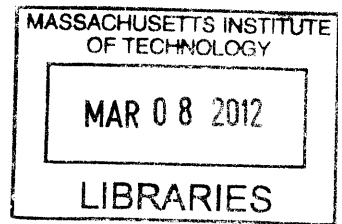


# Assessment Framework for Wireless V2V Communication-based ITS Applications

by

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Bachelor of Technology in Civil Engineering (2009)  
Indian Institute of Technology Bombay, Mumbai, India



Submitted to the Department of Civil and Environmental Engineering  
in partial fulfillment of the requirements for the degree of

Master of Science in Transportation

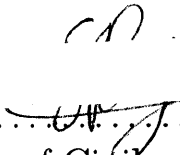
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## Abstract

Inter-vehicle communication enabled by wireless technology is an emerging area of Intelligent Transportation Systems (ITS). This technology has generated great interest among automobile manufacturers and ITS researchers alike because of its potential to improve safety and non-safety ITS applications by supporting data collection and dissemination at the individual vehicle level. A modelling framework based on a microscopic traffic simulator is presented in this thesis to explore the effects of wireless Vehicle-to-Vehicle (V2V) communication based ITS applications on traffic performance.

Microscopic traffic simulators describe the interaction between drivers and infrastructure at individual vehicle level. The behaviour models in microscopic traffic simulators describe driving decisions like route choice, car-following and lane-changing. The existing behaviour model is extended to incorporate the effect of V2V communication based applications by tying information generated by the application to the behaviour model.

A case study on a road network in Singapore with green light prediction application as the V2V communication application is implemented. The car-following model in MITSIMLab is modified to account for speed advisories generated by green light prediction application. The application shows gains in travel time savings and a smoother traffic flow as a result of the green light prediction. Higher improvements across penetration rates were observed at high demand levels. The incremental impact of the application on traffic performance tapers off at higher penetration rates. Drivers responding to the speed advisories also affect vehicles immediately following them. Hence the effective penetration rate of the application is higher than actual penetration rate. The results imply that the green light prediction application would reduce the average number of halts per trip by approximately 10% at existing travel demand. The current model can be extended to test other V2V based ITS applications and to couple with a wireless network simulator to represent wireless data flows more realistically.

Thesis Supervisor: Moshe E. Ben-Akiva

Title: Edmund K. Turner Professor of Civil and Environmental Engineering



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# Chapter 1

## Introduction

Traffic congestion is a source of significant economic and social costs in urban areas. According to the Urban Mobility Report developed by the Texas Transportation Institute in 2007 (Schrank and Lomax, 2007), the costs of congestion (realised as prolonged travel time and wasted fuel) in leading US cities has been steadily increasing. In 2007, an estimated amount of 4.2 billion hours and 2.9 billion gallons of fuel were wasted in the US due to traffic congestion.

Intelligent Transportation Systems (ITS) combine advances in information systems, communications, sensors, and advanced modelling and algorithms to improve the performance of surface transportation. For years ITS have been successful in addressing transportation problems and improving traffic performance. In the past, ITS applications were limited to deployment of fixed infrastructure based technology such as Variable Message Signs (VMS) which disseminate useful information or traffic guidance and automatic toll collections like Electronic Road Pricing (ERP) in Singapore (Tuan Seik, 2000). Research in wireless communications has opened a new area of ITS application by making communication between vehicles (Vehicle-to-Vehicle/V2V) possible which supports data collection and information dissemination at individual vehicle level. To model the impact of V2V communication based applications, a microscopic traffic simulation model is necessary.

Microscopic traffic simulators have been used as evaluation and planning tools for policies and initiatives to improve traffic performance (Barcelo, 2010). These simulators include driving behaviour models that represent interactions between vehicles by simulating driving decisions by individual drivers. These behaviour models are sensitive to information provided by fixed infrastructure based ITS applications like VMS and Variable Speed Limit Signs (VSLs). However, ITS applications enabled by wireless V2V communication can pro-

vide important traffic information to vehicles irrespective of the location of VMS or VLS. To analyse the effects of these applications, the underlying driving behaviour models need to be modified. This thesis presents a modelling framework for behavioural models that are sensitive to V2V communication based ITS applications.

The next section provides an overview of V2V communication and examples of applications, followed by a summary of our microsimulation framework. Finally the funding project Future Urban Mobility (FM) is described and the objectives and organisation of this thesis are presented.

## **1.1 V2V Communication**

V2V communication, also referred to as inter-vehicle communication, is a communications technology that allows the vehicles on a network to “talk” to each other. The technology was first developed and successfully demonstrated for safety purposes by General Motors in 2005 (AutomotiveWorld.com, 2005).

### **1.1.1 Technology**

Communication is established through Dedicated Short Range Services (DSRC) devices (ITS Standards Advisory, 2003) installed on individual vehicles which allows high-speed communications between vehicles and infrastructure. In October 1999, the Federal Communication Committee granted the use of 5.9 GHz frequency with a 75 MHz wide spectrum for DSRC with a stipulation for priority to public safety uses (Research and Innovative Technology Administration, 2003). DSRC devices have a range up to 1000 metres and after accounting for various obstacles in the message transmission, the wireless connectivity range can be around 300 metres (ITS Standards Advisory, 2003). Thus communication over DSRC enables vehicles to exchange data with other vehicles that are out of the visibility distance and even line of sight. Vehicles can even “relay” the messages onwards to form a multihop network where the connectivity range can go well beyond the radio range.

### **1.1.2 Application**

The goal of the wireless network of participating vehicles to increase traffic safety is well summarised by the vision for V2V as stated by Research and Innovative Technology Administration (RITA, 2011):



- “Eventually, each vehicle on the roadway will be able to communicate with other vehicles and that this rich set of data and communications will support a new generation of active safety applications and safety systems.”

Vehicle collectively scout a large area of a road network while making their trips to respective destinations. With robust and reliable sensing technology, individual vehicles can be used as data collectors. This level of physical penetration of the network is not offered by other surveillance technologies which rely on fixed infrastructure. Hence a higher level of data collection and sharing can be achieved by enabling wireless connectivity among moving vehicles. This rich set of data and communications can also be leveraged to realise informational (non-safety) applications.

Information disseminated over the wireless network connecting vehicles via wireless V2V communication can include valuable information about road congestion, physical condition of the road, facility locations, etc. As a result, users on this wireless network can potentially have information about a broader area of road network. This information could have significant effects on driving decisions and improve capacity of the network.

### 1.1.2.1 Potential Applications

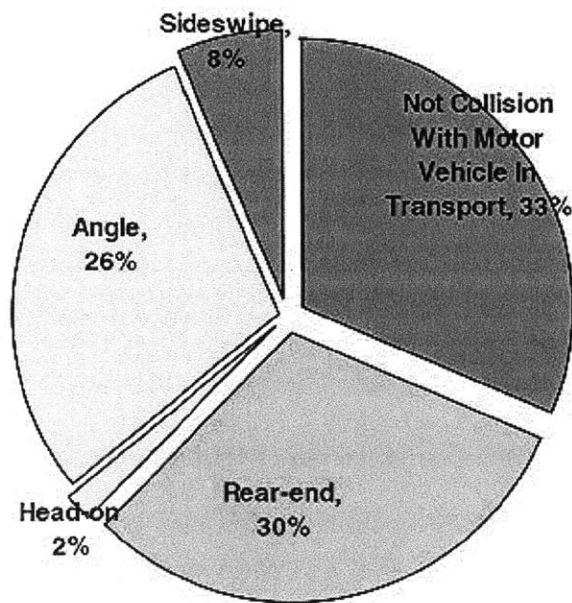


Figure 1.1: 2004 US Crash statistics classified by manner of collision

Source: Carter et al. (2009)

The importance of V2V communication can be accentuated with the help of the crash statistics depicted in Figure 1.1. It gives the distribution of the 6.2 million crashes reported in 2004 via NHTSA's General Estimate System (GES). Data for GES is comes from nationally representative sample of police reported motor vehicle crashes (National Highway Traffic Safety Administration, 2011). V2V communication combined with GPS enables a 360 degree field of view which covers the "blind spots" in the limited field of view of conventional radars which only cover head-on and angle crashes. Rear-end, head-on, angle and side-swipe collisions, all are relevant to V2V communication amounting to a total of 66% of annual crashes. Thus, V2V applications can prevent a larger share of accidents amounting to about 4 million crashes annually. Initially, V2V communication was implemented primarily for safety applications (AutomotiveWorld.com, 2005); e.g., the VSC-A project (Carter et al. 2009) developed interoperable crash avoidance applications. Hence the use of V2V in the traffic safety application is of extreme importance as realised by the automobile manufacturers. Because of its immense potential to increase traffic safety, there has been a great government interest in V2V communication (Shulman and Deering, 2007). IntelliDrive is an initiative from US DOT to leverage V2V communication for traffic safety (RTA, 2010).

#### **1.1.2.2 IntelliDrive**

IntelliDrive is a US Department of Transportation (US DOT) initiative which enables safe, interoperable networked wireless communications among vehicles, the infrastructure, and passenger's personal communication devices in an attempt to make surface transportation safer, smarter and greener. The IntelliDrive approach can increase the efficiency of the roadway systems and provide economic and environmental benefits. The IntelliDrive system will combine technology solutions – advanced roadside infrastructure, wireless communications, advanced vehicle sensors, onboard computer processing, and GPS navigation – to provide vehicles the capability to detect threats and hazards on the roadway and to communicate this to the driver through alerts and warnings.

#### **1.1.2.3 Non-Safety Applications: Green Light Prediction**

The potential applications of V2V communication also go beyond safety purposes. For example, SignalGuru (Koukoumidis, Peh and Martonosi; 2011) is a software service that uses a collection of mobile phones mounted on the wind-shields of vehicles to detect traffic signals with the cameras, collaboratively communicate and learn traffic signal schedule patterns to predict their future schedule. The application was tested only on 5 vehicles mounted with iPhones carrying SignalGuru application, travelling around three intersections in Cam-

bridge, MA. Using SignalGuru to generate Green Light Optimal Speed Advisories showed fuel consumption savings of 20.3%. A larger scale experimentation of this application has not been carried out. To predict the impact of such an application on traffic performance would require running various hypothetical scenarios on a simulation framework.

## 1.2 Simulation approach

As we have seen above there are several opportunities to exploit this technology to mitigate traffic problems. Since these applications are relatively new and their experimental deployment in the field is costly, traffic simulation offers a practical way to evaluate the efficiency and the impact of these technologies. These applications need to be tested under different scenarios varying across penetration rates, reliability of technology, etc. for a comparative study of their practicality and benefits.

In case of the deployment of V2V communication, there are two distinctly different systems interacting with each other:

- The wireless network system comprising mobile nodes capable of telecasting signals over a wireless network and;
- The transportation network system comprising drivers interacting with each other and the infrastructure to arrive at desired destination.

Since this technology involves smarter vehicles with communication capabilities, the best approach would be to simulate the traffic flow and the wireless connectivity at the same time. These two systems can be modelled separately in a simulation environment. The wireless network simulators use wave propagation and interference models to compute the strength and range of the signal transmitted, whereas traffic simulators use behaviour models to predict vehicle movements. Hence to model V2V communications completely, it is beneficial to couple these simulators together in a closed feedback loop.

In this coupling scenario, the traffic simulator can receive the state of the wireless network in terms of the wireless connectivity and data transfer taking place between the vehicle. To make the driving behaviour models sensitive to the V2V communication technology, we need to incorporate this dynamic information exchange in our modelling framework. Thus we modify the behavioural models to reflect the changes brought about by the conveyed information.

The use of microscopic traffic simulators as evaluation and planning tools has been well established by a number of case studies (Ben-Akiva et al., 2003; Choudhury et al., 2011). Microscopic traffic simulators provide the ability to model driving behaviour and the interaction between the vehicles at the level of granularity of individual vehicles and individual lanes. One of the approaches to driving behaviour models is based on frameworks that incorporate different stages of decision-making (Choudhury, 2007). In this model, driving behaviour of the user is viewed as a combination of his/her own intentions and his/her response to the surroundings based on the perceived information.

In this thesis, we focus on the traffic simulation side of this integrated simulation approach. We extend behaviour models that take into account ITS applications deployed as fixed infrastructure, to make them sensitive to these new technologies. The improved model can be linked to a wireless simulator to achieve the desired integration of the simulators.

### 1.3 Future Urban Mobility Project

This research is conducted as a part of the Future Urban Mobility (FM-IRG) project (Ben-Akiva, 2010). It is an inter-disciplinary research project funded by National Research Foundation (NRF), Singapore. The goal of the FM-IRG is to develop, in and beyond Singapore, a new paradigm for the planning, design and operation of future urban mobility systems. The basic premise of FM-IRG is that the advances in computing, communications and sensing technologies give us powerful capabilities to model, evaluate and optimise urban mobility systems.

One of the goals of this project is to leverage the devices on pedestrians, cars, roads, etc. to build a network of computation devices to enable better traffic control. These devices are excellent potential wireless nodes that can track the mobility of their user. The connection of all these devices over the wireless network forms a mesh network of mobile data collection/dissemination nodes over the road network. The connectivity of these devices can be extended to a server in the cloud via the internet to achieve real-time data exchange among the peers partaking in this mesh network of vehicles. The result is accessibility to a very large pool of data and its real-time dissemination. One of these applications will be used to test our modelling framework in a case study.

## 1.4 Objectives

Here we define our objectives for this thesis:

- Develop a modelling framework that is sensitive to changes brought to ITS by the use of wireless communication technology based V2V applications.
- Use this framework to model an application based on wireless V2V communication and test for its effect on traffic performance.
- Develop behaviour models in a traffic simulator in order to extend to implement the integration of a wireless and a network simulator in the future.
- Demonstrate the use of micro-simulation models to assess V2V communication based applications.

## 1.5 Thesis Outline

This thesis is organised in five chapters including this introductory chapter. Chapter 2 covers a literature review of the existing V2V applications and the approaches to analyse their impact with the help of microscopic traffic simulation, in some cases along with wireless network simulation. The various methodologies used to quantify the impacts are detailed.

In Chapter 3 we describe the conceptual framework and model structure. The modelling framework is generalised to be expanded into an integration approach in the future.

Chapter 4 presents a case study on the Bugis road network in Singapore. In this chapter, we test the modelling framework using a green light prediction application as an example of the V2V communication based technology.

Finally in Chapter 5, we draw conclusions and discuss the potential for future work.



# Chapter 2

## Literature Review

There has been a recent surge in research activity in the area of V2V communication and its applications in ITS for safety (Gallagher et al., 2006), route guidance (Weis and Sandweg, 2010), energy efficiency (Tsugawa and Kato, 2010), etc . Several different aspects of the use of DSRC technology to establish vehicular ad-hoc networks (VANET) have been explored in the previous work (Yin et al., 2004; Torrent-Moreno et al., 2004). The literature on the interaction of wireless network with transportation systems needs to be reviewed to understand state-of-the-art practices and gain insights on the potential of the V2V technology to improve the performance of traffic systems. It is important to understand its applications and possible approaches to assess their impact with a simulation platform. The literature review of these aspects is necessary to understand how the behavioural models need to be changed to make them sensitive to these changes in the technologies deployed in ITS.

The impact of V2V technology on traffic performance depends on the changes in driving experience in response to these technologies. The first step to understand this change is to understand the type and value of information provided to the user. This accuracy and reliability of information provided to the user via V2V communication depends on the deployed technology and the connectivity over the wireless network among the users. The information conveyed over the V2V communication can contain any data that can be collected/processed by other vehicles on the wireless network. This information can be leveraged to build a variety of ITS applications addressing different traffic problems. Hence the potential applications of V2V technology can affect the driving behaviour in different ways.

To assess the effect of V2V communication based ITS applications on traffic performance, we can create a physical experimental setup on a test-bed or conduct the same comparative

analysis on a simulation platform tool. The selection of the approach depends on trade-offs between the cost of experimentation and the extent of interactions captured.

In order to gain sufficient depth and clarity in the dynamics of this problem, we need to:

- Gain brief understanding of types of V2V applications and their inputs to the transportation system;
- Review physical experimental setups to justify a simulation approach and
- Review simulation studies to gain understanding of the various approaches used for the assessment of these applications.

In this chapter, we first briefly give an account of different types of applications of V2V communication. Later we present a review of different studies about the assessment of these applications. We begin with a few examples of physical experimentation studies followed by different approaches to model the wireless networks over a traffic network on a simulation platform. We develop the section further by detailing some of the integration approaches used for analysing such systems. We conclude the chapter by drawing motivation from previous works to identify areas to improve and to build our own methodology framework for the assessment of the technology.

## 2.1 Applications

The applications of V2V communication can be broadly categorised as follows:

- Safety related: collision avoidance, cooperative merging, etc.
- Incident report: dissemination of data regarding accidents on the network or breakdown/ blockage of a link, etc.
- Route Guidance: en-route guidance about the shortest path, route guidance for gas stations, etc.
- Miscellaneous: green light prediction, parking space availability, etc.



Safety related applications are among the first to be implemented using V2V communication technology. The basic applications typically include crash-avoidance and co-operative driving systems. Incident report and route guidance applications (Thiagarajan et al., 2009) disseminate information that is directly relevant to the driver and his/her immediate decision making process. Miscellaneous applications try to mitigate the problems that affect the traffic conditions in more indirect way; e.g., finding parking space is a major concern in urban areas. ParkNet (Mathur et al., 2010) is one such drive-by sensing technology that has been tested using physical experimentation. In fact research (Shoup, 2007) points out that the driver spends a significant amount of travel time at the end of the trip in an effort to find a parking space. The effects of this additional travel time are conspicuously visible in congested metropolitan areas such as New York City.

The impact assessment for these different types of applications can be done either by direct physical experimentation or simulation studies. In the simulation studies, the wireless network and the traffic system would be required to be modelled together in an integrated approach. In the following section we discuss the need for the simulation approach with the help of an example of physical experimentation. In the later sections we look into the literature about simulation approaches to gain any insights in the assessment of V2V technology and its applications.

