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Towards an Efficient and Equitable Motorway System using Ramp Metering and Variable Speed Limits

Duo Li

A thesis submitted in fulfillment of the requirements for the degree of Doctor of Philosophy,
The University of Auckland, 2015.
Abstract

Ramp metering (RM) and variable speed limits (VSL) are two important ITS tools aimed at improving the performance of motorway systems. The former improves the traffic flow conditions on motorway by limiting the inflow of vehicles from on-ramps; while the latter harmonizes the traffic flow on a motorway mainline by minimizing the variation in speed of vehicles obeying the VSL display. The main goal of this research is to improve the efficiency and equity performance of motorway systems using RM and VSL control measures. A number of RM and VSL control algorithms are proposed in this thesis to achieve this goal. They are assessed for a critical bottleneck section of Auckland Motorway using micro-simulation software AIMSUN.

First of all, two existing RM algorithms are assessed namely: ALINEA and HERO. HERO outperformed ALINEA in terms of efficiency and equity benefits. Then, a logic tree based VSL control algorithm is also assessed. The results revealed that the existing logic tree based VSL algorithm cannot improve significantly mobility performance of motorway systems and is rather rough for the speed control. Two alternative VSL control algorithms are proposed namely: a modified logic tree based controller and a fuzzy logic based controller. Both utilize optimized control logics and detector-controller configurations. The proposed algorithms outperformed the existing one in terms of their mobility benefits.

In the next step, an integrated RM and VSL control method is proposed to preserve the traffic flow at bottlenecks close to their capacity and avoid excessive delays at on-ramps. The integrated method shows prospect to improve further efficiency and equity performance of motorway systems than operating the RM and VSL controllers independently.
Finally, the relationship between efficiency and equity is investigated using a modified HERO strategy; this is aimed at achieving a balance between efficiency and equity gains from RM control. A combined index is proposed combining Gini coefficient and total travel time into one index, which can serve as an objective function to solve the bi-objective control design problem.
Acknowledgements

This work would not have been possible without the constant support by my supervisor Dr. Prakash Ranjitkar. I would like to express my deep-felt thanks to Dr. Prakash Ranjitkar for encouraging my interest in this field, and his mentorship throughout my study. I enjoyed very much learning from him and having the privilege to work with him. In Prakash, I found a supervisor whose boundless enthusiasm to discuss, debate and critically review all aspects of my work greatly enhanced the experience and inspired my learning. Sincere thanks to Professor Avishai Ceder, my co-supervisor for his advice and help.

I want to thank Mohsin Chaudry for his technical support and constant willingness to help; thank Gary See from NZTA for providing the traffic data that is necessary for this research; thank everyone in our ITS group for sharing their knowledge and experience with me; thank the editors from Wiley Editing Services for their proofreading.

Last and most importantly, I would like to extend my deepest gratitude to my parents Li Zhenjiang and Liu Zuhua and my wife Wang Xin for their support, understanding and love in countless ways.
Publications

Some of the chapters of this thesis are based on the following publications.

Chapter 4:

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## Acronyms

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<th>Definition</th>
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<tbody>
<tr>
<td>AMOC</td>
<td>Advanced Motorway Optimal Control</td>
</tr>
<tr>
<td>API</td>
<td>Application Programmer Interface</td>
</tr>
<tr>
<td>B</td>
<td>Big</td>
</tr>
<tr>
<td>CRM</td>
<td>Coordinated Ramp Metering</td>
</tr>
<tr>
<td>DC</td>
<td>Demand Capacity</td>
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<tr>
<td>FL-ALINEA</td>
<td>Flow based ALINEA</td>
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<tr>
<td>FLC</td>
<td>Fuzzy Logic Control</td>
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<tr>
<td>HERO</td>
<td>HEuristic Ramp metering coOrdination</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transportation System</td>
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<tr>
<td>LRM</td>
<td>Local Ramp Metering</td>
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<tr>
<td>LT</td>
<td>Logic Tree</td>
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<tr>
<td>M</td>
<td>Medium</td>
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<tr>
<td>MnDOT</td>
<td>Minnesota Department of Transportation</td>
</tr>
<tr>
<td>MOE</td>
<td>Measure Of Effectiveness</td>
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<tr>
<td>MPC</td>
<td>Model Predictive Control</td>
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<tr>
<td>NZTA</td>
<td>New Zealand Transport Agency</td>
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<tr>
<td>OASIS</td>
<td>Optimal Advanced System for Integrated Strategy</td>
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<tr>
<td>RM</td>
<td>Ramp Metering</td>
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<td>RMSE</td>
<td>Root Mean Square Error</td>
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<tr>
<td>S</td>
<td>Small</td>
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<tr>
<td>SH</td>
<td>State Highway</td>
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<tr>
<td>TTS</td>
<td>Total Time Spent</td>
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<td>TTT</td>
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UF-ALINEA  Upstream-Flow Based ALINEA
UP-ALINEA  Upstream-Occupancy Based ALINEA
VB          Very Big
VMS         Variable Message Signs
VS          Very Small
VSL         Variable Speed Limits
**Nomenclatures**

- $a$ is a control parameter ranging from 0 to 1
- $c_i$ is the centroid of the $i^{th}$ output class
- $C_{max}$ is the maximum cycle time
- $D$ is the distance to next station
- $d_c$ is the current density
- $d_e$ is the excess density
- $d(k-1)$ is the demand flow entering the on-ramp
- $d_l$ is the local density
- $D_n$ is the demand for the meter $n$
- $d_t$ is the target density
- $E$ is estimated volume by model
- $E_1, E_2$ are weight factors to stress the priority of each control objective
- $G$ is Gini coefficient value
- $i$ and $j$ are the $i^{th}$ and $j^{th}$ on-ramp
- $I_i$ is the area of the $i^{th}$ output class
- $k$ is the discrete time index
- $K$ is time horizon
- $K_1$ is the mainstream capacity
- $K_2$ is obtained based on slope of a straight line approximation of the left hand side of the fundamental diagram
- $K_f > 0$ is a regulator parameter
- $K_R > 0$ is a regulator parameter with a recommended value of 70veh/h
\( \bar{L} \) is the effective vehicle length which is a sum of actual vehicle length and detectable length of the loop detector in meters

\( n \) is the number of lanes

\( N \) is a number of measurement stations

\( o_{cr} \) is the critical occupancy

\( o_{in}(k-1) \) is the observed upstream motorway occupancy (%) during the period \((k-1)\)

\( O_{out}(k) \) is the observed downstream occupancy

\( \hat{O} \) is the desired downstream occupancy which is usually set as the critical occupancy

\( q_{cap} \) is the pre-specified downstream motorway capacity

\( q_{in} \) is the motorway traffic flow upstream of the on-ramp

\( q_{in}(k-1) \) is the observed upstream motorway flow (veh/h) during the period \((k-1)\)

\( q_{out} \) is the observed downstream flow

\( q_{ramp} \) is the measured inflow from the on-ramp

\( q_t \) is the target flow rate

\( q_{u} \) is the upstream flow rate

\( \hat{q} \) is the desired downstream flow

\( r \) is the metering rate

\( R \) is the volume reduction

\( r(k) \) is the on-ramp flow (veh/h) that will be applied during the period \( k \)

