	-0.10	-0.02	-0.05	-0.04	-0.07	-0.22	-0.11	0.36	0.21	-0.44	1.00			
ERP_GAIN	-0.04	0.11	0.04	-0.01	-0.02	0.15	0.12	0.12	-0.10	0.03	-0.15	0.35	-0.13	-0.11	1.00		
LESSFAM	0.16	-0.05	-0.06	0.03	0.03	-0.01	0.00	0.15	0.06	0.13	-0.01	0.04	-0.20	0.09	0.00	1.00	
PACE	-0.03	-0.13	-0.01	0.04	0.13	0.25	0.23	0.73	-0.02	0.44	-0.41	0.65	-0.67	0.08	0.19	0.14	1.00

Table 3 The Binary Probit Model Estimation Results with the Variable "GENDER"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.44651	0.308783	-4.68455	2.81E-06
GENDER	0.088161	0.10727	0.821868	0.411152
VMSINCID	-0.26025	0.0990996	-2.62619	0.008635
VMSMJAM	1.53577	0.163216	9.40945	2.89E-15
VMSJAM	1.07322	0.155895	6.88424	5.81E-12
VMSSLOW	0.797551	0.185059	4.30971	1.63E-05
PACE	0.421466	0.204084	2.06516	0.038908
TT_LOST	0.005164	0.00231779	2.22783	0.025892
TT_GAIN	-0.00187	0.000390303	-4.8034	1.56E-06
DIS_GAIN	-0.24223	0.0640371	-3.78271	0.000155
ATENTER	0.649145	0.100605	6.45243	1.10E-10
UNFAM	-0.3156	0.112217	-2.81243	0.004917
Rho	0	0		

$L(\beta) =$ -626.29681 $L(0) =$ -846.8163

Table 4 The Binary Probit Model Estimation Results with the variable "AGE"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.32251	0.326168	-4.05468	5.02E-05
AGE	-0.05305	0.0568481	-0.93316	0.350735
VMSINCID	-0.2589	0.0991054	-2.61235	0.008992
VMSMJAM	1.52899	0.162965	9.38234	2.89E-15
VMSJAM	1.07066	0.155693	6.87676	6.12E-12
VMSSLOW	0.807863	0.185085	4.36482	1.27E-05
PACE	0.416142	0.204007	2.03984	0.041366
TT_LOST	0.005196	0.00232149	2.23815	0.025211
TT_GAIN	-0.00184	0.000391117	-4.70326	2.56E-06
DIS_GAIN	-0.2436	0.0640233	-3.80478	0.000142
ATENTER	0.650823	0.100692	6.46353	1.02E-10
UNFAM	-0.30562	0.110675	-2.76138	0.005756
Rho	0	0		

$L(\beta) =$ -626.19775 $L(0) =$ -846.8163

Table 5 The Binary Probit Model Estimation Results with the variable "EDUCATION"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.49266	0.335977	-4.44276	8.88E-06
EDUCATION	0.026639	0.0530155	0.502468	0.615339
VMSINCID	-0.26295	0.0992158	-2.65029	0.008042
VMSMJAM	1.54222	0.164535	9.37325	2.89E-15
VMSJAM	1.07937	0.156991	6.87533	6.18E-12
VMSSLOW	0.809688	0.185542	4.3639	1.28E-05
PACE	0.412941	0.204253	2.02171	0.043206
TT_LOST	0.005099	0.00231634	2.20128	0.027716
TT_GAIN	-0.00187	0.000390493	-4.79026	1.67E-06
DIS_GAIN	-0.24287	0.0640436	-3.79226	0.000149
ATENTER	0.691785	0.132162	5.23439	1.66E-07
UNFAM	-0.29979	0.110351	-2.71671	0.006594
Rho	0	0		

$L(\beta) =$ -626.50723 $L(0) =$ -846.8163

Table 6 The Binary Probit Model Estimation Results with the Variable "ERP_GAIN"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.42106	0.307553	-4.62054	3.83E-06
VMSINCID	-0.25846	0.0992367	-2.60444	0.009203
VMSMJAM	1.52226	0.164433	9.25763	2.89E-15
VMSJAM	1.06021	0.157211	6.74389	1.54E-11
VMSSLOW	0.804026	0.184906	4.3483	1.37E-05
PACE	0.420591	0.204356	2.05813	0.039578
TT_LOST	0.005068	0.00231531	2.18892	0.028603
TT_GAIN	-0.00188	0.000391131	-4.7972	1.61E-06
DIS_GAIN	-0.2411	0.064182	-3.75654	0.000172
ERP_GAIN	7.78E-05	0.000210398	0.369724	0.711588
UNFAM	-0.29896	0.110451	-2.70673	0.006795
ATENTER	0.644996	0.101118	6.37863	1.79E-10
Rho	0	0		