## 2.2 Need for simulation approach

The utilisation of wireless communication technology goes beyond the safety measures that triggered the conceptualisation of V2V connectivity in the first place. ParkNet is one such example of addressing non-safety problems of transportation systems by using vehicles as mobile sensors. Other applications also support the view that vehicular wireless networks can be used to collect and disseminate critical traffic data to users. Physical experimentation is the direct way of assessing the performance of any technology. It involves deploying the technology in a controlled or uncontrolled environment; and observing a set of measures of performance reflecting the impact of the concerned technology. A large scale deployment of any new technology for experimental purposes comes with high costs in terms of money, time and efforts. Hence costs of the whole experiment needs to be justified by the depth of the insights gained by physical experimentation.

### 2.2.1 ParkNet

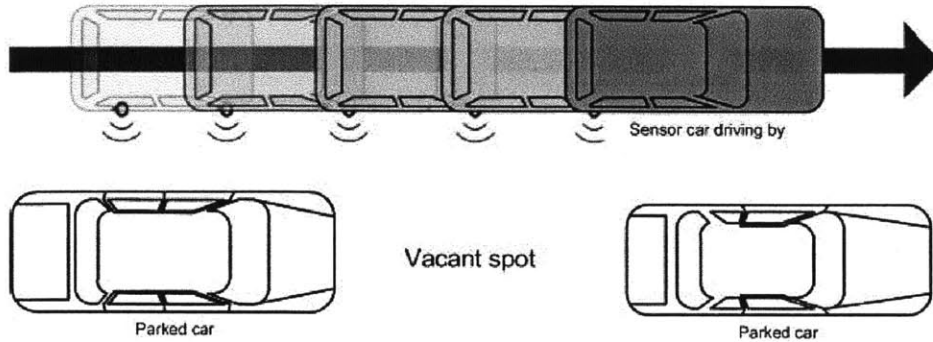


Figure 2.1: Ultrasonic sensor fitted on the side of a car detects parked cars and vacant spaces

Source: Mathur et al. (2010)

Mathur et al. (2010) describe a physical experimentation study to test ParkNet, a drive-by sensing technology to collect road-side parking statistics. The key idea of ParkNet is to leverage the mobility of vehicles that regularly comb a city, such as taxicabs. In the absence of ParkNet this service would be provided by more expensive fixed sensor infrastructure. The goal of ParkNet architecture is to reduce the number of sensors needed to offer this service. Each ParkNet vehicle is equipped with a GPS receiver and a passenger-side facing ultrasonic rangefinder to determine parking spot occupancy (Figure 2.1). The data is aggregated at a central server, which builds a real-time map of parking availability.

A physical experiment was conducted to assess the practicality of this application. About 500 miles of road-side parking data was collected by the taxicabs over a period of two months and matched against the observed parking data to check for accuracy of the parking space reporting. The accuracy of the GPS technology was found to be 95% in terms of the parking spots counts accuracy and 90% in terms of occupancy maps accuracy. The study also quantifies the amount of sensors required to provide adequate coverage in a city. The results show that ParkNet technology deployed on city taxicabs can provide adequate coverage and are more cost-effective by a factor of 10-15 as compared to a network with a dedicated sensor at every parking space. The technology restrictions limited this application only to single lane roads and some issues with power sources were also reported.

This study shows the feasibility of developing a technology to use individual vehicles as sensors and leverage the mobility of the participants that continuously traverse an area to build and maintain a database of a network. The big contribution of this study was proving the effectiveness and sufficiency of the regular fleet of taxicabs to generate a vehicle mobility based service in terms of the parking spots maps. Also the study observed certain drawbacks of the infrastructure which otherwise possibly would not have been detected on a simulation model. But the approach suffers from the drawbacks of a physical experimentation. The experiment had to be carried out in the field which is costly and may not be possible for every application. A simulation study perhaps, can be used to perform the same analysis over a broader range of scenarios.

### 2.2.2 En route connectivity

A similar approach to leverage existing infrastructure for *en route* connectivity of vehicles was presented in Bychkovsky et al. (2006). The authors discussed the practicality aspects of an unplanned *in situ* 802.11 (Wi-Fi) network service to provide reasonable performance to network clients moving in cars at vehicular speeds. The goal was to “open up” Wi-Fi Access Points (AP) in the vicinity of the route and leverage this connectivity to upload data to the cloud. This approach extends the wireless connectivity from inter-vehicle domain to the internet.

The study evaluates expected performance of these open Wi-Fi networks for users moving in automobiles. A measurement study was conducted in and around the Boston metropolitan area using several cars which logged a total of 290 “drive-hours” collected over 232 different days over a year. Nine cars, each out-fitted with a cell-phone embedded computer running the CarTel system software (Hull et al., 2006), collected data about Wi-Fi networks during the course of their driving. During the course of test run, cars were able to successfully associate with APs and transfer data at all speeds between 0 to 60 km/hr. The APs appeared in clusters and the mean inter-arrival duration for these clusters was found to be about 75 seconds. However frequent power disruptions and flash failures that corrupted the file-system and extremely time consuming data analysis were observed to be the two biggest challenges. The median AP coverage was found to be 96 metres with top 10 percentile having a coverage more than 300 metres. Uni-directional delivery rate of packets was about 90%. Overall the study was able to establish the promise of *in situ* wireless connections to upload the data over the internet.

Based on the observations of this experiment, authors were able to suggest some policies to give incentives to users and service providers to open their APs in order to exploit this connectivity in metropolitan areas. Such open Wi-Fi networks can be leveraged for a variety of vehicular applications that can tolerate some intermittent connectivity. The *en route* connectivity if achieved can become the basis of several other ITS applications. The experimentation was also successful in obtaining the critical parameter values to appraise the scope for “open Wi-Fi networks” in the future. The approach however was limited to only nine cars which is a typical restriction of physical experimentation. Transferring the setup to a simulation model can help run the scenarios with more realistic number of cars accessing the CarTel system software.

In these applications technology evaluation was conducted by actual physical experiments. To summarise:

- The use of the existing infrastructure in conjunction with the mobile computing devices carried by the users on the road was shown to be capable of sustaining the dissemination of key information and making it accessible to participating users.
- Also the experimentation was able to observe certain technical difficulties in the infrastructure which otherwise may not be detected on a simulation platform.
- However the costs involved in conducting these experiments motivate the need for the simulation studies.

In the next section we look at some simulation approaches to analyse the feasibility and the benefits of such systems.

## 2.3 Simulation approach

In almost all the V2V applications, deploying a prototype and analysing its effects is impractical because of the relatively high costs involved. A realistic penetration rate of technology to carry out experiments is not feasible to achieve in real life unless technology requires only a very simple modification to existing infrastructure. Hence simulation is a better way of assessing a modern technology like V2V communication. To evaluate their impact, traffic simulations based on an agent-based architecture that also take into account the communication between vehicles are needed (Fernandes and Nunes, 2008).

In the following sub-sections, we look into various studies that used simulation approach to model the wireless network and the traffic network separately followed by studies focussing on integrated approach.

### 2.3.1 Wireless network simulation

ElBatt et al. (2006) tested the suitability of DSRC for Cooperative Collision Warning (CCW) using simulation of wireless network. CCW is a class of vehicular safety applications where vehicles periodically broadcast short messages for the purposes of driver situational awareness and warning. The Forward Collision Warning (FCW) application was modelled using the QualNet (Scalable Network Technologies, 2011) as the simulation tool. QualNet is a simulation tool that contains detailed 802.11a radio and channel models, including widely accepted models for wireless propagation and interference. In FCW it was assumed that each vehicle carries some type of localisation device like GPS in addition to a wireless communication device using DSRC. Each vehicle periodically broadcasts the information regarding its current status like location, velocity, etc. The neighbouring vehicles which receive this information calculate the likelihood of collision based on their own status. The simulation runs were performed to assess the performance of the application in extreme vehicle densities and to explore potential broadcast enhancement techniques. The approach uses QualNet which applies widely accepted wireless propagation models, but the models governing the vehicle movements in the simulation run are not very clear.

Conceicao et al. (2008) used an integrated approach to simulate large scale V2V environments. The study makes use of a simulation prototype named DIVERT set up over road network of the city of Porto. It uses shortest path algorithm to generate random or pre-defined routes. To capture the inter-vehicle communication, a very simple broadcasting model, in which vehicles within certain threshold (determined by the transmission radius) are able to communicate with each other is used. Every “sensor” vehicle in the traffic simulation generates GPS-like messages with its position and speed. The communication layer in the wireless network simulator transmits this data package according to an algorithm to other vehicles within the threshold. The simulation runs had 5000 vehicles with 10% penetration rate of the inter-vehicle communication technology. To implement mobility based navigation, vehicles should have a good knowledge of traffic conditions at a given instant. Hence, the mobility propagation was used as the metric to test over a spectrum of conservative transmission ranges. With this approach, the authors were able to generate a map of segments about which more than 50% of the sensor vehicles had traffic information that

was fresher than the last 5 minutes. Though the study provides a good way of measuring the spread of traffic conditions across a large V2V network, it suffers from drawbacks on the traffic modelling side. The traffic simulator accounts for only the longitudinal motion. The approach can be improved by integrating the network simulator with a better traffic simulation model. Also the simplistic propagation model can be extended to include more rigorous models.

### 2.3.2 Traffic network simulation

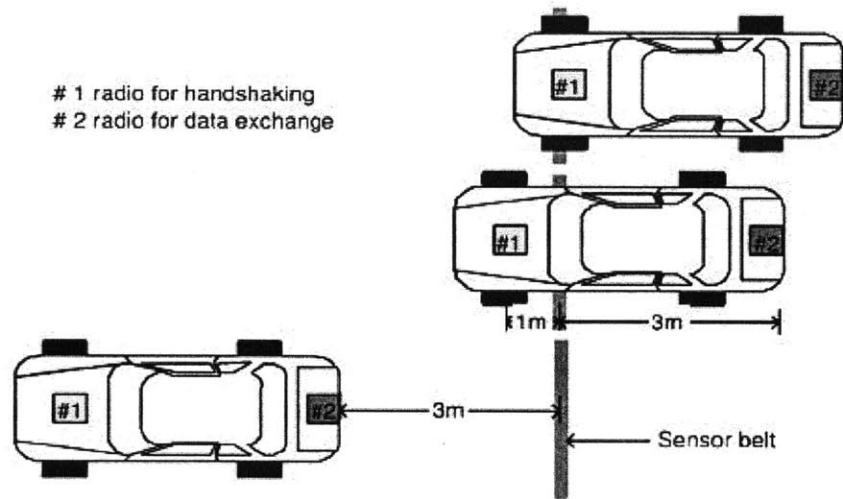


Figure 2.2: Sketch of communication between a car and a sensor belt in NOTICE architecture

Source: Rawat et al. (2008)

The wireless network side of the problem is addressed in the above studies. On the other hand, traffic simulation studies also have been used to assess the performance of inter-vehicle communication. Chiara et al. (2008) defined a Risk Index (RI) to assess the effects of inter-vehicle communication systems in terms of the risk of longitudinal collisions for vehicles. Aim-sun was used as the traffic simulator platform to analyse a hypothetical highway scenario where a vehicle suddenly brakes down. The RI values with the inter-vehicle communication showed significant improvement in the safety with respect to the current scenario without the technology. However the study is limited to single lane scenario and the improvements shown might be a little too idealistic.

Rawat et al. (2008) describe the NOTICE architecture for vehicular communications and use a traffic simulation approach to test the challenges in its implementation. NOTICE is a new concept in VANET that aims at providing automated notification of traffic incidents on the highways in order to reduce congestion and improve overall traffic safety. In V2V communication, vehicles are responsible for forwarding and exchanging information to fellow participants. This makes the system vulnerable to attacks from malevolent traffic participants. Hence to address these issues, in NOTICE architecture the communication takes place through a system of sensor belts embedded in the roadway (Figure 2.2) that collect information and provide driver notification in case of highway incidents.

A traffic simulator based on Intelligent Driver Model (IDM) (Abuelela et al., 2008) was used to evaluate the NOTICE architecture. The incident detection time was used as the metric to test the efficiency of architecture. The simulation analysis showed a U-shaped trend in detection time with respect to density whereas the incident detection time was shown to increase as distance between belts increases. The simulation was useful in identifying possible belt and traffic densities for a practical implementation of NOTICE architecture. This study provides a good example of investigating a proposed architecture using the traffic simulation approach.

Yeo et al. (2010) analysed the impact of V2V communication systems on traffic operations. The modelling of driving behaviour with V2V communication hazard alert system in incident situations on freeways was carried out for a range of traffic operations conditions. The NGSIM freeway flow algorithm was used to simulate the driving behaviour. This algorithm is an integrated car-following and lane changing model which also explicitly models “short gap” where drivers accept very small gaps in the target lane. Lane changing manoeuvres were classified as mandatory or discretionary depending on the situation.

To model the driver response to an incident, a blockage is introduced in one lane of a four-lane homogeneous freeway section. In a lane specific scenario, the vehicle involved in the incident sends a warning message with the location, time and lane of the incident. This message is relayed upstream by equipped vehicles within certain communication range  $R$  (Figure 2.3). Vehicles equipped with V2V receive the information about the incident wherever they are on the freeway. Drivers of unequipped vehicle have no information about the incident until it comes within their visibility distance. All warned drivers are assumed to be identical in their response to the warning message. Due to lower expected downstream speeds, larger gaps and slower speeds are generated.

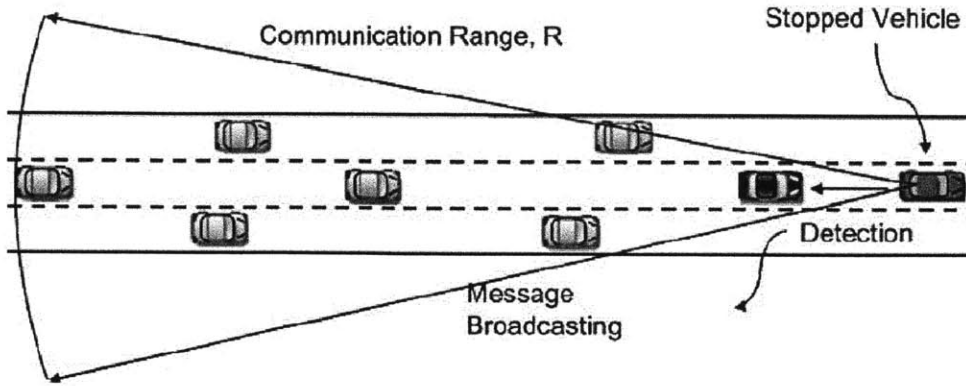


Figure 2.3: Simple incident message propagation scenario

Source: Yeo et al. (2010)

This is factored in the car-following model by modifying the safety constraint. The following deceleration rate is applied instead of the maximum acceleration rate:  $a_{n(E)}^L = \max(a_n^L, a_n^L(\gamma + \delta|l - l_{inc}|))$

where  $\gamma, \delta = \text{constants less than 1,}$

$l = \text{current lane, and}$

$l_{inc} = \text{incident-blocked lane}$

$a_n^L = \text{maximum deceleration rate of vehicle } n (< 0)$

The calculated deceleration rate for the equipped vehicle assumes a reduction in normal deceleration rate ( $\delta$ ) reflecting better safety constraints. When an equipped vehicle approaches within a distance  $E_n$  from the incident location it will start lane changing manoeuvre. It was assumed that the drivers can scan 50 metre ahead of all lanes and pick the fastest lane as the target lane. In the non-lane specific case, equipped drivers do not know whether they are travelling on a blocked lane. A 20% reduction in free flow speed is assumed because of the uncertainty about downstream conditions. It was observed that a higher flow can be sustained by increasing the market penetration of the equipped vehicles. Also larger communication range  $R$  meant larger space over which equipped vehicles could make mandatory lane changes. This approach provides a good example of modifying the driving behaviour to take into account the change in response to incident detection. However the selection of the chosen values of  $\gamma$ ,  $E_n$  and  $\delta$  can be questioned.



Wang et al. (2007) explored the benefit of applying simple traffic control strategy at a merging section in the presence of V2V connectivity. The goal was to promote collision free ways of effective “proactive” merging for improved throughput. The methodology involved dissociating the point of merging and point of decision making. Proactive action on the part of driver leads to more efficient merging manoeuvres. This merging strategy leverages the information communicated via the V2V technology at the decision point to compute a proper gap to prepare for merging. The information received includes the position, velocity and acceleration of competing vehicles. Along the approach to the merging point the vehicle adjusts its velocity to prepare for actual merging. A microscopic simulator IDM was used to test this strategy against the priority based, non-proactive merging strategy. The simulation results show a reduced delay in proactive merging to about only a third of the delay in the priority merging strategy. Also the throughput in proactive merging strategy is observed to be higher.

The studies mentioned in this sub-section show the importance of modifying the driving behaviour models to take into account change in the information provided to driver. The simulation approaches were able to model the changes in traffic flow while making certain assumptions about the wireless communication.

### **2.3.3 Integrated simulation approach**

The simulation approach can be extended to include traffic flow side of the problem by coupling together wireless network simulator and traffic simulator. An integration between a wireless network simulator with wireless propagation and interference models and a traffic simulator with vehicle movement models is a more complete way to address the problem.

Kim and Fujimoto (2009) presented a traffic simulation study to explore the effect of an ATIS architecture using wireless communications. The ATIS application under consideration was Dynamic Route Guidance System (DRGS) which attempts to search for the most cost effective route for a participating vehicle. An integration approach using an off-the-shelf microscopic simulation model with a Vehicle Communication Module (VCM) was used. A simple VISSIM traffic network is utilised across different demands and penetration ratios of enabled vehicles to evaluate travel time savings of participating vehicles. A simple incident is generated to trigger the DRGS which helps participating drivers to choose better routes. Some delay was observed between the incident start and the instant when it starts affecting the travel time estimates by the DRGS. As expected the travel time savings show an

increasing trend as the penetration ratio increases. The integration approach covers both sides of the problem. However the system suffers from some modelling drawbacks. E.g. the participating vehicles did not opt for the incident hit link even after the incident was removed. The travel time estimates are updated by the data collected by probing vehicles. When the vehicles are diverted away from the incident hit link, there is no further data collected regarding that link. Thus the DRGS does not redistribute the traffic even after the incident is removed. A better algorithm for route guidance can improve the impact of the technology in reducing congestion.