\( r'(k) \) is the amount of vehicles entering the motorway

\( r(k-1) \) is the metering rate during the period \( k-1 \)

\( r_{min} \) is a minimum admissible on-ramp flow
$R_{min}$ is the minimum metering rate

$R_n$ is the metering rate for the meter $n$

$\text{Sum}_W (i)$ is a sum of current queue lengths at each on-ramps within the coordination control string

$\text{Sum}_{W_{\text{max}}} (i)$ is a sum of the maximum admissible queue lengths at each on-ramp within the coordination control string

$T$ is the time interval

$TTT_{\text{non}}$ is TTT value computed using no control

$TTT_t$ is TTT value computed using tested measure

$V$ is field count

$w_i$ is the results of the aggregation of rules at the $i^{th}$ output class

$w(k)$ is the current queue length

$W_{\text{max}}(k)$ is the maximum admissible queue length of the respective on-ramp

$\hat{\omega}$ is the maximum permissible queue length

$\rho_i$ is density of a segment $i$

$\tau_i$ is the delay time on the $i$th on-ramp

$\bar{\tau}$ is the average delay time of all on-ramps

$\lambda_{in}$ is the number of mainstream lanes upstream of the on-ramp

$\lambda_{out}$ is the number of mainstream lanes upstream of the on-ramp

$\Delta_i$ is the distance between two measured stations $(i-1)$ and $(i)$
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Extent of contribution by PhD candidate (%): 90%

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Extent of contribution by PhD candidate (%)

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**Chapter 7:**

| Nature of contribution by PhD candidate | Prepared the data, developed the methodology, analysed the data and results, wrote the paper. |
| Extent of contribution by PhD candidate (%) | 90% |

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The undersigned hereby certify that:
- the above statement correctly reflects the nature and extent of the PhD candidate’s contribution to this work, and the nature of the contribution of each of the co-authors; and
- in cases where the PhD candidate was the lead author of the work that the candidate wrote the text.

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Chapter 8:

Nature of contribution by PhD candidate: Prepared the data, developed the methodology, analysed the data and results, and wrote the paper.

Extent of contribution by PhD candidate (%): 90%

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Chapter 1. INTRODUCTION

1.1. Background

With the emphasis of governments on wealth creation, demand for travel is increasing all over the world. The growth rate is particularly higher in and around metropolitan areas where most of the economic activities are concentrated. Motorways that are usually expected to provide a level of service, higher than that of other urban streets, are experiencing extensive daily traffic congestion and often reach stop-and-go state during peak periods. Adding capacity of road infrastructure is not always a viable option due to various social, spatial, financial and environmental constraints. Intelligent transportation systems (ITS) based measures aim for the optimal utilization of the available infrastructure incorporating distributed control and coordination system to ensure a safer, efficient and reliable transportation system. Ramp metering (RM) and variable speed limits (VSL) are two important ITS tools aimed at improving the performance of motorway systems. The former improves the traffic flow conditions on a motorway mainline by limiting the inflow of vehicles from on-ramps; while the latter harmonizes the traffic flow on a motorway mainline by minimizing the variation in speed of vehicles obeying the VSL display.

1.1.1. Ramp Metering

RM is widely used all around the world to regulate on-ramp traffic and is commonly regarded as one of the most direct and efficient countermeasures to mitigate traffic congestion on motorways (Papageorgiou, 2003). A great deal of experimental and simulation based studies conducted in the past have shown system-wide benefits from RM, which include reducing
travel times, increasing motorway throughputs, decreasing fuel consumption and emissions, and offering opportunities to provide priority entry to high-occupancy vehicles (Zhang and Levinson, 2005; Papageorgiou and Papamichail, 2007). As opposed to fixed-time based strategies, traffic responsive RM strategies improves the performance of motorway systems by regulating on-ramp traffic based on real-time measurements from the sensors installed in the motorway network. Over the years, a number of traffic responsive RM strategies have been developed, which can be broadly classified into two groups, namely: local ramp metering (LRM) and coordinated ramp metering (CRM). In LRM, the metering rate is determined based on local traffic conditions whereas CRM utilizes system-wide traffic measurements from an entire region of the network to control all on-ramps within that region. ALINEA is the most prominent example of LRM, which targets to a set point for the downstream occupancy or density (Papageorgiou et al., 1991).

CRM have distinct advantage over LRM when dealing with multiple bottlenecks, limited on-ramp storage spaces and inequity to travellers. A great deal of research works conducted in the past to come up with a number of CRM strategies. These strategies can be broadly classified into three categories, namely: optimal control strategies (Papageorgiou and Mayr, 1982; Zhang and Recker, 1999; Kotsialos et al., 2001; Kotsialos, 2004; Gomes and Horowitz, 2006), hierarchical control strategies (Papageorgiou, 1983; May, 1976; Geroliminis et al., 2012), and heuristic rule-based control strategies (MnDOT, 2003; Jacobson et al., 1989; Paesani et al., 1997; Papamichail et al., 2010).

Optimal control strategies employ relatively complex numerical solution, which makes it quite challenging to implement in the field. This might be the reason that most of the CRM strategies, implemented in the field, are heuristic rule-based strategies. Hadi (2005) compared the performance of a number of CRM strategies implemented in United States including Stratified Zone (MnDOT, 2003), Bottleneck (Jacobson et al., 1989) and Helper (Lipp et al.,
1991). More recently, Papamichail and Papageorgiou (2008) proposed a HEuristic Ramp metering coOrdination (HERO) strategy to overcome some of the drawbacks witnessed in the existing heuristic rule-based strategies. Using HERO, they claimed to have achieved an efficiency close to that of some sophisticated optimal control strategies discussed earlier. HERO strategy is in operation in Motorway A6 in Paris, France and Monash Freeway in Melbourne, Australia. Papamichail et al. (2010) conducted a before and after study of Monash Freeway and reported that HERO strategy has significantly improved the efficiency of the freeway system.

1.1.2. Variable Speed Limits

VSL is an emerging ITS tool, which can help to improve safety and efficiency of motorway systems through a better harmonization of traffic flow. It can reduce variation in speed of vehicles travelling along the controlled section. The implementation of VSL encourages a uniform driving behaviour and thus resulting in a better distribution of traffic over the motorway network, and better utilization of the road infrastructure (Hoogen and Smulders, 1994). VSL was used, for the first time, in Germany more than three decades ago. Nowadays, it appears in many European countries, North America and elsewhere (Elefteriadou et al., 2008).

Over the years, a number of VSL algorithms have been developed, which can be divided into two categories, namely: rule-based algorithms and optimal control algorithms. In rule-based algorithms, speed limits are determined by checking pre-specified threshold values while optimal control algorithms manage motorway mainline traffic through optimizing objective functions. Rule-based VSL algorithms are widely used in the field, which can be further subdivided into four groups, namely: flow-based algorithms (UK Highways Agency, 2004; Habtemichael and Picado-Santos, 2013), occupancy-based algorithms (Elefteriadou et al.,
2008), speed-based algorithms (Lee et al., 2004; Albania, 2013) and algorithms based on multiple parameters (Papageorgiou et al., 2008; Kianfar et al., 2013; Weikl et al., 2013). The effectiveness of optimal control algorithms to improve motorway performance has been verified by simulation studies (Papamichail et al., 2008; Popov et al., 2008; Carlson et al., 2010; Hadiuzzaman et al., 2012; Islam et al., 2013; Yang et al., 2013), however none of them are actually applied or operated in the field.