$L(\beta) =$ -626.56490 $L(0) =$ -846.8163

Table 7 The Binary Probit Model Estimation Results with the Variable "ERP_LOST"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.38458	0.309362	-4.4756	7.62E-06
VMSINCID	-0.2444	0.10002	-2.44348	0.014546
VMSMJAM	1.49143	0.165641	9.00397	2.89E-15
VMSJAM	1.03739	0.157407	6.59053	4.38E-11
VMSSLOW	0.747563	0.189413	3.94675	7.92E-05
PACE	0.431853	0.204665	2.11005	0.034854
TT_LOST	0.004831	0.00232582	2.07707	0.037796
TT_GAIN	-0.0017	0.000410118	-4.14943	3.33E-05
DIS_GAIN	-0.26631	0.0665089	-4.00414	6.22E-05
ERP_LOST	-0.09576	0.074105	-1.29224	0.196272
UNFAM	-0.29909	0.110639	-2.7033	0.006865
ATENTER	0.645325	0.1007	6.40842	1.47E-10
Rho	0	0		

$L(\beta) =$ -625.79863 $L(0) =$ -846.8163

Table 8 The Binary Probit Model Estimation Results with the Variable "DIS_LOST"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.4027	0.319808	-4.38606	1.15E-05
VMSINCID	-0.27299	0.112474	-2.42711	0.01522
VMSMJAM	1.53314	0.259768	5.90197	3.59E-09
VMSJAM	1.07079	0.214171	4.99969	5.74E-07
VMSSLOW	0.781062	0.205144	3.80738	0.00014
PACE	0.363754	0.220093	1.65273	0.098385
TT_LOST	0.005429	0.0023278	2.33217	0.019692
TT_GAIN	-0.00187	0.000420465	-4.44537	8.77E-06
DIS_GAIN	-0.23635	0.0752468	-3.14104	0.001684
DIS_LOST	0.098886	0.241842	0.408887	0.682623
ATENTER	0.684327	0.132877	5.15008	2.60E-07
UNFAM	-0.29852	0.117878	-2.53242	0.011328
Rho	0.004208	0.171787	0.024494	0.980458

$L(\beta)$ = -626.54865 L(0)= -846.8163

Model 9 The Binary Probit Model Estimation Results with the Variable "FLOW"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.22752	0.403069	-3.04543	0.002323
VMSINCID	-0.33664	0.141317	-2.38217	0.017211
VMSMJAM	1.67693	0.252962	6.62918	3.38E-11
VMSJAM	1.21906	0.252457	4.82878	1.37E-06
VMSSLOW	0.899829	0.225516	3.99009	6.60E-05
PACE	0.330181	0.233293	1.41531	0.156978
TT_LOST	0.00543	0.00235744	2.30321	0.021267
TT_GAIN	-0.00198	0.000417041	-4.74152	2.12E-06
DIS_GAIN	-0.25333	0.0654915	-3.86821	0.00011
FLOW	-6.06E-05	8.04E-05	-0.75468	0.450441
UNFAM	-0.30043	0.110497	-2.71886	0.006551
ATENTER	0.690855	0.115154	5.99942	1.98E-09
Rho	0	0		

$L(\beta) =$ -626.34847 $L(0) =$ -846.8163

Model 10 The Binary Probit Model Estimation Results with the Variable "VMSUPTO"

	Coeff.	Std.Err.	t-ratio	P-value
ONE	-1.25677	0.384855	-3.26556	0.001092
VMSINCID	-0.25795	0.134919	-1.91185	0.055895
VMSUPTO	0.827008	0.244955	3.37616	0.000735
VMSMJAM	1.81263	0.429807	4.21731	2.47E-05
VMSJAM	1.23621	0.331198	3.73255	0.00019
VMSSLOW	1.25499	0.33599	3.7352	0.000188
PACE	-0.03521	0.25445	-0.13838	0.889942
TT_LOST	0.005594	0.00283202	1.97513	0.048254
TT_GAIN	-0.00175	0.00049162	-3.55366	0.00038
DIS_GAIN	-0.27097	0.10742	-2.52258	0.01165
ATENTER	0.470693	0.132639	3.54867	0.000387
UNFAM	-0.36738	0.148534	-2.47334	0.013386
Rho	0.275808	0.23512	1.17305	0.240776

$L(\beta) =$ -624.52851 $L(0) =$ -846.8163