Bing Mei et al. (2010) use a simulation approach to test the impact of route guidance information disseminated over VANET on traffic performance. Modelling methodology involved two types of networks: a highway network and wireless VANET. When the two networks are in operation, highway traffic operations data are simultaneously collected, transmitted and analysed by and among vehicles. To model these networks together Aimsun was used as a platform for the integrated model. The programming language Python was used to develop a customised module to interface with Aimsun. Some of the vehicles loaded in the network were assumed to have onboard equipment that can identify the location of other vehicles, collect operations data and communicate with other similarly “equipped vehicles”. These vehicles can receive *en route* traffic information which can help drivers make decisions to improve their travel plans.

An incident was assumed to have occurred if the ratio of the average instant speed to the typical speed on the link fell below 0.5. If an incident was detected, an alarm was triggered which is immediately sent via VANET. All directions, single-hop broadcasting was used for message transmittals to other vehicles within a wireless transmittal range of 250 metres. In other words, if an equipped vehicle is within this range, it receives this message and then can forward it onwards. After the message is received it was checked for relevance to the current vehicle path. If deemed relevant, the message was evaluated for the reliability of the broadcasted traffic information. A reliability index was generated which reflects the significance of each message based on its age, frequency and the degree of atypicality. If this index is greater than a certain threshold, the driver was allowed to act on it. Two types of response types were modelled: dynamic route diversion (DRD) and variable speed limits (VSL). Normal control is resumed once the incident section is no longer on the vehicle’s path.

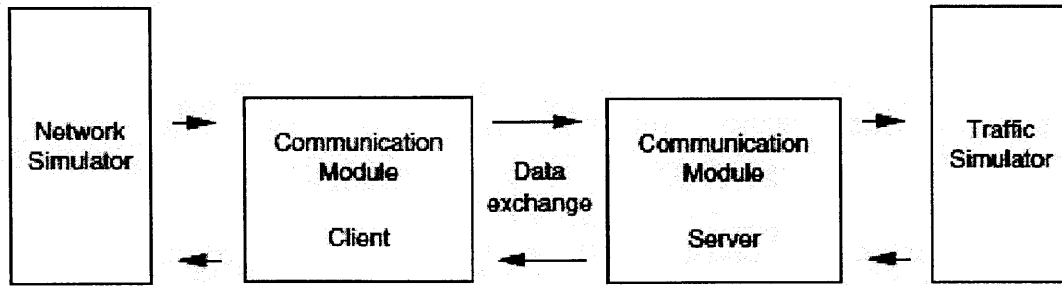


Figure 2.4: Coupling of network and traffic simulator

A small portion of the city of Victoria, Spain was used as a test bed. Eight different scenarios including a baseline scenario were tested.

Source: Eichler et al. (2005)

An incident was created on one of the links which takes 15 minutes to clear up. The results showed that most messages can propagate to the maximum range within 7 to 8 seconds. The average number of stops decreased slightly when VSL was deployed. Overall, an increased market penetration of the V2V vehicles in the fleet showed benefits for both appropriate incident response and better utilisation of network capacity. However in some cases, penalising alternative routes with excessive diversions were observed. The key observation to infer from this study is that the impact of this technology depends significantly on two factors: reliability of the information and penetration rate of the technology. These effects need not be intuitive and a simulation case study can provide a useful insight in the effectiveness of technology.

Eichler et al. (2005) analyse the effects of a real-time V2V warning message distribution application on road traffic. This paper presents the work on an integrated simulation environment with three components: Traffic Simulator CARISMA; Network Simulator NS-2; and an incident warning Application. CARISMA randomly chooses a start and destination point for every vehicle on the map and the vehicles choose the shortest path for their travel. It periodically receives the data regarding changes in the vehicle behaviour from the traffic simulator and sends node positions and connectivity patterns back to the network simulator (Figure 2.4).

A total of 900 cars of which 400 cars were equipped with wireless technology were used in the case study over 8 sq km city area. In the simulation one specific vehicle breaks down

at the beginning of a simulation run and starts periodically sending a warning message. V2V equipped cars have the assistance of route guidance which leads them to other routes, while not warned vehicles still drive through the affected zone and possibly get trapped in congestion. Several simulation runs over different vehicle densities and penetration rates of V2V technology showed significant travel time benefits for V2V enabled cars. The key observation from this study was that the loss of these travel time benefits as the number of informed cars goes up. The broadcast of warning message to a large number of users decreases the benefits from alternative routes.

Klunder et al. (2009) discuss the results of a field operational test to test the effect of adaptive cruise control (ACC) on driving behaviour. ACC is mainly a comfort system that manages car-following while the driver remains responsible for steering and collision avoidance. The study tested the effect of larger penetration rate of ACC on traffic safety, throughput and environment using ITS modeler, a microscopic simulator platform interfaced with Paramics, a traffic simulator. The implemented cooperative driver models specified active gap creation, active gap searching and adaptation to the speed in the left lane. The model also considered the on and off modes of ACC in the cases where the driver desires a different manoeuvre. The simulation setup included scenarios with different penetration rates and continuous or interrupted ACC activity. The results from the study showed significant impact on the traffic throughput in presence of ACC. The effect was observed to be higher during high congestion. Also the freedom to turn ACC on or off had a negative impact on the throughput while continuous use of ACC showed improvements in the throughput.

### **2.3.4 Conclusion**

The previous studies suggests that an integrated simulation module does a better job of assessing the application of V2V technology by capturing the interactions between the wireless network and the traffic network than individual simulation modules alone. The wireless network simulator modules used in these case studies follow the established message propagation models. However there is room to improve on traffic simulation models in these approaches. In the integration of simulators approach, wireless network simulators are able to simulate the wireless environment based on the technology specifications and vehicle traces. But the driving response is heavily dependent on the content of the information carried by messages. Thus driving response and hence the traffic performance can be expected to follow different trends for different applications. Therefore every application needs

to be classified based on the content of the information carried and should be addressed accordingly in the traffic simulator module. The previous simulation studies show considerable variation in the impact of the V2V technology across different penetration rate of the technology. Also the effects vary according to the type and content of the information disseminated and driver never relies or follows this technology perfectly. Therefore the reliability and compliance to the technology shall be considered in the traffic simulation model.

## 2.4 Summary

To summarise,

- There is a myriad of different possible applications of V2V technology. The benefits from the additional information communicated between the users are significant.
- We looked at a few examples of physical experiments that were carried out for the impact assessment. However the experiments are costly and may not be possible for all the applications.
- Though physical experiments to test the validity of these technologies are not practical, the simulation methodologies have proved to be a good way to predict the impact of these technologies.
- Integrating the wireless and traffic simulators together is a good way to represent both sides of the situation.
- Several scenarios across different penetration rates and reliability of the broadcasted information need to be modelled in the simulation to observe non-intuitive effects the technology might have on the network performance.
- Also the impact of every technology depends on the type and content of the information disseminated. A new simulation approach needs to be defined to analyse the impact of a new V2V technology application such as the green light prediction technology on the overall network performance.
- **Hence it is essential to modify the behavioural models to make them sensitive to the deployed V2V application.**

In the next chapter, we look at the methodology of our approach to analyse the impact of V2V technology on traffic performance.



# Chapter 3

## Methodology

This chapter presents a general methodology and framework to evaluate the impact of V2V communication technology on overall network performance. It is necessary to address the impact of technology on driving response in the traffic simulator module. The proposed methodology adds a layer to the traffic modelling framework where the effects of V2V based application are translated into behaviour models. The impact can be quantified by several measures like average travel times, number of halts, etc. depending on the application being tested. Section 3.1 describes the requirements of the simulator platform to be used. Section 3.2 presents the actors and the interactions involved and motivates a discussion about how they can be modelled. Later in Section 3.3 we discuss how these requirements can be implemented. We finish the chapter with a brief discussion of how the approach needs to vary to model any V2V application in the future.

### 3.1 Requirements

In the previous chapter, we noted that integration of a traffic simulator and wireless network simulator is a better way to approach modelling the impact of wireless based V2V technologies on traffic performance. Wireless networks can be simulated over off-the-shelf simulators like ns-3 which utilise widely accepted wave propagation and interference models. The selection of the traffic simulator, however, depends on the requirements of simulation experiments.

- The exchange of messages over wireless network occurs between individual vehicles. This message exchange over wireless networks is modelled by the wireless network simulator. The underlying models in these simulators take into account the relative position and relative speed of the “mobile” wireless nodes to simulate the data ex-

change. In the case of wireless technology based V2V communication these nodes are the individual vehicles. **Hence it is essential for the traffic simulator to keep track of the movements of the individual vehicles.**

- The wireless data exchange is dynamic and has a different impact on the movements of different vehicles. The dynamic interaction between the vehicles requires modelling of the responses from the driver to the information received. The traffic simulator needs to model the manoeuvres of the driver on the road along with its interactions with other vehicles in the surroundings. **Microscopic behaviour models are required to simulate the driving response at this level.**
- The driving response as modelled by the microscopic behaviour models is a combination of various manoeuvres like acceleration/deceleration, lane-changing, merging, etc. The road network needs to be represented at the level of individual links, lanes, intersections, traffic lights, etc. to accommodate the details of road geometry as required by the behaviour models.



## 3.2 Framework Design

### 3.2.1 Actors and interactions

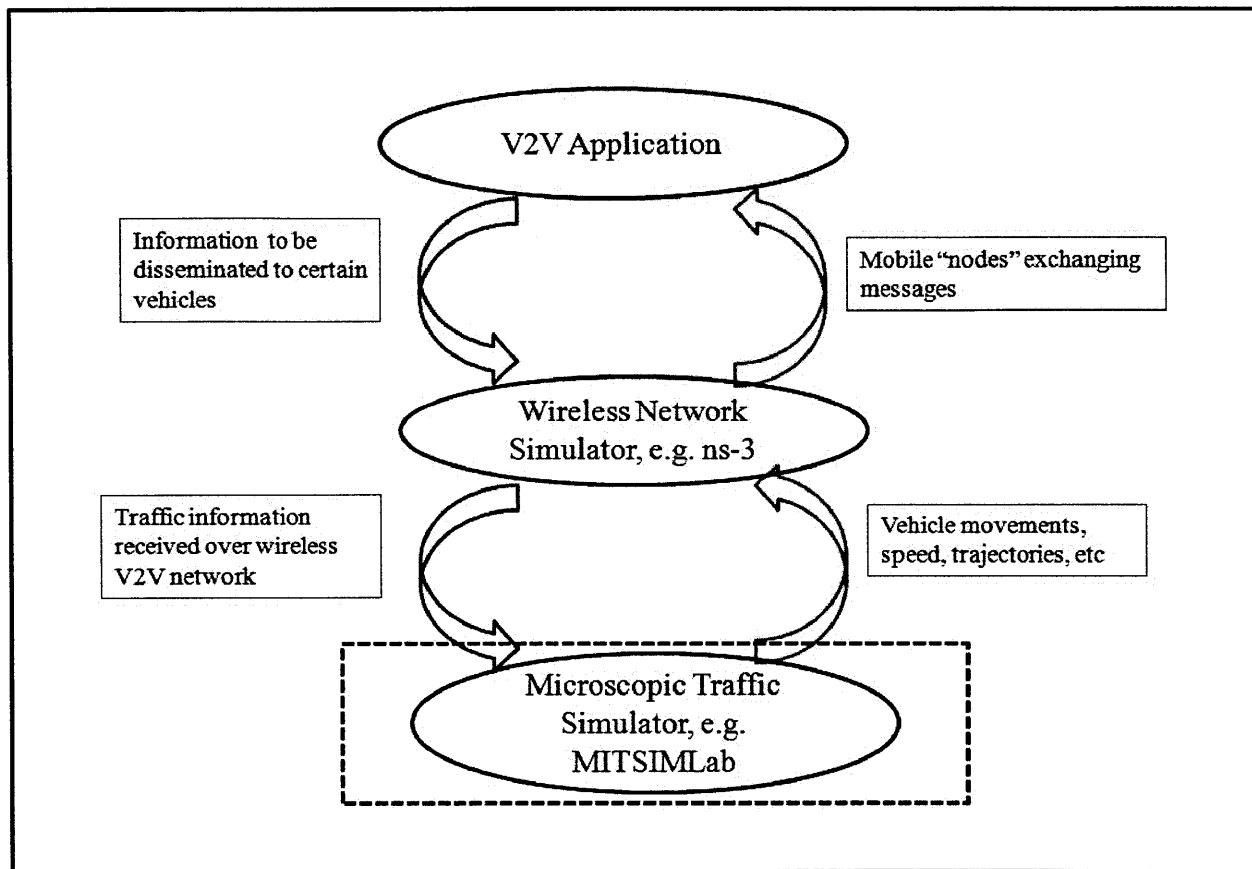


Figure 3.1: Driver - Wireless Network interaction

To model the impact of V2V technologies on traffic performance correctly, we need to make a clear distinction between the technological aspects of application and the information conveyed to driver. The wireless technology creates the “connections” between vehicles which can be used for data gathering and information dissemination. The content and extent of the information conveyed to the driver is the outcome of this technology and is the component that actually changes the way a driver responds. Hence the change in driving manoeuvres occurs as a response to the information conveyed by the technology (dotted rectangle in Figure 3.1). However the dynamics of data sharing among participating users and how information is disseminated on a larger scale is modelled in a wireless network simulator like ns-3. The traffic modelling part of the simulation is only concerned about the type and content of the information shared.

The drivers on the road network and the wireless network connecting the vehicles are the two main actors in this process. The interactions between them have been depicted in Figure 3.1. The drivers in the simulation run follow behaviour models in the microscopic traffic simulator like MITSIMLab. The interactions of individual drivers generates vehicle trajectories and traffic flow. Individual vehicle movements, speeds and trajectories are given as input to the wireless network simulator like ns-3. The wireless network simulator uses wave propagation and interference models to calculate wireless connectivity between the mobile nodes. The V2V application uses this as one of the inputs and generates information pertaining to the underlying algorithm of the application. Which users receive this information is calculated by a wireless connectivity pattern generated from outputs of the wireless network simulator. To complete the loop, the traffic simulator receives information from the V2V application which is made available to certain users. This information affects the driving behaviour and the behaviour models in the traffic simulator need to be modified to be sensitive to this information.

The traffic information received by the vehicles is perceived by the driver and helps him/her determine his/her next manoeuvre. The traffic information received over the wireless V2V network is used as an input to the microscopic traffic simulator like MITSIMLab. The models implemented in MITSIMLab describe both the longitudinal and lateral movements of the vehicles.

## **Longitudinal movement:**

### **Car-following models:**

Car-following models define how the vehicles in the simulation world move in the longitudinal direction. Acceleration and current speed are the key parameters calculated at each update time-step. The models take in to account parameters like relative speed and relative distance which are dependent on their surroundings. The acceleration regime generated for each vehicle is thus sensitive to changes in its immediate surroundings. Hence the information made accessible via V2V communication can alter the urgency in the longitudinal movements of the vehicle. e.g. a change in the perception of downstream traffic conditions may cause the driver to deviate from the usual regime and accelerate or decelerate.

This can be explained better by the following example. In a free flowing regime, the acceleration of the vehicle at the next time step is given by  $a_n(t) = \lambda[V_n^{desired}(t) - V_n(t - \tau)] + v_n(t)$

where

$t$  : time instant  
 $\tau$  : reaction time of the driver of vehicle  $n$   
 $\lambda$  : parameter  
 $v$ : error term

Thus the acceleration of the vehicle in the free flowing regime depends on the desired speed of the vehicle. The desired speed depends on a number of factors that affect the perception of the driver. If the V2V communication application increases the desired speed  $V_n^{desired}$  of the vehicle by  $\Delta V$  then the acceleration at the next time step increases by a quantity of  $\lambda \Delta V$ . This is one example of the ways in which the behaviour models are made sensitive to the information disseminated over V2V communication.

## Lateral movement:

### Lane change models:

The lateral movement of the vehicle is governed by the lane changing models. The lane changing manoeuvres are further classified as mandatory or discretionary. Mandatory lane changes are usually performed when it is necessary to follow the desired path or to avoid lane closure. The discretionary lane changes can be undertaken to achieve the desired speed, avoid slow vehicles or to avoid the merging traffic. Thus the lane changes are sensitive to any changes in the path selection, desired speed, traffic congestion, etc. If the ‘‘intention’’ to perform a lane change is communicated in advance to the other vehicles in the vicinity, a cooperative lane change can be executed by the driver. The lane change model would be required to incorporate this change in the driving behaviour.

For example, the lane changing manoeuvre involves selection of a target lane as the first step. This selection is based on the random utility terms of the lanes available in the choice set. The total utility of lane  $i$  to driver  $n$  at time step  $t$  is given by (Choudhury 2002):

$$U_{int}^{TL} = V_{int}^{TL} + \epsilon_{int}^{TL}$$

where  $V_{int}^{TL}$  is the systematic component of the utility term and  $\epsilon_{int}^{TL}$  is the random term.

The systematic utilities are expressed as:  $V_{int}^{TL} = \beta^{TL} X_{int}^{TL} + \alpha_i^{TL} v_n$

where  $X_{int}^{TL}$  is a vector of explanatory variables that affect the utility of the lane  $i$ , and  $\beta^{TL}$  is the corresponding vector of parameters.  $\epsilon_i^{TL}$  is the random term associated with target lane utilities with  $\alpha_i^{TL}$  being the parameter of the individual specific latent variable  $v_n$ .