1.2. Research Gap

1.2.1. Assess the Existing RM and VSL Control Algorithms

The two main reasons behind applying VSL on motorways are to improve the safety and mobility of motorway systems. Safety benefits of VSL are well established in the literature (Ha et al., 2003; Hegyi et al., 2005; Allaby et al., 2007). This is apparently because of the strong relationship between vehicle speed and traffic safety. However, there is a considerable discrepancy about the mobility benefits of VSL; even though there are a number of studies that demonstrated its advantages based on empirical and simulation based research. Hegyi et al. (2005) conducted a simulation-based study using second order macroscopic traffic flow model called METANET to implement a model predictive control (MPC) based VSL algorithm on a 12 km stretch of a hypothetical road network. They reported 21% reduction in total time spent (TTS) for the entire network. Long et al. (2008) conducted a similar simulation-based study using METANET model and the algorithm proposed by Hegyi et al., (2005); however they could not find any significant improvement in TTS. Van den Hoogen and Smulders (1994) conducted a field based study using the data collected from A2 freeway in the Netherlands, where a speed-flow based VSL algorithm was implemented. They stated
that no improvements were witnessed in the bottleneck capacity. Papageorgiou et al. (2008) analysed the data collected from a motorway in Europe equipped with speed-flow based VSL controllers. The results from the study were rather inconclusive concerning capacity improvements due to VSL. There is no mention about the name of the motorway and also the location for data collection in the paper. More recently, Hoogendoorn et al. (2013) conducted a field based study using the data collected from A20 freeway near Rotterdam in the Netherlands. The authors reported 4% increase in the bottleneck capacity after the implementation of a speed-flow based VSL algorithm. Based on the reported findings from simulation based and field based studies as discussed earlier, it is difficult to reach any conclusion on the mobility benefits of VSL, as the results are either inclusive or contradictory. Thus it is important and necessary to evaluate systematically the mobility benefits of VSL on motorway systems.

A number of rule-based RM control strategies were proposed in the literature that differ in terms of the control logic used, their complexity, calibration efforts needed and the most importantly, the efficiency that they can yield. Some weaknesses that are partially shared by several rule-based strategies include (Papageorgiou and Papamichail, 2007):

- usage of pre-specified flow capacity values for the motorway mainline, which may change from day to day, even with different environmental conditions; and
- feed-forward rather than feed-back control at either the local or the system-wide level or at both levels.

HERO is a closed-loop feedback RM strategy, targeting a desired occupancy value; this enables HERO to overcome the aforementioned drawbacks of the existing heuristic rule-based strategies. Furthermore, Papamichail and Papageorgiou (2008) claimed that HERO can achieve an efficiency close to that of some sophisticated optimal control strategies discussed earlier. However, HERO is yet to be assessed for its equity performance.
1.2.2. Limitations of the Existing Rule-based VSL Algorithms

Rule-based VSL control algorithms have been widely used in motorway traffic management systems due to their comprehensibility and ease of application. Allaby et al. (2007) proposed a logic tree based VSL control algorithm. They reported that their proposed algorithm improved safety at the expenses of increased travel time. The two main reasons for the loss of mobility in this case can be attributed to: 1) Each VSL controller is linked to an adjacent detector. This can lead to a situation where VSL controllers have no information about the traffic conditions at the bottleneck section and hence it may display speeds either too aggressively or conservatively with a risk of too-early or too-late activation. 2) The threshold values may not be well defined for mobility improvement. Hence, it might be useful to modify the logic tree based algorithm proposed by Allaby et al. (2007) by changing detectors’ location, control logic and using optimal threshold values to improve its mobility performance.

Non-stationary and nonlinear nature of the traffic system makes it difficult to use pre-specified rules to appropriately activate/deactivate control actions in real time, which can be rather rough for the speed control. When an attribute is not discrete but continuous, e.g. traffic flow, a so-called “cut-off point” over the domain of attribute values are used to discretize the attributes. This feature of rule-based algorithms makes it too sensitive to changes in traffic flow and can lead to misclassification of attributes (Park and Bell, 2011). Furthermore, rule-based algorithms dynamically change speed limits whenever the traffic measurement exceeds or drops below a certain threshold value (or “cut-off point”). This may lead to oscillations in traffic flow. A fuzzy logic control (FLC) based approach can be useful to deal with the sensitivity issues confronted by the existing rule-based VSL control algorithms. It uses fuzzy sets instead of crisp sets to allow the separation of attribute domains into several overlapping intervals (Park and Bell, 2011). The FLC based approach can be
more suitable for VSL controllers due to the following reasons: 1) it does not require a mathematical model, thus it is not limited by the accuracy of the system model; 2) it can utilize incomplete or imprecise information, thereby decreasing sensitivity to missing input data; 3) it generates more smooth outputs rather than oscillatory speed limits; 4) it is extremely suitable to combine objective knowledge (formulae and equations) and subjective knowledge (linguistic information); and 5) it is easy to tune by changing weight factor and the parameters of membership functions.

1.2.3. Limitations of the Existing Integrated Approach to Ramp Metering and VSL Control

In the last few decades, RM has been implemented and operated all around the world. However, its application has confronted several issues. Firstly, when experiencing high demands from a motorway on-ramp and mainline, RM is not an efficient measure to keep the mainline flow under or at its capacity. Secondly, RM can control the flow only from on-ramps, but not on the mainline. Thirdly, regulating in-flow of vehicles from on-ramps may result in a temporary formation of vehicle queues at on-ramps, which can interfere with the adjacent street traffic because of the limited on-ramp storage space.

The deployment of VSL control on the motorway mainline could partially address above issues and improve the effectiveness of the RM system (Hegyi et al., 2005). The main advantages of using the VSL are: 1) the VSL can provide a direct and effective control of the mainline traffic complementary to RM; and 2) the VSL has shown a potential to delay or prevent traffic congestion (Hegyi et al., 2005; Hoogendoorn et al., 2013).

A number of researches have been conducted in recent years to combine RM with VSL (Abdel-Aty and Dhindsa, 2007; Caligris and Sacone, 2007; Papamichail et al., 2008; Lu et al., 2010). Nevertheless, the methods proposed in the technical literature have apparently not yet
reached a sufficiently mature level for generic large-scale field implementation because of the following reasons: 1) MPC scheme is used in the most of the proposed methods, which is a relatively complex scheme to implement in the field; and 2) the nonlinear optimization used in the proposed methods might require frequent changes in speed limits, which is unlikely to be acceptable to drivers. Thus, it shall be useful to develop an integrated RM and VSL method, which uses synergy between RM and VSL to improve overall performance of the system and also easy to implement in the field.

1.2.4. Relationship between Efficiency and Equity

Equity is a broad and ambiguous concept. The lack of an explicit definition and measurement of inequality might be the main reason that road users’ inequality has not been adequately addressed in RM studies (Yin et al., 2000). Litman (2007) proposed a generally accepted taxonomy for the equity issue in transportation systems. He identified two general categories of equity that are horizontal equity also termed as egalitarianism, and vertical equity also termed as social justice. The former is concerned with treating everybody equally, regardless of factors such as race and income. While the latter is concerned with the distribution of the benefits between individuals or groups that has different needs and abilities.