One of the explanatory variables in the vector  $X_{int}^{TL}$  is the remaining distance to the point at which the lane change must be completed. If the information received over V2V communication application changes the location of this point, it affects the systematic utility part of the target lane. In other words, an application based on V2V communication that conveys route guidance advisories to the driver will affect the “urgency” of the driver to make the lane change. Thus lane changing behaviour is changed by linking this variable to the advisories the application.

### **Gap acceptance models:**

The gap acceptance models decide if the gap observed in the nearby lane is good enough for a lane change. This decision depends on several factors like the length of the gap, relative speed, the number of gaps already rejected, urgency of the lane change (reflected by the remaining distance to a mandatory lane change), traffic conditions, etc. The critical length of an acceptable gap can be reduced if the cooperative lane change is performed as described in the previous paragraph. Thus the threshold gap length will change significantly in the gap acceptance model.

These sets of behavioural models govern the entire movement of the simulated vehicles. These movements are sensitive to their traffic surroundings and the information received/perceived by the driver. The position, speed and acceleration of each vehicle is then used as the input to the wireless network simulator as shown in Figure 3.1. This completes the loop of interactions between the actors in our framework.

We propose the following modelling framework for the driving response to this conveyed information.

### **3.2.2 Driving Response**

The proposed modelling framework is shown in Figure 3.2. The simulation of the wireless network and message propagation is assumed to happen outside our framework (shown in dashed rectangle in Figure 3.2). A wireless network simulator like ns-3 reads in the trajectories and speeds of the individual vehicles as the input and generates the wireless connectivity and information dissemination patterns among the vehicles.

Our framework expects additional information parameters like the wireless connectivity and reliability of the message from the wireless network as an input. To act as a proxy

for the connectivity parameters generated by the wireless network simulator, we define two parameters :

- Penetration Rate
- Compliance Rate

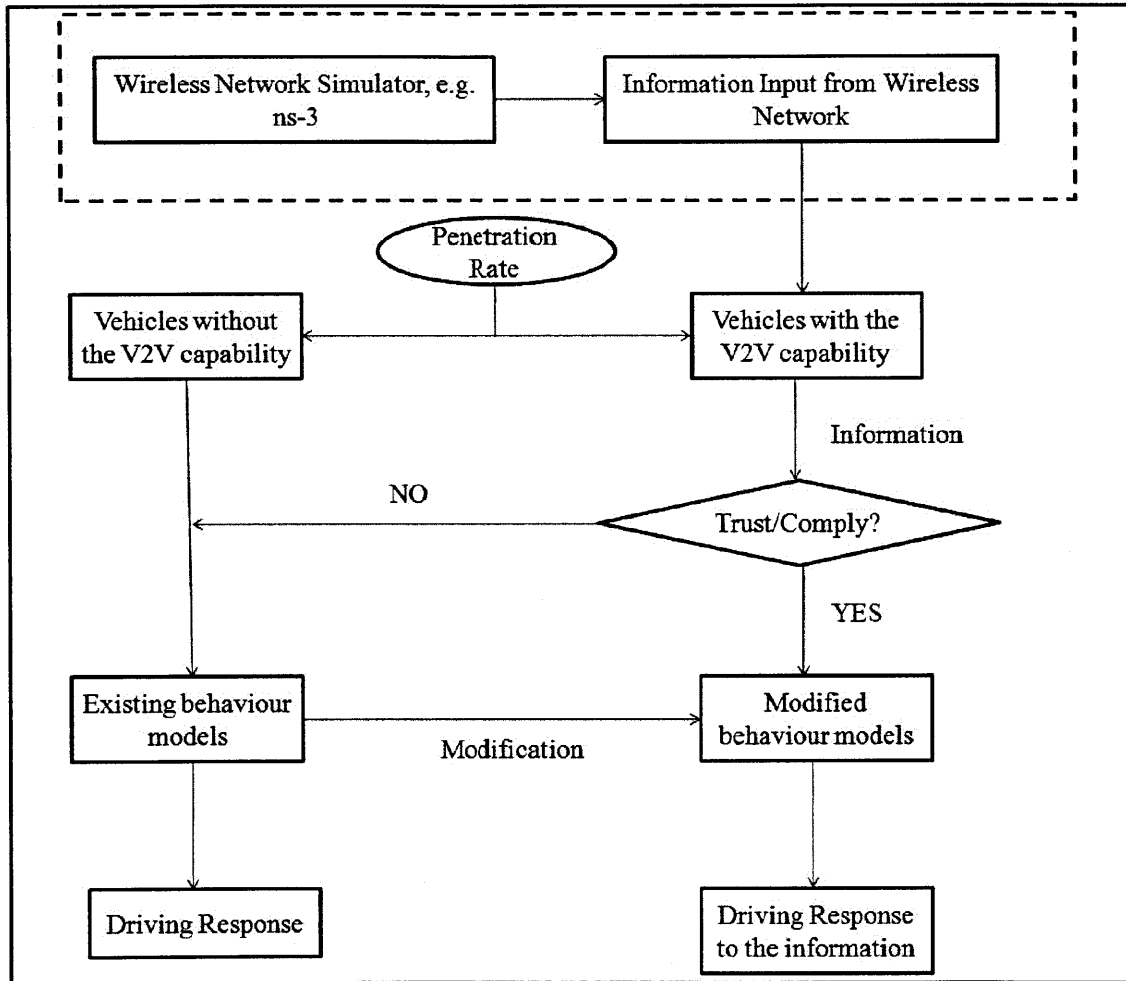


Figure 3.2: Modelling Framework

Based on the penetration rate only a certain section of driver population has access to the information disseminated over the vehicular network. Hence a population with two classes of drivers is generated: with or without the V2V capability. If the vehicle with V2V capability receives the information as determined by the wireless network simulator, it acts as one of the inputs to that driver’s behaviour model. The driver may or may not choose to trust or

comply with the information provided to him/her. These parameters could be used to build the linkage between the wireless network simulator and the traffic simulator for extending the proposed framework in the future.

According to the framework, vehicles without V2V capability follow existing behaviour models. The V2V enabled drivers, who do not receive traffic information or who choose not to trust or comply with the provided traffic information, also follow the same behaviour models. The behaviour models for drivers who receive the traffic information and who choose to trust and comply with it are altered. The modification of the models depends on the application of the technology being tested. The different behaviour models mark the difference between the two different classes of drivers.

To assess the impact of the V2V based application, the metrics shall be defined to reflect the goal of the technology. Such metrics may be average speeds, travel time savings, network capacity, etc. E.g. if the impact of the technology needs to be assessed in terms of the network performance in terms of the throughput, network capacity shall be used as one of the metrics. Rapolu (2010) defined network capacity (Appendix D) in terms of vehicle-km travelled per hour to assess the impacts of interventions on the network performance. Also the V2V communication technology is not yet deployed at a practical scale. Since the penetration rate of the technology in the future is unknown, it is interesting to analyse the impact of the technology over a spectrum of penetration rates.

## 3.3 Implementation

### 3.3.1 Traffic Simulator

A microscopic traffic simulator needs to be utilised to represent the traffic side of the simulation. MITSIMLab is one such microscopic traffic simulator tool that has been tested and applied successfully in several cities around the world. MITSIMLab (Yang and Koutsopoulos, 1996) is a simulation-based laboratory that was developed for evaluating the impacts of alternative traffic management system designs at the operational level and assisting in subsequent refinement. The overall structure and components of MITSIMLab have been described in Appendix A. The key modules of MITSIMLab are:

- MITSIM, the traffic simulator and
- TMS, the traffic management simulator

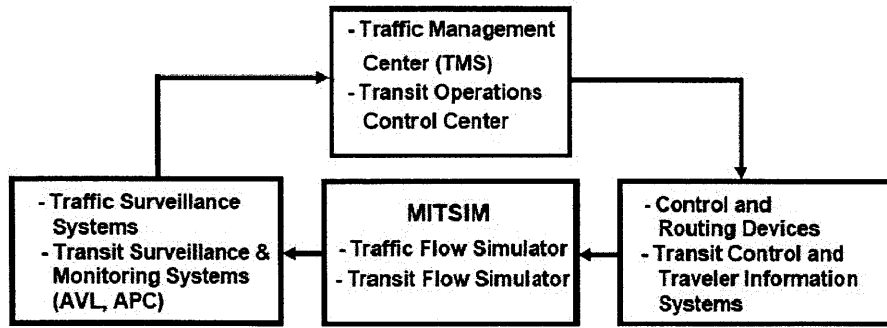


Figure 3.3: MITSIM-Traffic Management System Integration

The traffic simulator module, MITSIM contains all the driving behaviour models which govern the manoeuvres and responses of the drivers during the simulation. The traffic management simulator, TMS works on the logic and algorithms of the signalling and surveillance systems on the network. Hence during a simulation run, these two modules run simultaneously while providing inputs to each other in a closed loop formation (Figure 3.3).

The traffic management center, TMS may respond to the traffic conditions by altering the traffic signal timings or changing the speed limits conveyed via variable message signs (VMS). This information acts as an input to the behaviour models in MITSIM (as shown in Figure 3.3). Hence the dynamics of the traffic movements are captured by the behavioural models in response to the traffic surroundings and the control and routing devices.

### 3.3.2 Data needs

The underlying behaviour models in MITSIM have been successfully demonstrated to reflect better the real life conditions on the road in a simulation environment. The models are able to describe both the longitudinal and lateral movements of the vehicles by modelling the decision making process of the driver in response to the traffic conditions. First the behaviour models need to be calibrated and validated against the on-field data for the network under the study. The data required for these purposes can be detailed trajectory data or aggregate counts/speeds data from the sensors on the road network. Also the detailed geometry of road network along with sensor and traffic light positions is required to build the network model in the simulator.

The data required to represent the V2V technology components may vary from application to application.

### 3.4 Summary

This chapter presented a general methodology and framework to assess the V2V technology on the network performance using a microscopic traffic simulator. The methodology framework expects parameters like the V2V capability and reliability to be passed from a wireless network simulator. We defined two parameters to act as a proxy for the inputs from the wireless network simulator. Our framework assumes that the goal of the V2V communication system is to reduce the congestion delays and increase network throughput. Thus the impact can be measured by the change in the network capacity or reduction in travel times.

An aggregate calibration and validation method is described in the appendix (Appendix B). The model is calibrated for some key parameters in the behaviour models and validated against the on-field data. The calibrated model is used to assess the impact of an application of this technology over a range of penetration rates of the technology.

In the next chapter, we look at the application of this framework to a sub-network in Singapore.



# Chapter 4

## Case Study: Bugis Road Network, Singapore

The previous chapter described the overall modelling framework for analysis of the impact of V2V communication based applications on driving response and the resultant overall network performance. In this chapter, a real road network with complex traffic flow patterns has been used to assess the impact of the green light traffic prediction technology on the performance of the overall network. A network near Bugis MRT station on the East West Line of Singapore MRT has been used for this purpose. MITSIMLab has been used as the micro-sopic traffic simulation tool to perform the analysis. The behaviour models have been modified to account for the effects of speed advisories generated by the green light prediction application on driving response. The chapter is organised as follows: Section 4.1 describes green light prediction application as V2V based technology to be tested in the case study and explains the methodology behind it. We develop requirements to build the framework to model this application. We follow it by laying out our approach to model the green light prediction application in Section 4.2. In Section 4.3 we present an application of our framework in a simulation case study on a road network in Singapore. Finally in Section 4.4 we summarise the findings and observations from the case study.

### 4.1 Green light prediction application

The increased prevalence of personal devices, such as smart phones, tablets which include computational power, wireless connectivity, and multiple sensors opens up new avenues of research and development. Computing and communication devices on mobile users can provide richer pool of information about the state of the network to participating users

and system managers. Every user with such a device is a potential data collector and information provider. All these mobile devices when coupled with a resilient internet cloud can provide real-time information in a consistent and comprehensive manner. As part of the research under FM-IRG (Ben-Akiva, 2010), work is being done to build a framework to facilitate creation and evolution of such vehicular ad-hoc networks (VANET). This network can support technologies that enhance traffic and transit management, transportation and planning, emergency management, etc. The green light prediction application software, SignalGuru (Koukoumidis, Peh and Martonosi; 2011) is one such application.

### 4.1.1 Goal of the application

Most of the delays in travel time are experienced at the intersections. The deceleration to a come to complete halt at a red light and the subsequent acceleration by every vehicle in the queue when the light turns green are the two major points where the travel time delays pile up. Hence, the goal of the technology is to reduce this delay caused by traffic lights. With the help of traffic light prediction, the users try to avoid stopping at the downstream traffic light.

### 4.1.2 Data collection and prediction

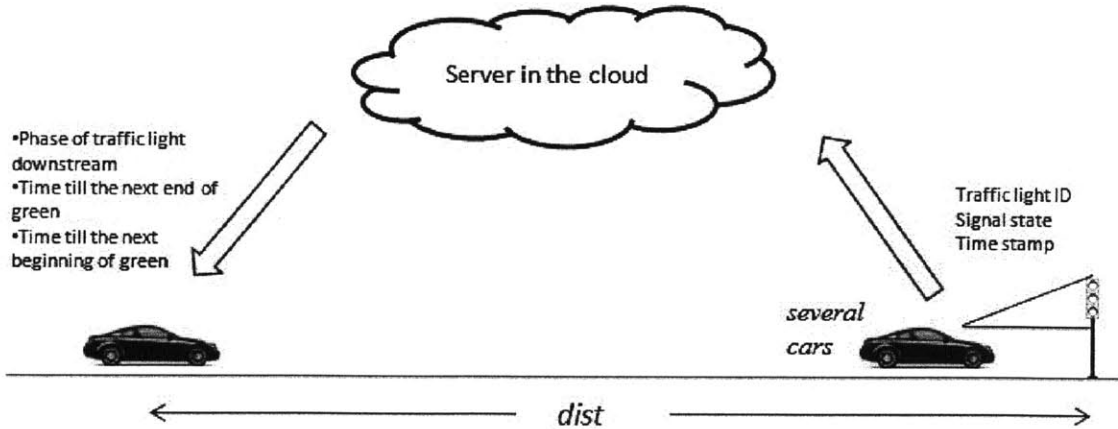


Figure 4.1: Schematic of green light prediction

The application is designed to run on a smart-phone device like an iPhone. The participating users with this application can mount their iPhone behind the wind-shield while driving. As the vehicle moves along its course, the iPhone device keeps on taking pictures at regular intervals. The application uses an image recognition technology to identify the traffic lights

encountered in the field of view (Figure 4.1) and associate it with an ID of the corresponding traffic light and time instant. Thus the application builds up a database of time-stamped array of phases of traffic lights encountered over the vehicle's route in the network.

The signal phase observed at that traffic light at that moment is associated with a time-stamp. This traffic light ID-signal state-time stamp combination is registered as a data point  $(i, s, t)$  in the database. This chunk of data can be shared with other iPhone users with this application within the wireless range and can be uploaded to the server in the cloud via internet. Thus the database on the common server is continuously enriched with such data points. Using these data points the application implements an algorithm to "decode" the phases of every traffic light in the network coverage. The algorithm reverse engineers the phase cycles of the traffic light to come with the predictions of the following key parameters:

- Current phase of the traffic light
- Time till the end of the current/next green phase
- Time till the beginning of the next green phase

This information along with the distance of the vehicle from a downstream traffic light can be made available to users of the application which are still connected to the wireless network. The application on iPhone uses these variables to predict the time of arrival of the vehicle at the downstream traffic light and generates speed advisories within safety constraints to avoid a stop at that traffic light. The user may or may not choose to follow these advisories based on a number of factors. The drivers are different in personalities, approach to driving (safe/risky), faith in the technology, familiarity with the network, etc. Thus population of drivers is heterogeneous with respect to their compliance to the advisories generated by the application. The longitudinal movement of the vehicle will change only if the driver chooses to follow the speed advisories.

To summarise, the application uses its subscribers as the data collectors and offers them speed advisories to avoid the stops at traffic lights. Thus the driver with this application is more informed with respect to drivers without this application who will show relatively myopic behaviour. Hence the driving behaviours of these two classes of drivers will differ. In the following section, we lay out our framework to incorporate the green light prediction application in behaviour models.

## 4.2 Modelling framework for the green light prediction application

We modify the way a driver reacts to the received information by adding another layer to the model (Figure 3.2) that governs the response to the traffic signal. In our model we strictly restrict ourselves to the way a driver reacts to the information. We assume that the information about speed advisories is received by the driver through the wireless communication. Based on this assumption we then develop our model to reflect the driving response to the green light prediction application. A *V2V\_penetration* parameter is defined to generate the population of drivers based on the penetration rate of technology for the simulation run. A compliance dummy variable is also defined to account for the reliability of speed advisories and compliance of the driver. To simulate the complete picture of the technology the traffic simulator shall be coupled with a wireless network simulator. This coupling of simulators is beyond our scope at this point of writing this document. Hence for the sake of simplicity the exact model governing the wireless message exchange is kept exogenous to the model described here. However we develop our model so that it can integrate with a wireless network simulator for future work.

To model driver's response to this information, we assume a steady state where the server in the cloud has gathered enough data points to make accurate predictions about all the traffic lights in the simulation for the entire duration of the simulation run. The information is reliable and is conveyed to every participating user on time whenever he/she is within a threshold distance from the downstream traffic light. It is advised to keep in mind that the speed advisories may not be generated with sufficient reliability if there are not enough vehicles with this application scouting the network. Also the wireless connectivity of the vehicle will define if the vehicle receives the advisories or not. In the absence of the coupling with the wireless network simulator the reliability issue is represented by a compliance factor that will be described later in this section.

The schematic of information relay is shown in Figure 4.1. The iPhone in the car passing by a traffic light takes a picture of the traffic signal light and relays that information to the server in the cloud. The server adds this information as another data point for that particular traffic light. The server uses the green light prediction algorithm to calculate the current phase of that traffic light. The information about the phase of the traffic light downstream is conveyed to the participating user at a distance *dist* upstream (Figure 4.1). This distance is usually much larger than the physical visibility distance of the particular

traffic light.