Pinnell et al. (1967) was the first to raise equity issues in RM control system. Nevertheless, most of the existing RM strategies are still concentrating on improving overall network efficiency without sufficiently taking into account equity. Mobility benefits may cost more to some individuals than others, leading to an unfair allocation of benefits among motorway users. Yin et al. (2000) stated that the lack of equity consideration among road users has adversely influenced public acceptance and hindered the widespread use of RM. Levinson et al. (2002) introduced Gini coefficient (1936) to the field of RM, which is a widely accepted measure in economic studies. Using Gini coefficient, they defined two equity measures:
spatial and temporal. Spatial equity reflects the distribution of delays among drivers using different on-ramps at the same time while temporal equity is a measure of inequity among drivers using the same on-ramp at different times. This thesis focuses only on spatial equity measure hence hereafter the term “equity” will be used to refer to “spatial equity”.

Zhang and Levinson (2005) suggested that although improving efficiency of motorway systems is the original and still the most important objective of RM, road users’ equity should be considered, at least, as the secondary goal to make it a viable system. Kotsialos and Papageorgiou (2001) observed a partially conflicting relationship between efficiency and equity. Zhang and Levinson, (2004) stated that the most efficient RM strategy is the least equitable one. However more recently, Zhang and Shen (2010) stated that the objectives of more efficient and equitable transport systems can be achieved simultaneously as they do not necessarily conflict with each other. Based on these contradictory findings as reported in the literature discussed earlier, it is difficult to establish a relationship between efficiency and equity. Hence, it might be useful to explore further the relationship between efficiency and equity for motorway system.

1.3. Aims and Objectives

The main goal of this research is to improve the efficiency and equity performance of motorway systems using RM and VSL control measures. A number of RM and VSL control algorithms are proposed in this thesis to achieve this goal. They are assessed for a critical bottleneck section of Auckland Motorway.

The specific objectives of this research can be outlined as follows:
➢ assess the efficiency and equity performance of the existing RM and VSL control strategies using AIMSUN micro-simulator;

➢ modify the existing logic tree based VSL algorithm to improve its mobility performance;

➢ develop a fuzzy logic based VSL controller to overcome limitations of the traditional rule-based VSL controllers;

➢ develop an integrated approach to RM and VSL control to maximize the efficiency and equity performance of the motorway system; and

➢ investigate the relationship between the efficiency and equity of the motorway system.

1.4. Scope of the Research

Field based trials can be quite useful for before and after study to assess the performance of newly implemented methods. However, they are generally time-consuming and expensive. Furthermore, it is not always feasible to conduct field trials. Simulation based study can be an economical and efficient alternative. Traffic micro-simulation software such as AIMSUN is a promising and relatively accurate tool to assess the performance of ITS measures such as RM and VSL. As with any other models, they have their own limitations to represent real world driving behaviour. AIMSUN traffic micro-simulator is used in this research to assess the performance of the proposed methods based on a critical bottleneck section of Auckland Motorway. Hence, the outcomes of this research are limited in scope by the use of a single test bed and the accuracy of AIMSUN micro-simulator.
Traffic data used in this study is collected from the loop detectors on on-ramps and the motorway mainline. The data found to have errors including miscount, which are carefully checked and excluded from analysis.

This research does not investigate effects of weather-related issues such as visibility, wind speed, precipitation severity, etc. There are a number of important performance measures for motorway system such as safety, efficiency, equity, comfort, user acceptance etc. However this research focuses only on efficiency and equity of motorway system. Total travel time, bottleneck capacity and vehicular emissions are used for efficiency measure, while some other important variables such as travel time reliability and delay are left out. Similarly, for equity aspect also only spatial equity aspect is used while temporal equity aspect is left out in this research.

1.5. Structure of the Thesis

The outline of the thesis is as follows. In Chapter 1, brief descriptions of the background, research gap, aims and objectives, and scope of the research are provided. Chapter 2 reviews the literature relevant to this research. In Chapter 3, the research design and methodology are explained including overall research framework, data collection and preliminary analysis, performance measures and AIMSUN model development. Chapter 4 provides the outcomes of assessment for existing RM and VSL strategies. In Chapter 5, logic tree based algorithm proposed by Allaby et al. (2007) is modified in terms of detector location and the governing VSL controller logic to achieve higher mobility gains. In Chapter 6, a fuzzy logic approach to VSL controllers is designed to overcome weaknesses of traditional rule-based VSL algorithms. In Chapter 7, an integrated method combining RM and VSL is proposed to improve the performance of motorway systems in terms of efficiency and equity. Chapter 8
investigates the relationship between equity and efficiency using a modified CRM strategy and a proposed index. Final remarks are given in Chapter 9, as well as a brief discussion of the future direction for using RM and VSL.
Chapter 2. LITERATURE REVIEW

Motorway traffic management tools aim to improve the performance of existing motorway systems. A great deal of research has been performed in recent years to develop and evaluate motorway traffic management tools to achieve this goal. This chapter reviews the literature relevant to this research.

2.1. Local Ramp Metering Strategies

RM schemes can be classified into two categories based on the level of complexity of the control approach: LRM strategies and CRM strategies. In LRM, the metering rate is determined by the traffic conditions in the vicinity of an individual on-ramp; in CRM, multiple on-ramps are controlled in a region of a road network using system-wide traffic measurements. Currently, the demand-capacity strategy, ALINEA and its variations are the most common LRM strategies.

2.1.1. Demand-capacity Strategy

Demand capacity (DC) strategy is a feed-forward control, based on the motorway capacity and the traffic demand on the motorway. The metering rate \( r(k) \) is calculated by a pre-specified capacity value and the upstream traffic flow (Masher et al., 1975):

\[
r(k) = \begin{cases} 
q_{\text{cap}} - q_{\text{in}}(k - 1) & \text{if } o_{\text{in}}(k - 1) \leq o_{\text{cr}} \\
\frac{r_{\text{min}}}{r_{\text{min}}} & \text{else}
\end{cases}
\] (2.1)
where,

\[ k = 1, 2, \ldots \] is the discrete time index;

\[ r(k) \] is the on-ramp flow (veh/h) that will be applied during the period \( k \);

\[ q_{in}(k-1) \] is the observed upstream motorway flow (veh/h) during the period \((k-1)\);

\[ r_{min} \] is a minimum admissible on-ramp flow;

\[ o_{in}(k-1) \] is the observed upstream motorway occupancy (%) (averaged over all lanes) during the period \((k-1)\);

\[ o_{cr} \] is the critical occupancy and \( q_{cap} \) is the pre-specified downstream motorway capacity.

The DC strategy aims to add reasonable on-ramp flow \( r(k) \) to the last measured upstream flow \( q_{in}(k-1) \) to reach the pre-specified downstream motorway capacity. However, if the last measured upstream occupancy \( o_{in}(k-1) \) exceeds the critical occupancy in some cases (i.e., there is congestion), the on-ramp flow \( r(k) \) is decreased to the minimum flow \( r_{min} \) to release the apparent congestion. Then if \( r(k) \) obtained from Eq. (2.1) is smaller than \( r_{min} \), it is truncated to prevent on-ramp closure.

**2.1.2. Occupancy Strategy**

The occupancy strategy (Masher et al., 1975, Koble et al., 1980) only makes use of the upstream occupancy measurement \( o_{in} \) which is employed as the sole means to identify congestion. This strategy contains two constants: \( K_1 \) is the mainstream capacity and \( K_2 \) is obtained based on slope of a straight line approximation of the left hand side of the fundamental diagram. The metering rate \( r(k) \) in the next period \( k \) is calculated by:

\[
r(k) = K_1 - K_2 o_{in}(k-1)
\] (2.2)
2.1.3. ALINEA Strategy

As shown in Figure 2.1, ALINEA is a closed-loop feedback RM strategy, in which the metering rate is proportional to the difference between the desired (or critical) occupancy and the observed downstream occupancy (Papageorgiou et al., 1991).

\[ r(k) = r(k-1) + K_R \left[ \hat{o} - o_{out}(k) \right] \quad (2.3) \]

where,

- \( K_R > 0 \) is a regulator parameter; when the occupancy is measured in the range \([0,100]\) \%, \( K_R = 70 \text{ veh/h/\%} \) is recommended;
- \( \hat{o} \) is the desired downstream occupancy which is usually set as the critical occupancy;
- \( o_{out}(k) \) is the observed downstream occupancy; and
- \( r(k-1) \) is the metering rate during the period \( k-1 \).

The resulting metering rate \( r(k) \) is truncated if \( r(k) \) exceeds the range \([r_{min}, r_{max}]\) (\( r_{max} \) is usually the capacity of the on-ramp). The truncated metering rate is used as \( r(k) \) in Eq. (2.3) in the next period \( k \) in order to prevent the wind-up effect of the integral regulator.

Eq. (2.3) is known as an I-type (integral) regulator in the classical automatic control theory. This regulator automatically leads to \( o_{out} = \hat{o} \) under stationary average conditions, i.e., when traffic conditions are not changing significantly. The ALINEA strategy includes the following stationary features (Papageorgiou and Papamichail, 2007):

- Any stationary (average) value of \( q_{in} \) is automatically rejected by the control loop;
- Any stationary error (bias) in the realization of the ramp flow value \( r(k) \) by the regulator is automatically rejected by the control loop.
2.1.4. Modified ALINEA Versions

Several variants of the ALINEA strategy were proposed in the literature, including FL-ALINEA, UP-ALINEA, UF-ALINEA and X-ALINEA/Q (Papageorgiou and Papamichail, 2007; Smaragdis and Papageorgiou 2003).

*Flow-based ALINEA (FL-ALINEA)*

The main reason for using occupancy values rather than traffic flow values in the ALINEA strategy is that traffic flow cannot uniquely characterize the traffic state. However, occupancy values may not be readily related to the classic traffic flow variables, which are known to rely on the traffic composition, the detector sensitivity and various installation conditions. Furthermore, in the case of a central network-wide specification of set values for the LRM, it may be easier to specify set values for volumes rather than for occupancies. For these reasons, application of the following FL-ALINEA (Smaragdis and Papageorgiou, 2003) may be useful under certain conditions.
\[ r(k) = \begin{cases} r(k-1) + K_f \left[ \hat{q} - q_{out} (k-1) \right] & \text{if } q_{out} (k-1) \leq ocr \\ r_{\min} & \text{else} \end{cases} \] (2.4)

where,
\[ K_f > 0 \] is a regulator parameter;
\[ \hat{q} \] is the desired downstream flow; and
\[ q_{out} \] is the observed downstream flow.

**Upstream-Occupancy Based ALINEA (UP-ALINEA)**

In some cases, ALINEA strategy cannot be implemented or tested in the field due to the lack of detection devices downstream of the on-ramp, however detection devices are available upstream of the on-ramp on the motorway. This issue can be addressed, if suitable estimates for \( o_{out}(k) \) can be made available for use in Eq. (2.3). Smaragdis and Papageorgiou (2003) obtained the following estimate \( \tilde{o}(k) \) of the downstream occupancy; this estimation is based on measurements of the upstream occupancy, the upstream flow and the on-ramp flow:

\[ \tilde{o}_{out}(k) = o_{in}(k) \left[ 1 + \frac{q_{ramp}(k)}{q_{in}(k)} \right] \frac{\lambda_{in}}{\lambda_{out}} \] (2.5)

where,
\[ q_{ramp} \] is the measured inflow from the on-ramp;
\[ q_{in} \] is the motorway traffic flow upstream of the on-ramp;
\[ \lambda_{in} \] is the number of mainstream lanes upstream of the on-ramp; and
\[ \lambda_{out} \] is the number of mainstream lanes upstream of the on-ramp.

Thus, the UP-ALINEA is given by (Smaragdis and Papageorgiou, 2003):

\[ r(k) = r(k-1) + K_r \left[ \hat{o} - \tilde{o}_{out} (k - 1) \right] \] (2.6)

with \( \tilde{o}_{out} (k - 1) \) provided by Eq. (2.5).
Upstream-Flow Based ALINEA (UF-ALINEA)

For similar reasons that lead to the design of UP-ALINEA, one might be interested in applying the FL-ALINEA strategy based on measurements obtained upstream of the on-ramp. An estimate of the downstream flow may be obtained using (Smaragdis and Papageorgiou, 2003)

\[ \tilde{q}_{out} = q_{in} + q_{ramp} \]  \hspace{1cm} (2.7)

Thus, UF-ALINEA is given by (Smaragdis and Papageorgiou, 2003)

\[ r(k) = \begin{cases} r(k-1) + K_f \left[ \tilde{q} - \tilde{q}_{out} (k-1) \right] & \text{if } \tilde{q}_{out} (k-1) \leq o_{cr} \\ r_{min} & \text{else} \end{cases} \]  \hspace{1cm} (2.8)

with \( \tilde{q}_{out} (k-1) \) and \( \tilde{q}_{out} (k-1) \) provided by Eq. (2.5) and Eq. (2.7) respectively. if (Smaragdis and Papageorgiou, 2003):

- \( K_f \) is exactly equal to 1 (which is a reasonable choice),
- \( q_{ramp}(k-1) \) is equal to \( r(k-1) \) (which will often be the case) and
- \( \hat{q} \) is equal to \( q_{cap} \).

then UF-ALINEA becomes identical to the DC strategy, except that \( \tilde{q}_{out} (k-1) \) replaces \( o_{in}(k-1) \) in the switching condition (Smaragdis and Papageorgiou, 2003).

Ramp-Queue Control (X-ALINEA/Q)

Smaragdis and Papageorgiou (2003) stated that one side effect of RM is the formation of a vehicle queue on the ramp. If the vehicle queue exceeds a certain length, it may interfere with the adjacent street traffic. They designed a genuine ramp-queue controller X-ALINEA/Q in which the maximum permissible queue length is set. The metering rate of X-ALINEA/Q is calculated using:

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\[ R(k) = \max\{r(k), r'(k)\} \tag{2.9} \]
\[ r'(k) = \frac{1}{r} \left[ \hat{w} + w(k) \right] + d(k - 1) \tag{2.10} \]

where,
- \( r(k) \) is the metering rate decided by any of the previously described RM strategies;
- \( r'(k) \) is the amount of vehicles entering the motorway;
- \( \hat{w} \) is the maximum permissible queue length;
- \( w(k) \) is the queue length at the time-instant \( k \cdot T \); and
- \( d(k-1) \) is the demand flow entering the on-ramp.