Thus the application knows the amount of green time left at that traffic signal downstream, *greenleft*, and the time left till the beginning of the next green phase, *greenbeg* (Figure 4.3). Based on these two variables and distance from the traffic light, one of the following things is performed by the application.

- If the manoeuvre at the current speed is sufficient enough to reach the intersection during the green time, the desired speed is left unchanged. If the current manoeuvre is estimated to lead to a red light downstream, the application first tests for the possibility of an accelerated manoeuvre within safety constraints to arrive at the intersection before the light turns red.
- If such a manoeuvre is not possible, the application suggests a slowing down approach to arrive at the intersection during the next green light phase. Thus appropriate advisories are generated to alter the desired speed so as to reach the intersection either before the the end of the current green cycle or after the beginning of the next green cycle.

The generated advisories take into account the speed limits and maximum acceleration for the vehicle type.

The compliance to the generated advisories will depend on the personality of the user and the perceived reliability of the information. Hence, a compliance rate is defined to incorporate the differences in the willingness to follow the advisories among the population. If the compliance dummy is zero, the user ignores the advisories and adheres to the driving behaviour in typical conditions. This compliance rate can be later used to communicate the reliability of the message received from the communication module in an integrated approach.

### 4.2.1 Driving Response

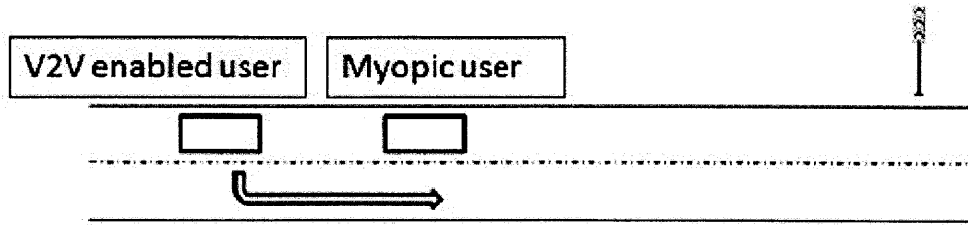


Figure 4.2: Lane change by the V2V enabled driver to pass the myopic driver

The driving behaviour is governed by two types of models: car-following and lane changing. The car following model describes the longitudinal movement whereas the lane changing model reflects the lateral movement decisions made by the driver. The car following model is influenced by several factors such as headway between the cars, desired speed, aggressiveness of the driver, etc. The lane changing decisions are affected by the density and average speed in the neighbouring and current lanes as well as the perceived utility of a lane to make certain manoeuvres. The added information received from the green light prediction technology changes the urgency of the longitudinal movement. Since the goal of the driver is to reach the intersection during a green cycle, the only affected variable is the desired speed and hence the desired acceleration. This intent to accelerate, however is limited in action by the surrounding vehicles. If the leading vehicle has a different desired speed less than the concerned vehicle, the vehicle may choose to perform a lateral movement according to the lane changing models (Figure 4.2).

Hence the change occurs in the car following model to reflect the driver response to green time prediction. The response to the green light prediction advisory is calculated based on the compliance of the user in terms of the acceleration required to reach the intersection during a green cycle. Since this information might not be available to all the users, other users in the simulation may be myopic in their behaviour. These myopic drivers follow the regular car following model and become aware of the traffic signal only when within its visibility distance. Thus these myopic drivers act as hurdles to the informed drivers and keep them from enjoying complete benefits of the technology. However we can expect the benefits of this technology to be prominent at higher penetration rates of the technology.

The behaviour model in response to this green light prediction is shown in the flow-chart (Figure 4.3). In our behaviour model, the users are differentiated based according to the

possession of such a device with the green light prediction application. The users without such capability are unaware of the phase of the traffic light downstream and hence do not respond to it until it comes within the physical visibility distance for that traffic light. These users follow the usual car-following behaviour in response to the traffic light.

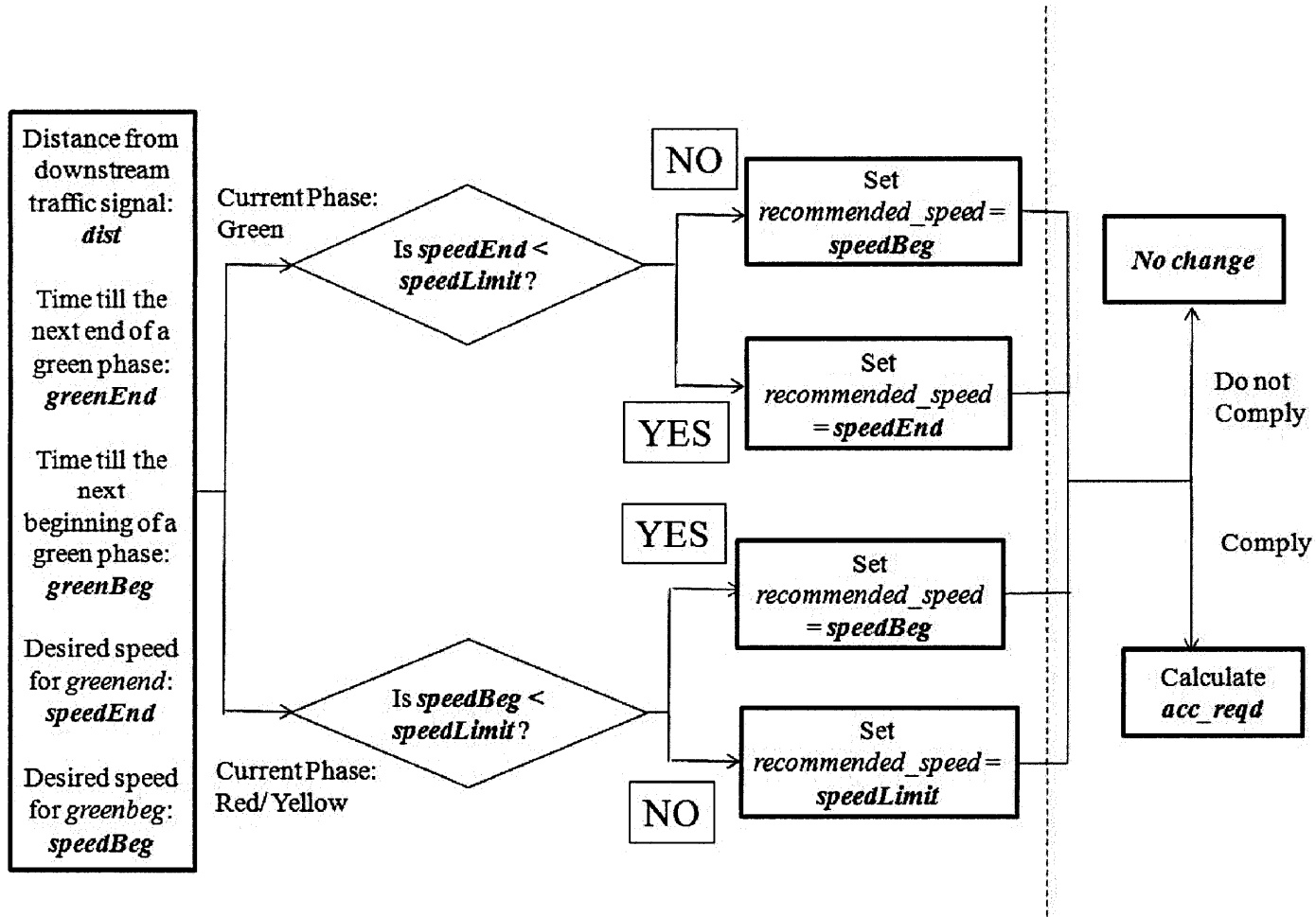


Figure 4.3: Driver response to green light prediction flow-chart



When the users with the green light prediction capability are at a distance  $dist$  from the traffic light, they receive the prediction parameters for that traffic light. The model first decides if the current state of the traffic light is green or red. If the current state is green (i.e.  $greenend < greenbeg$ ), the model checks for the possibility of reaching the intersection by the end of the current green light while staying within the speed limit. If this is possible, the desired speed is set at the speed limit. Otherwise the desired speed drops down to the  $speedbeg$  so as to arrive at the intersection at the beginning of the next green. If the current state is red or yellow (i.e.  $greenend > greenbeg$ ), the model checks if the manoeuvre required to reach at the beginning of the next green cycle is possible within the speed limit. If this is possible, the desired speed is set at  $speedbeg$  so as to arrive at the beginning of the next green cycle. Otherwise, the desired speed is set at  $speedend$  so as to arrive at the intersection by the end of the next green cycle.

In both of these cases, the accelerations calculated are bound by the maximum acceleration possible for that particular vehicle. This  $acc\_reqd$  reflects the driver's response to the advisory. The driver's response is initiated only if he/she decides to comply with the advisory. Since not all the vehicles in the model have the green light prediction capability, some vehicles are "myopic" with respect to the traffic light. The interaction between these two types of vehicles is then governed by the conventional car-following models in MITSIMLab.

### Measures of Effectiveness

The goal of the technology is to make the driver aware of signal timings of a traffic light downstream and suggest speed advisories to reduce the number of halts at the intersection. Hence to quantify the impact of the technology, we define MOEs which reflect the savings in travel times and the smoothness of the uninterrupted traffic flow. For the purpose of the case study we use the following MOEs:

1. Average speed: The mean of average speeds of every vehicle in the simulation run.
2. Average travel time: The mean of the time required to complete each trip in the simulation run. A complete trip is defined as an instance of a vehicle successfully reaching its destination.
3. Average number of halts: The mean number of halts encountered by each vehicle per trip. A halt is defined as the instance when the instantaneous speed of the vehicle falls below a preset minimum threshold speed.

## 4.3 Application of the framework in a Case Study

### 4.3.1 Dataset Description

#### 4.3.1.1 Study Area

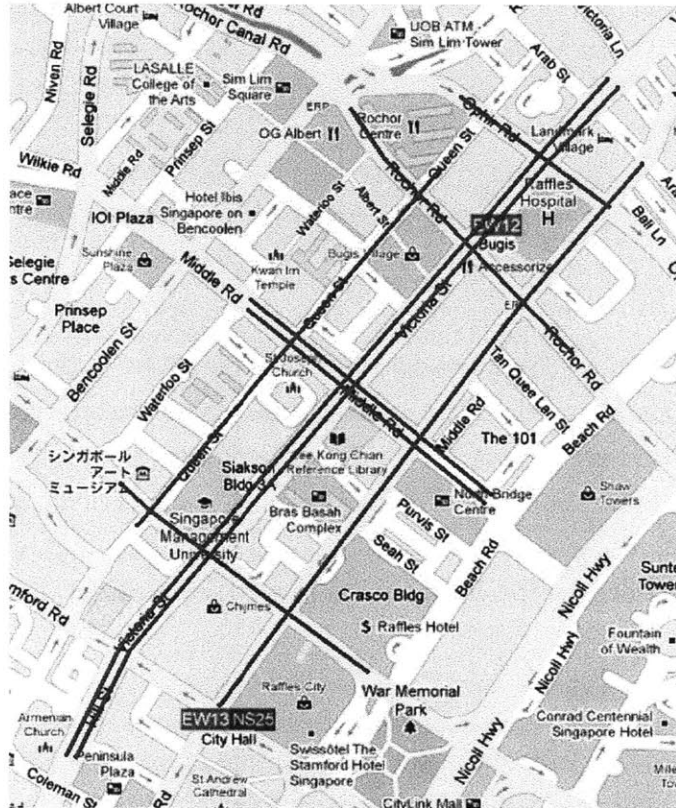


Figure 4.4: Bugis Network

Source: Google Maps

The chosen study dataset is from the traffic data around the Bugis MRT in Singapore (Figure 4.4). Bugis MRT is a major station on the East West line of the Singapore MRT. The road network around the MRT sees busy traffic because of the connectivity to many shopping malls and several other busy parts of the city like Bugis Village and Bugis Junction. This location was chosen as the network to deploy pilot applications of the green light prediction technology because of the complex traffic flows during the peak periods. The network considered in this study consists of all major urban roads around this MRT station.

The road network modelled in MITSIMLab is shown by red lines in Figure 4.4. The network file in MITSIMLab consists of 44 nodes, 56 links and 31 signal heads. The signal traffic controllers used in this are pre-timed controllers.

#### **4.3.1.2 Dataset Overview**

Data collected from the loop detectors in the study area was used to derive the counts data. The counts data for a total of 22 loop detectors covering the Bugis network was obtained. The dataset in its original form records the number of vehicles passing a certain lane at a granularity of about a couple of minutes. For consistency among the data collected from all the loop detectors, the counts data was aggregated over 15 minute intervals. The data was available for 90 minutes of morning peak period over 10 days in the month of June 2010. Hence the processed data contains vehicle counts data for six 15 minute intervals for each of the ten days. The counts data was used to generate OD matrices for the whole network which are used as the demand files for the simulation runs. Figure 4.5 shows the locations of the loop detectors on the network.

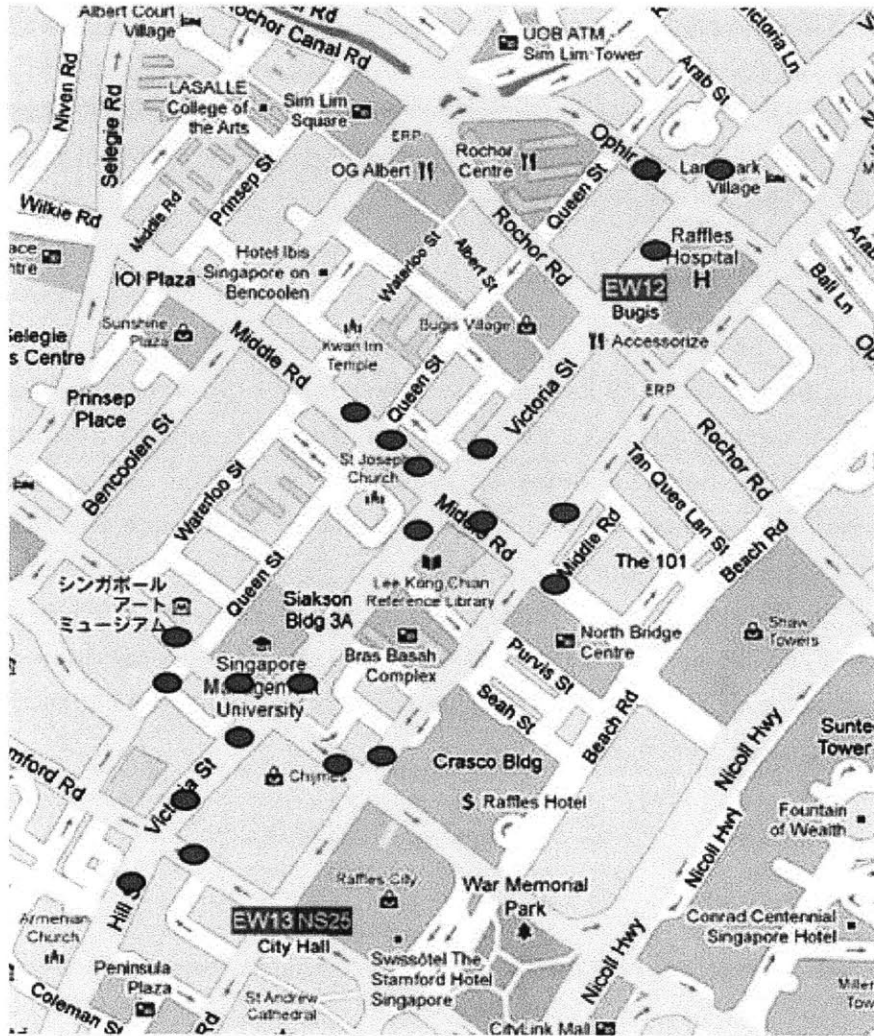


Figure 4.5: Location of loop detectors on the Bugis Network

Source: Map - Google Maps, Sensor Locations - Land Transportation Authority, Singapore

Sensor ID	Average Counts
1	164
2	364
3	288
4	1338
5	68
6	885
7	260
8	242
9	908
10	419
11	53
12	266
13	147
14	112
15	128
16	12
17	77
18	161
19	326
20	210
21	307
22	132

Table 4.1: Statistics of Count Data

The sensors in the network are located on both sides of the road. Overall there are 22 loop detectors, each of which records counts at different locations in the network. The statistics for average counts over a fifteen minute interval are presented in Table 4.1.

### 4.3.2 Aggregate Calibration

Aggregate calibration of the model has been formulated as an optimisation problem which seeks to minimise the deviation of the simulated traffic measurements from the observed measurements. The optimisation process has been performed using MATLAB following Box's complex algorithm (Box, 1965). The details of the calibration methodology have been discussed in B.

Calibration of all the parameters in the behavioural models of MITSIMLab is too costly. Based on previous experience, the following parameters have been selected for calibration:

- **Car-following parameters:**

- Acceleration constant
- Deceleration constant
- **Desired Speed**
  - Mean
  - Standard Deviation
- **Critical Gaps**
  - Lead gap constant
  - Lead gap standard deviation
  - Lag gap constant
  - Lag gap standard deviation
- **Lane Utility model**
  - Current Lane constant
  - Right-most lane constant

<b>Parameter</b>	<b>Initial Value</b>	<b>Calibrated Value</b>
Acceleration constant	0.0916	0.0730
Deceleration constant	-0.0278	-0.0259
Desired Speed Mean	0.100	0.260
Desired Speed Standard Deviation	0.166	0.154
Lead Gap Constant	2.6241	3.5255
Lead Gap Standard Deviation	0.5961	0.7592
Lag Gap Constant	-0.4693	0.0410
Lag Gap Standard Deviation	4.8637	1.3309
Current Lane constant	3.7063	3.9443
Right-most Lane constant	-0.5631	-0.3213

Table 4.2: Calibration Results

The calibration process is carried out to match the model to observed counts data as closely as possible. Table 4.2 shows the initial and calibrated values of the parameters:

RMSPE	0.798
MPE	-97.74

Table 4.3: Validation Results - Measures of effectiveness for counts

To test the goodness of fit of our calibrated model, we validated the model against the count data from another 3 weekdays of data for the same network. The results of the validation process are tabulated in Table 4.3. The results of the validation can be improved with additional data like speeds or trajectory data to calibrate our model.