By selecting the maximum value between \( r(k) \) and \( r'(k) \), the X-ALINEA/Q strategy works as follows: If the motorway demand is low, the RM strategy will allow for a high on-ramp flow \( r(k) \), because the motorway is far from being congested. In contrast, the combined strategy will deliver a low ramp flow \( r'(k) \), so that the queue grows towards the maximum permissible queue length. Note that X-ALINEA/Q can be combined with any RM strategy producing \( r(k) \).

2.1.5. Discussion

Previous studies have demonstrated that traffic flow breakdown in merging areas may occur at different flow capacities on different days, even under similar environmental conditions (Lorenz and Elefteriadou, 2001; Cassidy and Radjanakanoknad, 2005). Thus any RM strategies targeting a pre-fixed capacity value may be too permissive on some days or too restrictive on other days. Both the DC strategy and the occupancy strategy target a pre-specified capacity value, which may result in an efficiency reduction due to the uncertainty of flow capacity as explained above. In contrast, ALINEA employs a more robust and efficient target for RM operation, which is occupancy value. The critical occupancy value was found
to be fairly stable (Cassidy and Radjanakanoknad, 2005), even under different environmental conditions (Keen et al., 1986; Papageorgiou et al., 2006).

Because the metering rate \( r(k) \) in the DC strategy is calculated based on the upstream traffic flow, this strategy is a feed-forward disturbance-rejection scheme rather than a feed-back control. The feed-forward control is generally known to be sensitive to various non-measurable variables. The occupancy strategy is also a feed-forward strategy. This strategy is even more inaccurate than the DC strategy because it is based on the linearity assumption for the fundamental diagram. Motorway operators aim to control the motorway traffic conditions downstream of the on-ramp. Thus a genuinely feedback control strategy involves a measurement of the traffic conditions that are being controlled. Because ALINEA targets the downstream critical occupancy value, it does not suffer from the degraded efficiency of a feed-forward control (Papageorgiou and Papamichail, 2007).

### 2.2. Coordinated Ramp Metering Strategies

Though various CRM strategies have been proposed in the technical literature, there are only a few field applications (mainly in the United States). The CRM strategies can be subdivided into three categories namely optimal control strategies, hierarchical control strategies and rule-based strategies (Papageorgiou and Papamichail, 2007). The following paragraphs will provide an overview of the existing CRM strategies.

#### 2.2.1. Optimal Control Strategies

The application of optimal control to CRM on motorways has a long history (Papageorgiou and Katsivalis, 2002). Recently proposed tools include AMOC (Advanced Motorway Optimal Control) developed by Technical University of Crete, Greece and OASIS (Optimal
Advanced System for Integrated Strategy) developed by INRETS in France. Optimal control strategies use a macroscopic traffic flow model (e.g., METANET) which runs several iterations in order to obtain the optimal metering flows over an optimization time-horizon. More specifically, optimal control strategies take into account (Papageorgiou and Papamichail, 2007):

- the storage capacity of the on-ramp;
- the demand predictions over the optimization time horizon;
- the current traffic state of the mainstream and the on-ramp;
- incidents present in the motorway network; and
- the nonlinear traffic flow dynamic.

Due to this comprehensive information, the strategy produces optimal traffic states and controls for the whole motorway network in order to (Papageorgiou and Papamichail, 2007):

- optimize an objective criterion (e.g., total travel time)
- respect all present constraints; and
- consider equity among road users at different on-ramps (Kotsialos and Papageoriou, 2004)

The strength of optimal control strategies is that they pro-actively provide the best achievable countermeasures under any possible situation. This feature enables them to be useful tools for providing the best possible results, which can be used as a reference case for the assessment of the sub-optimality level of other simpler methods. The disadvantages of these strategies are (Papageorgiou and Papamichail, 2007):

- they require future demand predictions;
- they are sensitive to the difference between demand predictions and reality-model;
- they are open-loop, instead of close-loop methods; and
- they are complex method with a black-box nature for the traffic operator.
2.2.2. Hierarchical Control Strategies

The open-loop character of optimal control strategies may lead to a mismatch between real traffic states and calculated ones because of errors associated with the initial state estimate, future demand predictions and the model parameters used (Papageorgiou and Papamichail, 2007). In order to solve the reality-model mismatch, a receding-horizon method is used. This method is applied to the hierarchical control system, which includes three layers (Kotsialos, 2004).

The Estimation/Prediction Layer receives the historical input data, incident information and real-time traffic conditions from measurement devices installed in the motorway network. Then, the information is processed to provide the future demand predictions and the current state estimate to the Optimization Layer.

The Optimization Layer (e.g., AMOC) regards the current time as the initial point and the state estimate as the initial state. Based on the future demand predictions, the optimal control problem is addressed by producing the optimal control trajectory and the corresponding optimal state trajectory. These trajectories are sent as input data to the Direct Control Layer which will realize the suggested control actions. Because this layer is run in an iterative way in real time with updated demand predictions and initial state, the strategy is equipped with a feed-back loop for improved robustness.

The Direct Control Layer contains several ALINEA controllers, which take the optimal results produced from the second layer as set values in their operation. At times and locations in which AMOC produces capacity flow, the set values of ALINEA are set equal to the corresponding critical occupancies in order to avoid the uncertainty of flow capacity. A flow chart of the hierarchical Control Strategy is presented in Figure 2.2.
2.2.3. Rule-based Strategies

Rule-based CRM strategies make their real-time decisions through checking proper heuristic rules and activating related actions at on-ramps. Because there is no general method for this type of strategy, rule-based CRM strategies can be quite different in complexity, approach, calibration effort and efficiency. Several commonly used rule based strategies will be presented in the following paragraphs.
HERO Strategy

Papamichail and Papageorgiou (2008) proposed a HEuristic Ramp metering coOrdination (HERO) strategy to overcome some of the drawbacks witnessed in other CRM strategies. It claims to have achieved efficiency close to that of some sophisticated optimal control strategies discussed earlier.

HERO incorporates ALINEA strategy at the local level in a group of on-ramps along a critical bottleneck section. At network level, when queue length at any on-ramp exceeds a pre-specified threshold value, HERO assigns it as a master on-ramp and then gradually employs successive upstream on-ramps to serve as slave ramp meters. This strategy exploits storage spaces of upstream on-ramps to improve the storage capacity of critical bottleneck section by maintaining minimum queue lengths at each of the slave on-ramps. The main objective is to prevent queue length at the master on-ramp from spilling back to the nearest intersection and to control the inflow onto the motorway to maintain an optimal mainline flow at the bottleneck. The main advantages of HERO include (Papageorgiou and Papamichail, 2007):

- Make up the weaknesses of ALINEA strategy by coordinating local ramp meters in an appropriate way;
- No need for external disturbance prediction;
- Be generic (i.e. directly applicable to any motorway network) without further calibration;
- Approach the efficiency of complex optimal control;
- Be simple and transparent (rule-based).

The working principle of the HERO strategy as proposed by its developers can be outlined as follows:
1) At each control time interval $T_c$, HERO controllers receive from local controllers the information on current on-ramp queue length and traffic states of the mainline; based on which it decides a possible coordination action.

2) Whenever a relative on-ramp queue length exceeds a pre-specified activation threshold value, HERO control strategy is activated and the respective on-ramp is turned as a “master”. The “master” gradually employs successive upstream on-ramps as “slaves”.

3) HERO assigns minimum queue lengths to the successive upstream on-ramps to avoid long queues at the “master” on-ramp. The minimum queue length is computed as follows:

$$W_{\text{min}}(k) = \frac{W_{\text{max}}(k) \times \text{Sum}_W(i)}{\text{Sum}_{W_{\text{max}}}(i)}$$

(2.11)

where,

- $W_{\text{max}}(k)$ is the maximum admissible queue length of the respective on-ramp;
- $\text{Sum}_W(i)$ is a sum of current queue lengths at each on-ramps within the coordination control string; and
- $\text{Sum}_{W_{\text{max}}}(i)$ is a sum of the maximum admissible queue lengths at each on-ramp within the coordination control string.

4) For each $T_c$, HERO updates the minimum queue lengths at each “slave” on-ramps so that the relative queue lengths at each on-ramps can be kept close to each other.

5) HERO gets deactivated when the relative queue length of the “master” on-ramp drops below the deactivation threshold value.

Figure 2.3 presents a flowchart of HERO strategy, where $W(i)$ is an observed queue length for an on-ramp $i$. $\text{act} (j)$ and $\text{deact} (j)$ are activation and deactivation threshold values respectively. As shown in this figure, HERO works in three different steps. The first step is
detection of master on-ramp is followed by the second step to define dissolution of the coordination string. In the third and final step, minimum queue lengths for each “slave” on-ramps are determined using Eq. (2.11) formulation.

**FIGURE 2.3.** Flow chart of HERO strategy

HERO strategy is in operation in Motorway A6 in Paris, France and Monash Freeway in Melbourne, Australia. Papamichail et al. (2010) conducted a before and after study of
Monash Freeway and reported that HERO strategy has improved efficiency of the freeway system.

**Stratified ZONE Strategy**

ZONE strategy was first implemented in the Twin Cities, Minnesota and a revised version, Stratified ZONE Metering strategy, was developed by MnDOT (Minnesota Department of Transportation) in late 2001 and is now being implemented on many of Twin Cities highways (MnDOT, 2003). The main features of the Stratified ZONE strategy are (Jacobson et al., 2006):

- Ramp queue lengths are calculated depending on queue detector measurements. The maximum on-ramp waiting time is set as a pre-fixed value and the metering rate is increased in order to ensure that this condition is met.

- Processed mainstream loop detector data in 30-second intervals is employed for the metering rate setting.

- Spare capacity is determined based on measured mainstream speed and volume data.

- Ramp meters are grouped into zones. Zones are organized by “layers”. Higher-level layers feature larger zones with greater overlap among zones.

- The number of vehicles that are allowed to enter the motorway for each ramp is determined by dispersing the spare capacity among the on-ramp in a zone. If the obtained metering rates are below the minimum metering rates, the metering rates are recalculated for the next higher layer. This process is repeated several times until all the metering rates meet the requirement.

In Stratified ZONE strategy, detectors from half a mile to three miles apart are employed as endpoints to individual zones. In each zone, stratified zone strategy aims to keep the number
of vehicles entering a zone below the number leaving. The variables used in Stratified ZONE strategies are defined in Table 2.1.

TABLE 2.1. Variables in Stratified ZONE strategy (modified from MnDOT, 2003)

<table>
<thead>
<tr>
<th>Variables</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>M</td>
<td>Metered Entrances - Entrance ramps onto any given freeway that are metered</td>
</tr>
<tr>
<td>A</td>
<td>Upstream Mainline Volume - Total number of vehicles entering a zone through the station at the beginning of the zone</td>
</tr>
<tr>
<td>U</td>
<td>Unmetered Entrances: Entrance ramps onto any given freeway that are not metered</td>
</tr>
<tr>
<td>X</td>
<td>Exits: all exit ramps off any given freeway</td>
</tr>
<tr>
<td>B</td>
<td>Downstream Mainline Volume: Total number of vehicles leaving a zone through the station at the end of the zone. Regardless of actual station volume, the value for the B station is set to the approximate capacity of that station: Right lane 1800, all other lanes 2100 veh/hr. A (B) station value based on anything other than capacity would often result in an unreasonable volume.</td>
</tr>
<tr>
<td>S</td>
<td>Spare Capacity: If a zone is free-flowing with little traffic, there is said to be “spare capacity” on the mainline, and meters will not need to be as restrictive. For this reason, the spare capacity is regarded as an output. This variable is calculated using average freeway densities for free-flowing traffic compared to current freeway densities</td>
</tr>
</tbody>
</table>

The main objective of stratified zone strategy is to use metering control to keep the total volume exiting a zone exceeding the volume entering through metering control. For this purpose, the relationship between the inflows and the outflows in a selected zone is as follows:

\[ M + A + U \leq B + X + S \]  

(2.12)
and therefore,

\[ M \leq B + X + S - A - U \]  \hfill (2.13)

Stratified zone strategy is designed to distribute \( M \) throughout the zone in a reasonable way based on demand \( D \) which is the total number of vehicles that need to enter a motorway. In order to distribute \( M \) properly, the metering rate is calculated one zone at one time from upstream to downstream as follows:

\[ R_n = \frac{M \times D_n}{D} \]  \hfill (2.14)

where,

- \( R_n \) is the metering rate for the meter \( n \); and
- \( D_n \) is the demand for the meter \( n \).

The calculation starts with Zone 1-1 in the first layer. After the metering rate has been determined for the first layer, the calculated rates for all of the meters are compared to the minimum rates and the demand for each related ramp meter. Minimum rate is given by:

\[ R_{\text{min}} = \frac{3600}{C_{\text{max}}} \]  \hfill (2.15)

\[ C_{\text{max}} = \frac{240 \text{(seconds in 4 minutes)}}{T} \]  \hfill (2.16)

where,

- \( R_{\text{min}} \) is the minimum metering rate;
- \( C_{\text{max}} \) is the maximum cycle time;
- \( T \) is the number of vehicles can be stored on the ramp.
**Bottleneck Strategy**

The Bottleneck strategy (Jacobson et al., 1989) calculates both a local control metering rate and a bottleneck metering rate. The bottleneck metering only needs to be launched when both of the following situations occur:

- the occupancy exceeds the threshold; and
- the section is storing vehicles.

When these conditions are not met, only the local metering rate is calculated. The local metering rate depends on the mainstream occupancy adjacent to the on-ramp. For each on-ramp, a metering rate/mainstream occupancy relationship is pre-specified by five occupancy-metering rate groups. The bottleneck strategy matches the mainstream occupancy to pre-specified occupancy-metering rate groups. The metering rate is calculated by interpolating between these groups for the actual mainstream occupancy.

The bottleneck metering rate is calculated using the traffic flow rates measured downstream of the on-ramp. A specific number of upstream on-ramps are identified for each motorway segment, defined by two adjacent mainstream detectors. The bottleneck metering rate decreases the flows entering the mainstream from identified on-ramps by the number of vehicles stored in the motorway segment. Due to the overlap of zones, every on-ramp may have more than one bottleneck rate associated with it. In that case, the most restrictive metering rate is selected as the final bottleneck rate. Finally, the bottleneck strategy compares the obtained bottleneck metering rate with the local metering rate and chooses the more restrictive of the two rates.
**Helper strategy**

Helper strategy (Lipp et al., 1991) was first applied in Denver area in 1981. In Helper strategy, a motorway is divided into six groups and each group contains up to seven on-ramps. At the local level, every ramp meter chooses one of six available metering rates depending on the upstream mainstream occupancy. At the system-wide level, when a long queue forms on a ramp that is regarded as critical, its metering burden will be sequentially dispersed to the corresponding upstream on-ramps.