### 4.3.3 Base-line Scenario

The base-line scenario reflects the current situation without the use of green light prediction application. To simulate the baseline scenario, the penetration rate of the application in our model is kept at zero. Since the expected benefits from the green light prediction are the travel time savings achieved by avoiding the delays at the red light, the average speed can be used as proxy to represent the network performance. This value along with the average number of halts per trip for the vehicles during the simulation run are used as the datum bar against which different V2V scenarios can be assessed. The base-line average speed depends on a number of factors like the network configuration, incidents, etc. To account for the stochasticity of the underlying models, the simulation is run 8 times to calculate the average values. The network is assumed to reach its base-line capacity without any deployment of the V2V technology when the spill-back queues start to form at the entry nodes at the critical OD matrix scaling factor (Appendix D). The critical scaling factor is used to run simulations to reflect maximum travel demand on the network.

For the Bugis network, the average speed in the base-line scenario was found to be **11.64 km/hour**. In the next section, we look at the network performance analysis under different penetration rates of the V2V technology.

### 4.3.4 Scenario Analysis

Since the technology under consideration has never been deployed, we do not have any previous experience and ideas about the level of acceptance or penetration of the technology. Hence for a complete assessment of the impact of the technology, we define several different scenarios across three parameters:

- Penetration rate: fraction of driver population with green light prediction application

- Compliance rate: fraction of total advisories followed by drivers
- Travel Demand level: One-third of existing demand, Two-third of existing demand, Existing demand, Maximum demand; where Maximum demand is the travel demand served by the network at its capacity (Appendix D).

In the following sub-sections, we see the variation in the impact of the technology across different penetration rates at different travel demand levels. Then we go on to see the variation in the impact across different compliance rates to the technology. The average speed, travel time savings and the average number of halts per trip during the simulation runs has been used as the measure to assess the impact of the technology across these scenarios. To take into account stochasticity of the underlying models in MITSIMLab, for every scenario simulations were run 8 times. The average MOEs across the 8 simulation runs are reported in the following section.

#### 4.3.4.1 Average Speed

We use average speed as a proxy to measure any travel time savings that can be realised by the green light prediction application. We calculate the average speed for simulation runs across different penetration rate, compliance rate and travel demand levels.

#### Penetration Rate

In this test, we observe the variation of traffic performance across different penetration rates of green light prediction application. The changes in the penetration rates are reflected in MITSIMLab model by the parameter `V2V_penetration`. For example, when the `V2V_penetration` is set at 0.80, 80% of the vehicles entering the simulation have the V2V capability. Hence these vehicles have pre-knowledge of state of the downstream signal and remaining green time. These vehicles alter their manoeuvres to try to comply with speed advisories. The rest of the 20% population of vehicles follows the regular car-following behaviour.

As the penetration rate of application increases informed behaviour can be expected from a larger portion of the users. In the extreme case of 100% penetration, the scenario shall turn in to a collaborative driving case where the manoeuvres by all the users act towards a common goal. Hence we can expect a gradual improvement as the penetration rate increases.



Penetration Rate	Average Speed (km/hr)	Percentage change in average speed
Base-line	15.48	0
0.1	15.67	1.23
0.2	15.80	2.07
0.3	15.85	2.39
0.4	15.86	2.45
0.5	16.05	3.68
0.6	16.06	3.75
0.7	16.07	3.81
0.8	16.32	5.43
0.9	16.36	5.68
1.0	16.42	6.07

Table 4.4: Network performance across different penetration rates at One-third of existing travel demand

Table 4.4 shows the impact of the different penetration rates on the traffic performance measured in terms of average speed at One-third of existing travel demand.

The variation in the average speed across the range of penetration rate suggest a gradual improvement in the average speeds over the whole network. The model predicts a significant increase of **6.07%** in the average speed at the complete penetration of the technology. As more number of people on the road start using the application, the flexibility to leverage the information increases. At low penetration levels the myopic behaviour by the uninformed drivers acts as a constraint to the movement of informed drivers. Hence as the penetration rate increases more travel time savings benefits can be realised as a result of informed manoeuvres by most of the drivers.

Penetration Rate	Average Speed (km/hr)	Percentage change in the average speed
Base-line	14.01	0
0.1	14.09	0.57
0.2	14.13	0.86
0.3	14.16	1.07
0.4	14.16	1.07
0.5	14.16	1.07
0.6	14.17	1.14
0.7	14.20	1.36
0.8	14.20	1.36
0.9	14.21	1.43
1.0	14.22	1.50

Table 4.5: Network performance across different penetration rates at Two-third of existing travel demand

Table 4.5 shows the variation in the impact of green light prediction technology across different penetration rates at Two-third of existing travel demand.

The variation in the average speed is very gradual across the penetration rates at Two-third of existing travel demand. However the trend still shows travel time saving benefits because of the green light prediction technology. Also a drop in average speed is noticed as the traffic demand increases from the last scenario.

Penetration Rate	Average Speed (km/hr)	Percentage change in the average speed
Base-line	11.75	0
0.1	11.78	0.26
0.2	11.79	0.34
0.3	11.84	0.77
0.4	11.85	0.85
0.5	11.87	1.02
0.6	11.88	1.11
0.7	11.91	1.36
0.8	11.94	1.62
0.9	11.99	2.04
1.0	12.00	2.13

Table 4.6: Network performance across different penetration rates at existing travel demand

Table 4.6 shows the variation in average speed limits across different penetration rates at existing travel demand. The average speed at complete penetration of the application at existing travel demand was found to be **12.00 km/hour** with a standard error of 0.13 km/hour for 8 number of observations. The increase in the average speed with respect to the baseline scenario was 1.85 times of the standard error.

<b>Penetration Rate</b>	<b>Average Speed (km/hr)</b>	<b>Percentage change in the average speed</b>
Base-line	7.23	0
0.1	7.31	1.11
0.2	7.77	7.47
0.3	8.25	14.11
0.4	8.37	15.77
0.5	8.52	17.84
0.6	8.53	17.98
0.7	8.68	20.06
0.8	9.05	25.17
0.9	9.19	27.11
1.0	9.36	29.46

Table 4.7: Network performance across different penetration rates at Maximum travel demand

Table 4.7 shows the variation in the average speed of all the vehicles entering the simulation at High traffic demand.

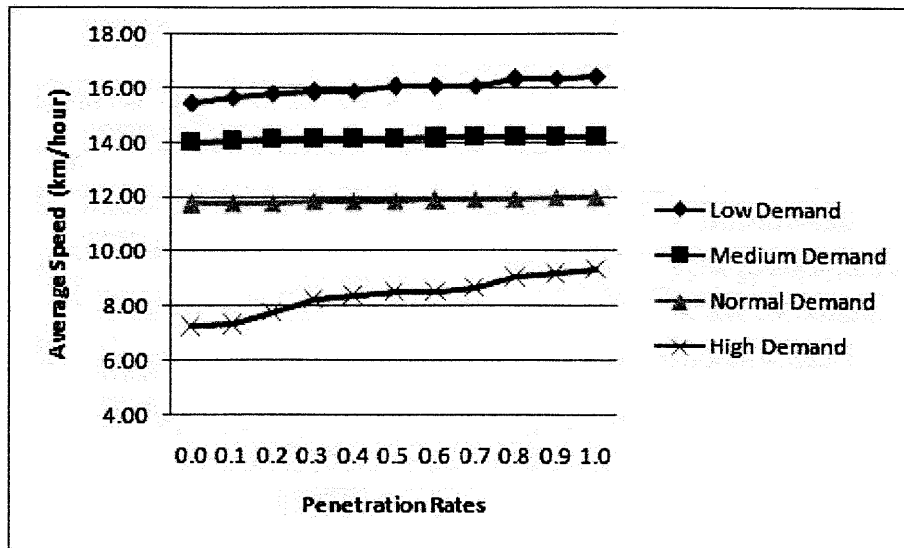


Figure 4.6: Average Speed across penetration rates over different travel demand levels

Figure 4.6 shows the variation of average speed across the penetration rate at different travel demand levels.

As we can see from Figure 4.6 the variation in the average speed is found to be most significant at Maximum travel demand level. The slopes for the trends at Two-third of existing and existing travel demand levels are smaller than those at One-third of existing or Maximum travel demand levels. In the absence of competing vehicles at One-third of existing travel demand levels, the driver has better flexibility in altering his/her manoeuvres in response to the green light prediction advisories. Hence higher benefits are expected from the technology at One-third travel demand. The benefits have been observed to drop when the travel demand rises to Two-third of existing and existing level. The benefits in terms of average speeds are better at Maximum travel demand level. This may be the result of heavy penalties in terms of travel time at peak congestion without green light prediction speed advisories. Given that during peak congestion the traffic suffers the most from the delays from halts in the trip, the application has a better window of potential benefits to achieve. By using the green light prediction speed advisories, users are able to leverage this knowledge to their advantage by reducing this delay from their total travel time.

### Travel Demand Level

As the travel demand level increases the travel time between the same OD pair increases. Hence a decrease in average speed is expected as we increase the travel demand in our

model.

Figure 4.7 shows the variation in the average speed across different travel demand levels over a spectrum of penetration rates. The average speeds show the expected decreasing trend with the increase in the travel demand across all the penetration rates.

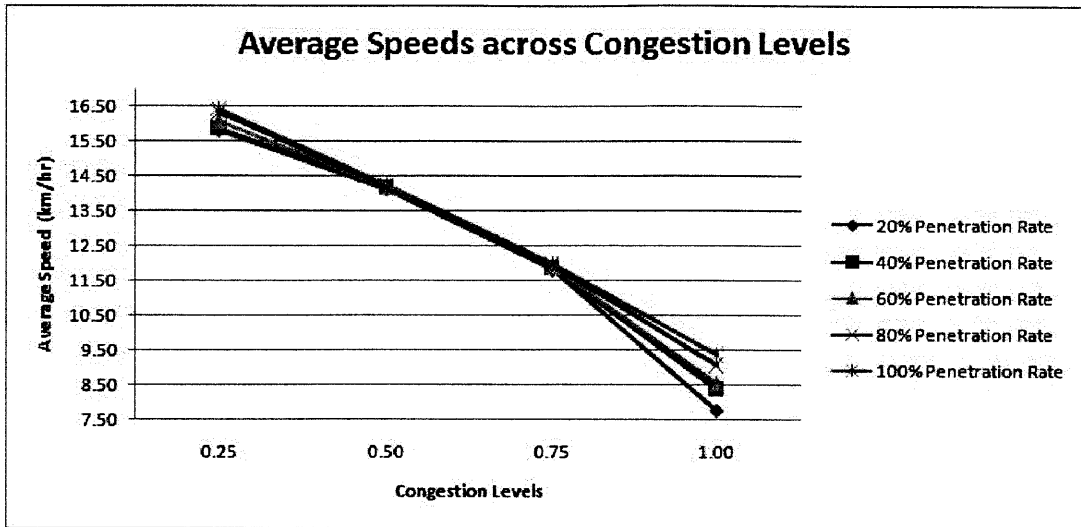


Figure 4.7: Average Speed across travel demand levels over different penetration rates

One interesting observation from Figure 4.7 is that the plots of average speeds across the travel demand levels tend to merge together at Two-third of existing and existing traffic demand levels. In other words, the impact of green light prediction application is diminished as compared to One-third of existing or Maximum travel demand levels. The One-third of existing and Maximum travel demand levels show significant increase in the average speed, with highest increases in average speeds observed at the Maximum travel demand level.

### Compliance Rate

In this test, we see the variation of the traffic performance across different rates of compliance to the green light prediction technology. The compliance rate provides a way to factor in the reliability of the technology as perceived by the user. Also the compliance factor can be used to account for the wireless connectivity in the behaviour model. The changes in the compliance rates are reflected in MITSIMLab by the parameter V2V\_compliance. e.g when the V2V\_compliance is set at 0.30, 30% of the times during the simulation run drivers of the vehicles with V2V capability entering the simulation trust and follow the green light prediction advisory. Hence the V2V enabled vehicles follow the regular car-following behaviour for 70% of the times an advisory is generated.

Penetration Rate	Average Speed (km/hr)	Percentage change in average speed
Base-line	15.48	0
0.1	15.67	1.24
0.2	15.84	2.32
0.3	15.91	2.77
0.4	15.91	2.77
0.5	16.05	3.72
0.6	16.08	3.91
0.7	16.13	4.23
0.8	16.21	4.74
0.9	16.22	4.80
1.0	16.39	5.89

Table 4.8: Network performance across different penetration rates at 25% compliance rate

Table 4.8 shows the impact of the different penetration rates on the traffic performance measured in terms of average speed at 25% compliance rate.

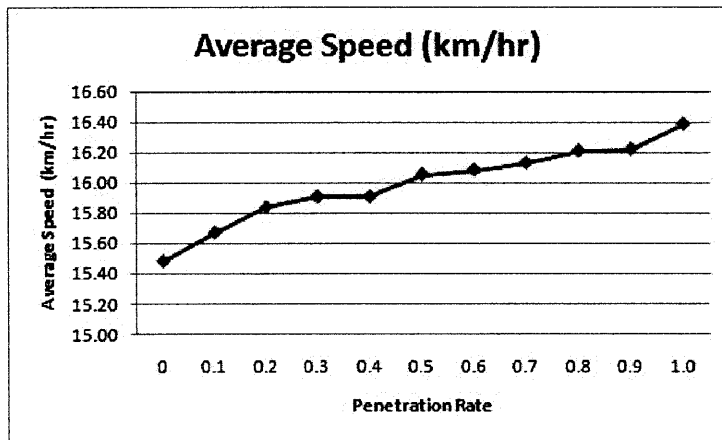


Figure 4.8: Average speed across different penetration rates at 25% compliance rate

The variation in the average speed across different penetration rates is as plotted in Figure 4.8.

The variation in the average speed across the range of penetration rates suggest a gradual improvement in the travel time savings for the whole network. As more people on the road start using the application, the flexibility to leverage the information increases. Hence as

the penetration rate increases more travel time savings benefits can be realised as a result of informed manoeuvres by most of the drivers.

Penetration Rate	Average Speed (km/hr)	Percentage change in the average speed
Base-line	15.48	0
0.1	15.91	2.77
0.2	16.06	3.76
0.3	16.07	3.82
0.4	16.07	3.82
0.5	16.16	4.40
0.6	16.16	4.44
0.7	16.24	4.92
0.8	16.29	5.24
0.9	16.34	5.57
1.0	16.39	5.89

Table 4.9: Network performance across different penetration rates at 50% compliance rate

Table 4.9 shows the variation in the impact of green light prediction technology across different penetration rates at 50% compliance rate.

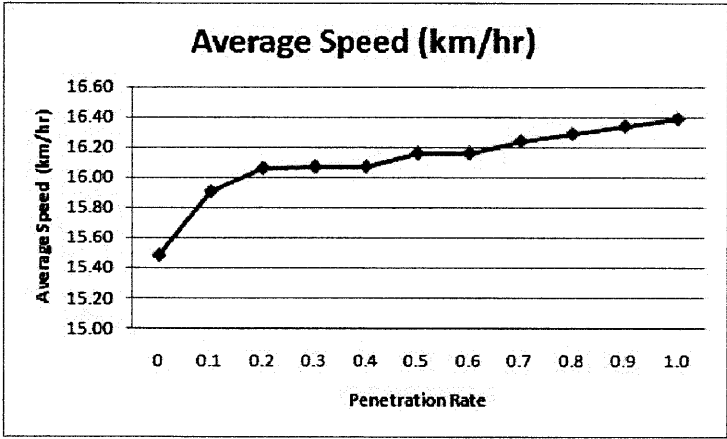


Figure 4.9: Average speed across different penetration rates at 50% compliance rate

The variation in average speed across the penetration rates at 50% compliance rate is shown in Figure 4.9.



The variation in the average speed is very gradual across the penetration rates at 50% compliance rate. However the trend still shows travel time saving benefits because of the green light prediction technology. Also a drop in average speed is noticed as the compliance rate increases from the last scenario.

Penetration Rate	Average Speed (km/hr)	Percentage change in the average speed
Base-line	15.48	0
0.1	16.00	3.37
0.2	16.01	3.43
0.3	16.11	4.08
0.4	16.13	4.21
0.5	16.16	4.40
0.6	16.18	4.53
0.7	16.20	4.66
0.8	16.22	4.79
0.9	16.35	5.63
1.0	16.41	6.02

Table 4.10: Network performance across different penetration rates at 75% compliance rate

Table 4.10 shows the variation in average speed limits across different penetration rates at 75% compliance rate.

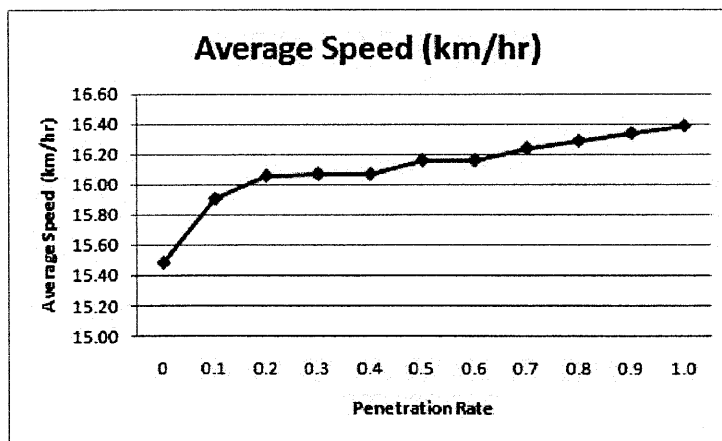


Figure 4.10: Average speed across different penetration rates at 75% compliance rate

The variation in average speed across the penetration rates at existing travel demand is shown in Figure 4.10.

The variation in the average speed follows the expected trend across the penetration rates with lower average speeds as compared to the last scenario.

As the compliance rate to the speed advisories increases most of the benefits in terms of the increase in average speeds are realised at lower penetration rates. The graph tends to taper off at higher penetration rates of the technology. At lower compliance rates, the increase in the benefits is more uniform over all the penetration rates. In other words, as the reliability of the technology increases most of the benefits from the technology can be realised by achieving relatively lower penetration rates of the technology.

#### 4.3.4.2 Travel Time

##### Penetration Rate

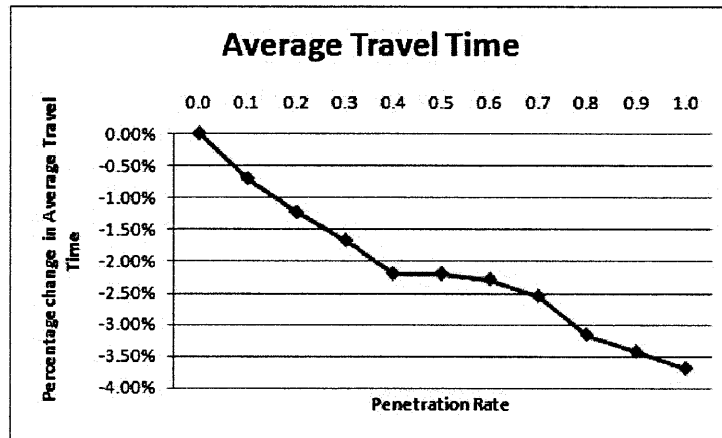


Figure 4.11: Average travel time across penetration rates at existing travel demand level

The trend of average travel time per trip across the penetration rates is shown in Figure 4.11. The incremental savings in the average travel time are slightly more at lower penetration rates as the penetration rate increases. The incremental benefits in the travel time savings by increasing the penetration rate of application gradually diminish across the range. At the 100% penetration of the technology, the average travel time is found to be **2.48 minutes** with a standard error of 0.06 minutes for 8 number of observations. The reduction in travel time with respect to baseline scenario was 1.55 times of the standard error.

## Compliance Rate

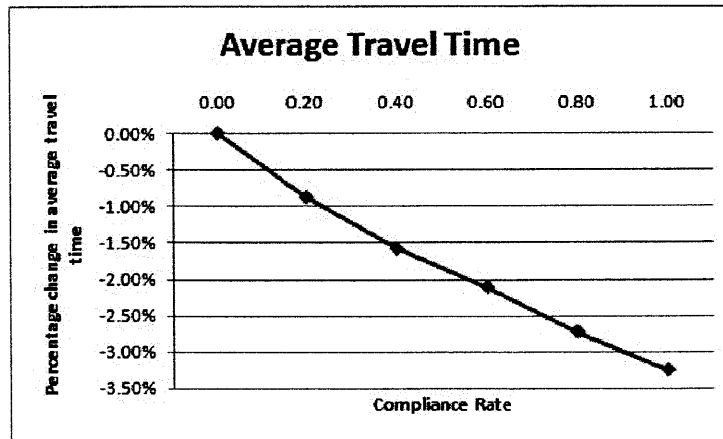


Figure 4.12: Average travel time across compliance rates at existing travel demand level

The trend of average travel time across the compliance rate is shown in Figure 4.12. The trend in average travel time follows an almost linear pattern across the compliance rates. The incremental increase in the average travel time is marginally larger as the compliance and trust for the technology goes up.

### 4.3.4.3 Halts

The goal of the green light prediction application is to avoid the halts at the intersections. Hence to assess the impact of the technology on the network performance we need to observe the trend of the average number of halts per trip across different penetration rates. We define a halt as an instance where the speed of a vehicle drops below a certain pre-determined threshold like 3 km/hr. We calculate this parameter across different penetration and compliance rates.

## Penetration Rate

Penetration Rate	Average number of halts per trip
0.0	3.64
0.1	3.56
0.2	3.52
0.3	3.45
0.4	3.44
0.5	3.37
0.6	3.33
0.7	3.29
0.8	3.29
0.9	3.27
1.0	3.25

Table 4.11: Average number of halts per trip across penetration rates

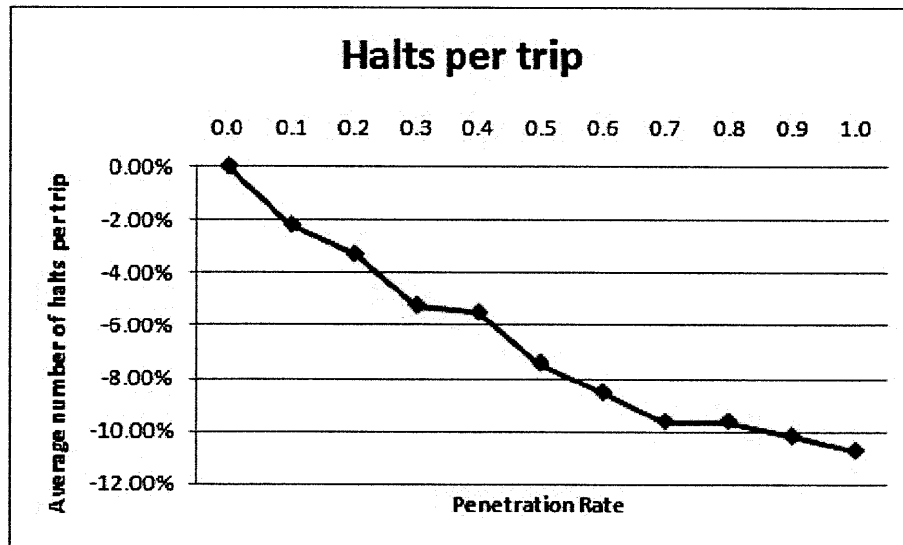


Figure 4.13: Percentage change in average number of halts per trip across penetration rates

The variation of the average number of halts per trip across different penetration rates is shown in Table 4.11 and Figure 4.13. The average number of halts per trip at complete penetration of the application at existing travel demand was found to be **3.25**, with a standard error of 0.13 for 8 number of observations. The reduction in average number of halts per trip with respect to baseline scenario was 2.87 times of the standard error.

The reduction in the average number of halts per trip is observed to be approximately linear. The incremental effect of the technology is more predominant for lower penetration rates. The potential increment in benefits from the technology begin to taper off as the penetration rate rises. These observations are in agreement with the travel time benefits across the penetration rates.

### Compliance Rate

The variation of average number of halts per trip was calculated across different compliance rates at a 100% penetration rate of the technology. The trend is shown in Table 4.12 and Figure 4.14.

Compliance Rate	Average number of halts per trip
0.0	3.64
0.2	3.49
0.4	3.47
0.6	3.46
0.8	3.36
1.0	3.10

Table 4.12: Average number of halts per trip across compliance rates

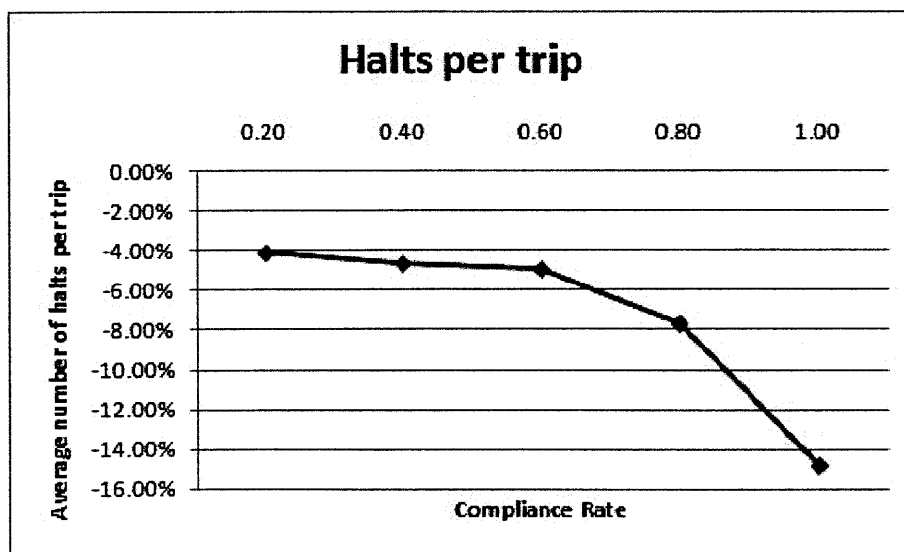


Figure 4.14: Percentage change in average number of halts per trip across compliance rates

The number of interruptions reduce as the compliance and trust in speed advisories increases. The incremental benefits show a peak at higher rates of compliance. In other words, the

vehicles trips are smoother with less interruptions as the reliability of the speed advisories increases. At lower compliance to the speed advisories, the model essentially replicates the scenario without any V2V application. The resultant vehicle trips are still abruptly by the stops at the intersections. As higher reliability of the speed advisories is achieved, the traffic flow shows signs of cooperative driving where all the vehicles drop or increase their speeds to avoid the delay at the intersections. Hence higher benefits in terms of halts per trip may be observed at higher compliance rates.

## 4.4 Summary

In this chapter, we use a real road network near the Bugis MRT station in Singapore to perform a case study analysis. The driving response to the green light prediction was modelled by using the received information to generate speed advisories. The goal of the speed advisories is to reduce delays at the intersections by avoiding the red light. Compliance to these advisories alters car-following behaviour of the driver. The compliance in turn depends in the reliability of the speed advisories as perceived by the user and his/her familiarity with the network.

Since the technology is not yet deployed and there are not reliable predictions about the penetration rates of this application, the analysis was carried out over a range of different scenarios. These scenarios encompassed the variation in impact of the technology across different penetration rates, travel demand levels and compliance rates. Since the goal of the technology is to reduce the number of halts at the red light, we use average speed, travel time and average number of halts per trip as the measures of effectiveness.

The results of the analysis across these scenarios show significant improvement in the average speeds as the penetration rate of the application increases. For existing conditions, the average travel time and average number of halts per trip were found to improve by **3.69%** and **10.71%** respectively, at complete penetration by the green light prediction application when compared to the scenario without the application.

The increments in average speeds are mostly uniform across penetration rates with lower penetration rates yielding slightly higher incremental benefits in terms of average speeds. The compliance rate is seen to have a similar effect on the benefits achieved by the application. As the travel demand goes up, an expected drop in average speed is observed. An interesting observation was that most of the benefits of the application were observed

at one-third of existing or maximum travel demand levels. At two-third of existing and existing travel demand levels the benefits of the technology seemed to diminish.

The average travel times and average number of halts per trip are observed to follow the expected reducing trend as the penetration rate of the application increased. Most of the benefits in terms of both of these metrics are observed to be realised at lower penetration rates of the technology with higher penetration rates not yielding significant increments in the benefits.

It must be mentioned that reliability of speed advisories in our model follows random distribution whereas in reality it will depend on the number of vehicles passing a traffic light, wireless connectivity among vehicles, etc. The observed trends can be improved by considering these interactions by coupling this model to a wireless network simulator.

To summarise, the green light prediction technology can improve average speed in the order of 2% at existing travel demand level, by reducing the delays at the traffic light intersections, even at relatively low compliance and reliability of the technology. These travel time savings, if monetised, along with the fuel savings and the environmental benefits, can be used to justify the deployment of such a technology in real life. Since significant benefits have been observed at lower penetration rates with tapering incremental benefits at higher penetration rates, we can find an optimal penetration rate where the incremental monetary benefits match the incremental costs of the technology deployment.

In the next chapter, we draw conclusions and inferences from the case study. We also identify the next step in development of this approach for future directions for research.





# Chapter 5

## Conclusion

In this chapter we summarise the research and the findings reported in this thesis. We highlight the major contributions and conclude the chapter by suggesting possible directions for future work along the line of research presented in this thesis.

### 5.1 Thesis Summary

The objective of this thesis is to explore the applications of wireless technology and its deployment for ITS purposes and to develop a simulation framework in order to assess their impact on traffic performance.

The first step is to gain an understanding of the applications of this technology and the approaches used to assess its performance. The goal of the literature review is to identify the ways to make the driving behaviour models sensitive to the V2V technology applications. From previous work, integration of a wireless network simulator with a traffic simulator is observed as a better approach than using individual simulators. However the need to make behaviour models sensitive to the V2V application is observed.

An integrated modelling framework is proposed to capture the effects of a wireless V2V communication application in a simulation study. The wireless network simulators expect the relative position, speed and wireless device capability of every individual network in the simulation as the input. The wireless network simulator reads these inputs as “mobile nodes” with wireless capabilities and uses wireless message propagation and interference models to establish wireless “connectivity” and “reliability” of the message exchanged between the vehicles. Wireless connectivity is established among two vehicles if they can exchange a

message over the wireless network. Reliability of the message reflects the confidence in data collection accuracy and algorithm used to generate advisories.

In the proposed modelling framework, we demonstrate that the “connectivity” and “reliability” of the message exchange affects the way the information disseminated over the wireless network affects the driver. Driving behaviour models like car-following and lane-changing predict the manner in which a driver reacts to the surrounding traffic and information. Hence depending on the goal V2V communication application, driving behaviour models are modified to reflect the knowledge of the information to the driver. To account for less than 100% penetration rate of the technology, the drivers are categorised as either ordinary or V2V enabled. Each class of user follows the models pertaining to the respective class.

The proposed modelling framework is used to develop a case study on the Bugis road network in Singapore. A green light prediction application was the application chosen for the purpose of the case study. The purpose of the application is to generate speed advisories in order to avoid any halts at the red traffic light downstream. The application is designed to operate on a smart phone installed behind the windshield of a vehicle. It takes pictures of traffic lights in its field of view and collaboratively shares this information with other user. Based on this collaborative database of time-stamped traffic light phases, the application generates optimal speed advisories.

A model for a road network near the Bugis MRT station in Singapore is developed in the microscopic traffic simulator laboratory MITSIMLab. The road network has several signalised intersections and has complex traffic flows during peak hours. The model is calibrated and validated using counts data to replicate the traffic flow behaviour on the network. The calibrated model was validated against counts data for another set of weekdays. Then the model was run for a base-line scenario which reflected the existing traffic pattern without any V2V application considered.

The impact of the green light prediction application is incorporated in the car-following models. A certain section of the driver population which has the V2V capability based on the penetration rate of the technology carries the application on their vehicle and responds to the advisories. Also a compliance rate was defined for every driver to reflect the *reliability* of the advisories which in turn depends on the *wireless connectivity* of the vehicles. Based on this compliance rate the drivers may or may not choose to follow the advisories.

Since the technology is yet to be deployed, a number of scenarios were generated based on the penetration rate of the technology and the compliance to the advisories. The goal of the technology is to reduce the number of halts and promote uninterrupted traffic flows. Hence average speeds, average travel time and average number of halts per trip were used as the MOEs across the alternatives.

As expected, traffic performance improved as the penetration rate of green light prediction application increased. The greatest improvement in traffic performance is seen at higher level of demand. One reason for this might be that, the traffic performance drops rapidly as demand rises and traffic approaches crawling speed. Thus the application has a bigger window of potential improvement in traffic performance. As expected, average speed increases as the reliability and hence the compliance to the technology increases. The observed trends for average travel time and average number of halts agree with the trends for average speeds. One key observation is that incremental benefits taper off at higher penetration rates.

The SignalGuru application was evaluated by (Koukoumidis, Peh and Martonosi; 2011) and the results showed 20.3% savings in fuel consumption, on average. Even though the relationship between in fuel consumption and average speed might not be linear; the findings from physical experimentation are higher compared to the findings of this study. The physical experimentation had only five vehicles with the application scouting a network, while our simulation approach considers higher penetration rates of application. Physical experimentation captures all interactions of wireless connectivity whereas it is exogenous to our model at the moment. Our approach shall be explored further to produce results to compare with physical experimentation.

The study gives empirical evidence about the potential benefits that can be achieved from green light prediction application. Also the cost of the technology may depend on the penetration rate and the desired reliability of the advisories. Hence the trends presented in this thesis can be used as an indication of the optimal point where the benefits could be maximised while keeping the costs within the budget constraints.

## 5.2 Contribution

The thesis proposes a modelling framework to modify behaviour models to account for the impact of V2V communication based applications on traffic performance. The framework suggests coupling of a microscopic traffic simulator with a wireless network simulator to

capture both sides of the problem. However, in this thesis we limit ourselves to developing behavioural models to incorporate the driving response to the V2V communication based technologies. The step of modification of behaviour models depends on the kind and content of information made available by the use of the technology. The effect of V2V communication based ITS applications is linked to the changes in certain parameters in the behavioural models reflecting the perception of the driver.

The proposed modelling framework is developed for a case study in Singapore with green light prediction application as the V2V communication application. The car-following model is modified to account for driver's knowledge of speed advisories to avoid red lights. The modification in car-following model changes the urgency of the driver to reach the intersection.

The green light prediction application has been presented as the technology enabled by wireless V2V communication. The speed advisories generated are incorporated with the car-following model in response to the concerned traffic light. The model accounts for the various penetration rates of the technology and uses compliance rate as a proxy for the reliability of the delivered message. The study used average speeds and average number of halts per trip as the MOEs to assess the improvement in the traffic performance as a direct result of the technology. The trends of these MOEs across different penetration rates and compliance rates were obtained. The trends are indicative of the potential benefits of the technology and may be used to find the optimal point for the deployment of the technology.

### 5.3 Future Directions for Research

The research presented in this thesis focussed on the traffic simulation side of the simulation approach to model wireless V2V communication. However there is a lot of scope for work to be done in the future in this direction. Some of those ideas are described below:

- **Expansion to integration of simulators:**
  - The presented case study assumes a certain penetration rate of the technology. All the users with the device are assumed to receive “accurate” advisories which they follow based on a certain “compliance factor”. In practice, not all the vehicles will receive accurate advisories all the time. This simplification can be removed by introducing a wireless network simulator in the study. A wireless network simulator coupled with the traffic simulator will be able to generate parameter

values like reliability of the message transfer among vehicles. These values would be important to determine which vehicles will receive the advisories. The current model can be modified to inform only these drivers about the advisories.

- **Evaluation of green light prediction algorithm:**

- The speed advisories generated by the green light prediction application depend on the knowledge of the phases of traffic lights in the network. Hence if a particular intersection is traversed by very low amount of traffic, the application might not be able to generate speed advisories or may generate advisories with low reliability for that traffic light. A simulation study on the integrated platform can be used to determine the minimum traffic throughput at an intersection to sustain reliable predictions from the application.

- **Reliability of the advisories:**

- The reliability of speed advisories has been represented in terms of the compliance factor in this model. The reliability of advisories can be linked to the reliability of the message transfer as generated by the wireless network simulator. Also every person in the population may comply to the technology differently. The approach could be improved by modelling this heterogeneity of population with respect to the technology.

- **Refining the behaviour model:**

- In the presented study, the behaviour models were calibrated and validated using aggregate data. The model can further be refined by obtaining and using disaggregate trajectory data for the site. A model calibrated on the disaggregate data will be able to predict the behaviour more accurately.

- **Incorporating route choice:**

- The current model looks into the changes in desired speed in response to the advisories from the green light prediction application. The application can be extended to generate route advisories to avoid halts at red traffic light. The model can be transferred to a bigger network to incorporate the route choice framework.



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# Appendix A

## MITSIMLab: Micro-scopic Traffic Simulation Laboratory

### A.1 MITSIMLab

MITSIMLab (Yang and Koutsopoulos, 1996) is a simulation-based laboratory that was developed for evaluating the impacts of alternative traffic management system designs at the operational level and assisting in subsequent refinement. Examples of systems that can be evaluated with MITSIMLab include advanced traffic management systems (ATMS) and route guidance systems.

MITSIMLab is a synthesis of a number of different models and has the following characteristics:

- Represents a wide range of traffic management system designs;
- Models the response of drivers to real-time traffic information and controls;
- Incorporates the dynamic interaction between the traffic management system and the drivers on the network.

The various components of MITSIMLab are organized in three modules:

- Microscopic Traffic Simulator (MITSIM)
- Traffic Management Simulator (TMS)
- Graphical User Interface (GUI)

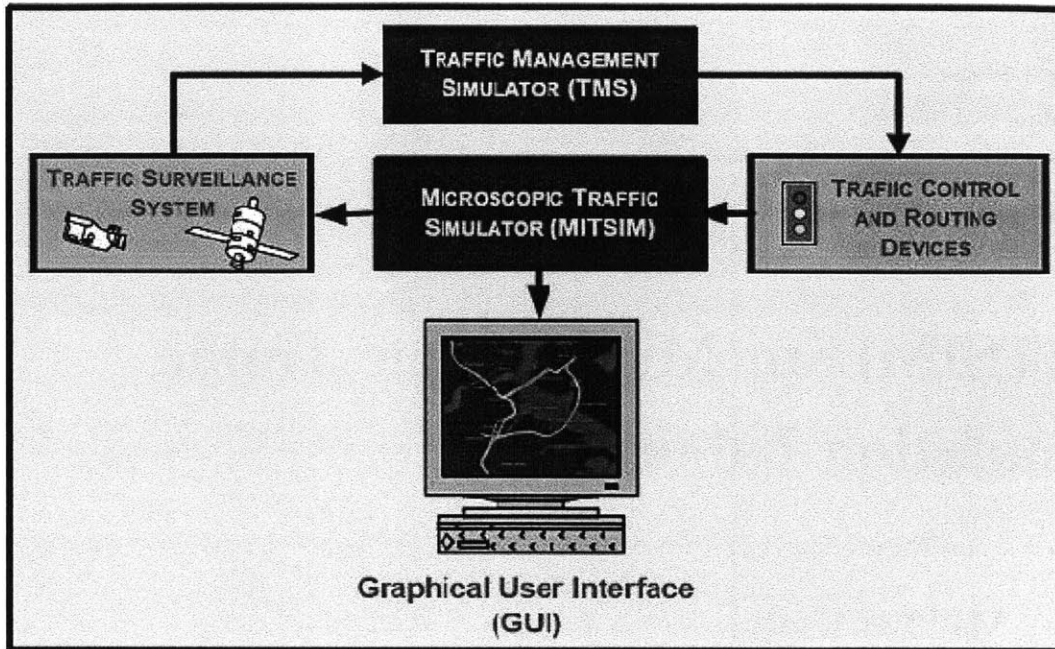


Figure A.1: MITSIMLab Framework

The interactions among the various MITSIMLab modules are shown in Figure A.1. A microscopic simulation approach, in which movements of individual vehicles are represented, is adopted for modelling traffic flow in the traffic flow simulator (MITSIM). This level of detail is necessary for an evaluation at the operational level. The Traffic Management Simulator (TMS) represents the candidate traffic control and routing logic under evaluation. The control and routing strategies generated by the traffic management module determine the status of the traffic control and route guidance devices. Driver behaviour is a response to the control strategies and a result of the interaction with other drivers in the model.

### A.1.1 Traffic Flow Simulator (MITSIM):

Traffic and network elements are represented in detail in order to capture the sensitivity of traffic flows to the control and routing strategies. The main elements of MITSIM are:

- **Network Components:** The road network geometry along with the traffic controls and surveillance devices are represented at the microscopic level. The road network consists of nodes, links and segments with lateral segmentation in to lanes.
- **Travel Demand and Route Choice:** A time-dependent origin to destination trip table is loaded as the demand input in to the traffic simulator. These OD tables

represent either expected conditions or are defined as part of a scenario for evaluation. A probabilistic route choice model governs the route choice decisions of the drivers once they enter the simulation.

- **Driving Behaviour:** The origin/destination flow demand creates a number of vehicles about to enter the network at different times during the simulation run. The driver is identified with the vehicle itself. Thus the behaviour parameters (such as desired speed, aggressiveness, etc.) and vehicle characteristics are assigned to every vehicle entity to generate a realistic population of network users. MITSIM moves vehicles according to car-following and lane-changing models. The car-following model captures the response of a driver to conditions ahead as a function of relative speed, headway and other traffic measures. The lane-changing model distinguishes between mandatory and discretionary lane changes. On-ramp merging and response to control devices like traffic signals, VMS, toll-booths, etc can also be modelled.

### A.1.2 Traffic Management Simulator (TMS):

The traffic management simulator mimics the traffic control system in the network under consideration. A wide range of traffic control and route guidance systems can be simulated, such as:

- Ramp control
- Freeway mainline control
- Lane control signs (LCS)
- Variable speed limit signs (VSLS)
- Portal signals at tunnel entrances (PS)
- Intersection control
- Variable Message Signs (VMS)
- In-vehicle route guidance TMS has a generic structure that can represent different designs of such systems with logic at varying levels of sophistication (from pre-timed to responsive).

### **A.1.3 Graphical User Interface (GUI):**

The simulation laboratory has an extensive graphical user interface that is used for both debugging purposes and demonstration of traffic impacts through vehicle animation.



# Appendix B

## Aggregate Calibration Framework

### B.1 Calibration Framework

Source: Rapolu (2010)

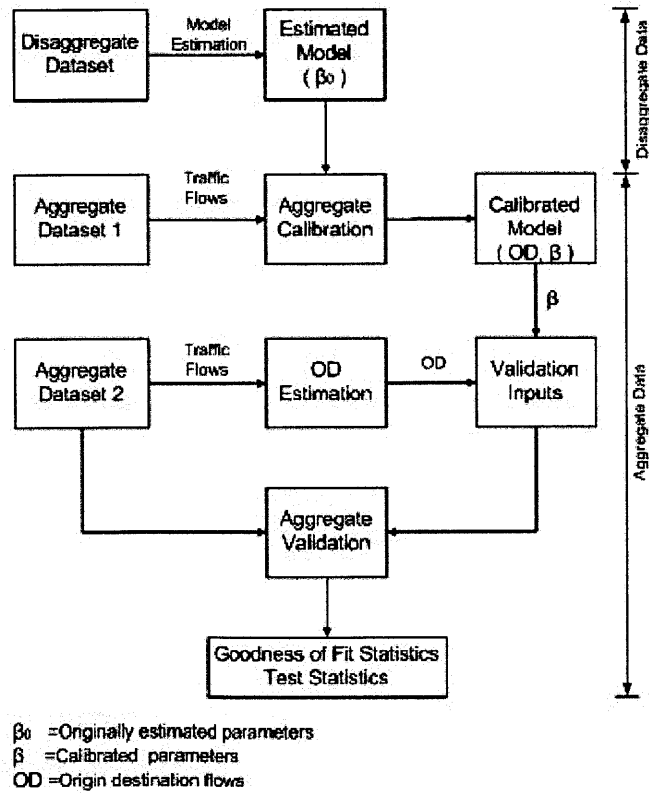


Figure B.1: Calibration Framework

The process of calibration of the simulation system aims to set the various parameters in the models so that observed traffic conditions are replicated as closely as possible. The overall calibration framework is summarized in Figure B.1.

The calibration process consists of two steps: first, the individual models of the simulation are estimated using dis-aggregate data. Dis-aggregate data includes detailed driver behaviour information such as vehicle trajectories.

In the second step, the simulation model as a whole is calibrated using aggregate data such as: flows, speeds, occupancies, time head-ways, travel times, queue lengths etc. The purpose of aggregate calibration of the simulation system is to adjust the various parameters so that observed traffic conditions are replicated as closely as possible. These parameters consist of the parameters of the behaviour model (initially estimated parameters  $\beta_0$  adjusted to  $\beta$ ) and the travel demand (expressed in terms of origin - destination or OD flows). In case of unavailability of the dis-aggregate dataset for a parameter, the values of these omitted parameters can be captured during the aggregate calibration.

Once the calibration is complete, the values of the full set of behavioural parameters are fixed ( $\beta$ ) and a second set of data is used for validation. Application of the simulation to replicate this dataset also requires OD flows as input. However, these may be different from the ones obtained in the calibration phase and so the OD estimation component of the calibration must be re-done for this dataset. These new OD flows and the calibrated parameter values are used as inputs to the simulation system.

### **B.1.1 Problem Formulation**

Aggregate calibration can be formulated as an optimization problem, which seeks to minimize a function of the deviation of the simulated traffic measurements from the observed measurements and of the deviation of calibrated values from the a-priori estimates of the OD flows and the estimated behaviour parameters.

The formulation is shown below. The first and second terms in the objective function are a measure of deviation between observed and simulated measurements and between a priori OD flows and the estimated OD flows respectively. The first constraint shows the dependence of simulated measurements on the driving behaviour parameters, OD flows and the network conditions. The second constraint is a non-negativity constraint for the OD flows.

$\min_{\beta, OD} \sum_{i=1}^N (M^{sim} - M_i^{obs})^T W^{-1} (M^{sim} - M_i^{obs}) + (OD - OD^0)^T V^{-1} (OD - OD^0)$  such that  $M^{sim} = S(\beta, OD)$

where

$\beta$  = driving behaviour parameters

$OD$  = OD flows

$OD^0$  = a-priori OD flows

$N$  = number of days for which sensor data is available

$M^{sim}$  = simulated measurements

$M_i^{obs}$  = observed measurements for day  $i$

$S$  = the simulation model function, which generates simulated traffic measurements

$W$  = variance-covariance matrix of the sensor measurements

$V$  = variance-covariance matrix of the OD flows

The sensor measurements in this case constitute the traffic flows at all sensor stations and all time intervals. The formulation presented above is difficult to solve because of the absence of analytical formulations that relate the affect of behaviour parameters to the sensor measurements and relatively large number of parameters to calibrate. An iterative solution approach is therefore adopted. In each iteration, first the driving behaviour parameters are kept fixed and the OD flows are estimated. Then the OD flows are kept fixed and the driving behaviour parameters are estimated.

The number of behaviour parameters in the simulation model is very large. It is not feasible to calibrate all of them. A sensitivity analysis is often done to identify the parameters that contribute most in improvement of the objective function. In sensitivity analysis, the impact of an individual factor on the overall predictive quality of the simulator is measured while keeping all other parameters at their original values.

Since the technology we need to test is not being implemented, we do not have any data that represents the driving behaviour in response to the technology. Hence we will calibrate our model to adjust for the travel flows observed on the field for the real life scenario. This model will then be used to test the impact of green light prediction over a range of different penetration rates.

## B.2 Goodness of fit measures

Model validation typically includes in it the tasks of aggregate calibration and aggregate validation.

The aggregate calibration process involves adjusting the values of the parameters of the behavioural models and estimating travel demand, in the form of OD flows, on the network being studied in order to obtain a better fit of the model output with the actual traffic flow. The aggregate validation process involves using the calibrated model on a different dataset to determine the extent to which the model accurately replicates traffic behaviour.

A number of goodness-of-fit measures can be used to evaluate the overall performance of the simulation model. Popular among them are the root mean square error (RMSE) and root mean square percent error (RMSPE). The two measures are given by:

$$RMSE = \sqrt{\frac{1}{N} \sum_{n=1}^N (Y_n^{sim} - Y_n^{obs})^2}$$

$$RMSPE = \sqrt{\frac{1}{N} \sum_{n=1}^N \left(\frac{Y_n^{sim} - Y_n^{obs}}{Y_n^{obs}}\right)^2} \quad \text{where } Y_n^{sim} \text{ and } Y_n^{obs} \text{ are the averages of observed and simulated measurements at space-time point } n, \text{ calculated from all available data.}$$

RMSE and RMPSE penalise large errors at a higher rate relative to small errors.

# Appendix C

## Communication Technologies

Coverage	Technology	Pros	Cons
Wide Area	Satellite Data	Global coverage	Very expensive, low data rate
Wide Area	AM/FM Radio	Regional coverage, ubiquitous deployment	Only broadcast, low data rate, no uplink
Wide Area	Digital Satellite Radio	Continent coverage, exclusive data channel	Only broadcast, no uplink
Wide Area	Digital Audio Broadcast	Regional coverage, high data rate	Only broadcast, not widely deployed yet, no uplink
Wide Area	Cellular	Sufficient population coverage, reasonable data rate	Relative expensive for data, low data rate
Local Area	Wireless LAN	No license cost, inexpensive, high bandwidth, strong industry support	Hotspot coverage
Local Area	Infrared	No license, inexpensive, already established	Limited range, limited bandwidth, only line of sight
Personal Area	Infrared	No license, inexpensive	Limited range, limited bandwidth, only line of sight
Personal Area	Bluetooth	No license, inexpensive	Limited range, limited bandwidth
Personal Area	UWB	No license, very high bandwidth	No standards

Table C.1: Wireless Communication: Technology Options

Source: Holfelder (2004)

Establishing a wireless communication network among mobile vehicles is a challenge and there is no perfect technological solution. While selecting the underlying technology, we need to consider three competing factors: Cost, Quality of Service and Availability. There are several options for the technology to be used to establish the V2V communication. Each of these technologies have a set of certain pros and cons (Table C.1; Holfelder, 2004). The initial use of sensors on vehicles involved radar or ultrasonic systems for safety applications. Though these systems provide additional safety, they have their natural limits. The traditional sensors are short-haul, have limited data capabilities and are relatively expensive.

Wireless communication established over a LAN (WLAN) can be used as a sensor collage which enables a vision for the driver encompassing a larger range on both the space and time dimensions. The extended local environment effectively extends the driver's horizon and can be used for a new class of safety and guidance applications.

To realise the effective communication, it is essential to establish a common "language" for all the participating vehicles. In 1999, the US Federal Communication Commission (FCC) allocated 75 MHz of spectrum at 5.9 GHz to be used exclusively for V2V and V2I communication in the US. This reserved spectrum is also referred to as the Dedicated Short Range Communication (DSRC). DSRC is based on the IEEE 802.11 WLAN standards family. IEEE 802.11 is a set of standards for implementing WLAN which follow the same protocol for communication. The research in this field has been dynamic with the development of a new standard, IEEE 802.11p Wireless Access in Vehicular Networks (WAVE) (Eichler, 2007). The approximate range of DSRC devices can be up to 1000m.

# Appendix D

## Network Capacity

Capacity is typically defined for a particular link in the network. The lack of common currency for the network capacity that can be used to make comparisons across different networks and situations makes the analysis difficult. A framework to calculate the network capacity that can be used across different networks and scenarios was developed in the work by Rapolu (2010). This currency is particularly useful in assessing the impact of any futuristic technology application such as V2V on the network performance.

The conventional link-based network analysis defines capacity as the maximum number of vehicles that can pass through a point in a unit time. This definition works fine for an individual link. However these capacities cannot be summed up over the entire network to get an idea of the network performance. Also this capacity value depends highly on the other traffic flows and the route patterns in the system creating an in-separable problem. e.g. the network performance changes significantly if a bottleneck is introduced in the network. Also the number of vehicles that can be physically accommodated in a given network is not an efficient way to define network capacity. A network which can physically accommodate fewer vehicles at a given time can still allow better throughput of vehicles in unit time. Thus, both static and throughput capacities contribute to the effective capacity of a network. Therefore, the unit of measurement for network capacity was defined as the vehicle miles travelled in a unit time (VMT/time). It is a logical measure of the network capacity as it denotes the maximum amount of travel possible in a given amount of time.

This definition of network capacity can be used to assess the network performance across different scenarios. To determine the network capacity, we perform multiple runs of every scenario on a microscopic traffic simulator like MITSIMLab. The demand file in MIT-SIMLab is a time based OD matrix for the whole network. During a simulation run, the

simulator keeps track of the vehicles which might queue up outside the network and have to wait to enter the network. If the network is not operating at its capacity it shall be able to accommodate more vehicles. Hence to determine the capacity of the network, we scale up the OD matrix to increase the demand. We keep increasing the scaling factor for the OD matrix until we observe a queue piling up outside the network. That scaling factor is called the critical scaling factor and the network is said to be operating at its capacity. Then multiple simulation runs can be performed at the critical scaling factor to determine the network capacity.