This two-level structure of the strategy enables it to be more flexible when dealing with a congested situation. The Helper strategy is able to be and in fact was modified to address special situations (e.g., HOV lanes and bus bypasses). Because there is no systematic way of designing the metering look-up table at the local level and calculating the assignment rates at the system-wide level, experience with local traffic patterns and trial-and-error is indispensable in utilizing the efficiency of Helper strategy. However, Helper strategy is useful when accurate traffic flow models and origin-destination information are not accessible to the controller.

**Linked Strategy**

The Linked Strategy (Banks, 1993) has been in use in the San Diego area since 1968. This strategy was developed based on the demand-capacity approach; the local metering rate is calculated based on the volume measurement upstream of each on-ramp:

\[ r = q_l - q_u \]  \hspace{1cm} (2.17)
where,

\[ r \] is the metering rate;
\[ q_t \] is the target flow rate;
\[ q_u \] is the upstream flow rate.

The coordination part of the Linked strategy functionally resemble that of the Helper strategy; more specifically, whenever the metering rate of an on-ramp is in one of the lowest metering rates, then the upstream on-ramps apply more restrictive ramp metering.

**Fuzzy Logic Strategy**

Taylor and Meldrum (2000) proposed a new strategy that is based on fuzzy logic. Fuzzy logic is able to deal with multiple objectives (by weighing the rules that implement these objectives) and to apply the tuning process by using linguistic variables instead of numerical variables. The rule groups employed by this strategy include:

- the quality of the ramp merge;
- the ramp queue occupancy;
- the local mainstream occupancy and speed;
- the downstream occupancy and speed.

There are six input types for the fuzzy logic controller including occupancy and speed measurements from the mainstream and downstream detectors, the queue occupancy detector and the advanced queue occupancy detector which is installed at the upstream end of the on-ramp.

Fuzzification converses every numerical input into a set of fuzzy classes. For local occupancy, the fuzzy classes employed are very small (VS), small (S), medium (M), big (B), and very big (VB). The degree of activation shows how true that class is (in the range of 0 to 1), i.e., when
the local occupancy is 20%, the M class is true to a degree of 0.2, and the B class is true to a degree of 0.8, meanwhile the rest classes remain at 0, as shown in the top of Figure 2.4. The downstream occupancy only employs the VB class, which starts to activate at 11%, and reaches full activation at 25%, as shown in the bottom of Figure 2.4. The downstream speed employs the VS class, which starts to activate at 64.4 km/h and reaches full activation at 88.5 km/h. The queue occupancy and the advance queue occupancy employed the VB class. For on-ramps that are equipped with on-ramp detectors, the default activation starts at 12% and reaches full activation at 30%. After determining the fuzzy state, weighted rules are used to produce the metering rate. Finally a numerical metering rate is generated based on the rule weight and the activation degree of every rule outcome. Table 2.2 shows an example of weighted rules.

FIGURE 2.4. Fuzzy logic classes (Jacobson et al., 2006)
TABLE 2.2. Example of rules used in Fuzzy Logic strategy (Jacobson et al., 2006)

<table>
<thead>
<tr>
<th>Rule</th>
<th>Default Rule Weight</th>
<th>Rule Premise</th>
<th>Rule Outcome</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>3.0</td>
<td>If local speed is VS and local occupancy is VB</td>
<td>Metering Rate is VS</td>
</tr>
<tr>
<td>10</td>
<td>4.0</td>
<td>If downstream speed is VS and downstream occupancy is VB</td>
<td>Metering Rate is VS</td>
</tr>
<tr>
<td>12</td>
<td>4.0</td>
<td>If advance queue occupancy is VB</td>
<td>Metering Rate is VB</td>
</tr>
</tbody>
</table>

**SWARM Strategy**

SWARM strategy (Paesani, 1997) consists of two independent control strategies: SWARM1 and SWARM2. SWARM1 employs linear regression and the Kalman filter process in order to predict system evolution and restricts the real-time density from exceeding a pre-specified saturation density for every motorway segment.

As shown in Figure 2.5, in SWARM1 each detector predicts the density trend based on the past data. The time of the future prediction is a tunable variable called $T_{crit}$. The forecast density trend is calculated, and then it is combined with $T_{crit}$ to determine the excess density (the portion above the saturation density). The target density for the next control cycle is calculated based on the excess density, current density and $T_{crit}$:

$$d_t = d_c - \left( \frac{1}{T_{crit}} \right) \cdot d_e \quad (2.18)$$

where,

- $d_t$ is the target density;
- $d_c$ is the current density;
- $d_e$ is the excess density.
The volume reduction is given by:

\[ R = (d_I - d_l) \times n \times D \]  

(2.19)

where,

- \( R \) is the volume reduction;
- \( d_I \) is the local density;
- \( n \) is the number of lanes;
- \( D \) is the distance to next station.

SWARM2 is a local control strategy which is much simpler than SWARM1. During each time interval, the overall SWARM strategy compares the metering rates of both independent strategies and selects the more restrictive of the two.

FIGURE 2.5. SWARM prediction (Paesani, 1997)
**ACCEZZ Strategy**

The ACCEZZ ramp metering strategy (Bogenberger, 2001) was developed based on fuzzy logic. The rule base is defined as the set of rules in the fuzzy logic strategy, and it integrates human expertise. As it is easy to define change or delete rules, simple modifications are allowed in this strategy.

ACCEZZ strategy addresses uncertainty by defining the input variables as fuzzy logic sets. This strategy achieves coordinated ramp metering control via implementing fuzzy logic control on certain on-ramps where the interaction of ramp operations is considered. The control includes a two-stage process. In each upstream on-ramp, the current traffic conditions at the downstream bottleneck are taken into account. At the second stage, ACCEZZ strategy obtains the dynamic traffic state evolution and coordinates all related ramps to achieve a system-wide optimum via integrating a queuing model and a traffic flow model into the metering approach, as shown in Figure 2.6.

**2.2.4. Discussion**

CRM strategies have advantages over LRM strategies when dealing with multiple bottlenecks, limited on-ramp storage spaces and inequity to travellers. Though optimal control strategies are valuable tools for pro-actively producing the best possible solution, these strategies employ relatively complex numerical solution, making it quite challenging to implement in the field. This might be the reason that most CRM strategies that are implemented in the field are heuristic rule-based strategies. The rule-based strategies described above are actually implemented and operated, although comparative evaluations are limited. Some weaknesses that are partially shared by several rule-based strategies include (Papageorgiou and Papamichail, 2007):
- usage of pre-specified flow capacity values for the motorway mainline, which may change from day to day; and
- feed-forward rather than feed-back control at either the local or the system-wide level or at both levels.

![Diagram of ACCEZZ fuzzy logic control](image)

**FIGURE 2.6.** ACCEZZ fuzzy logic control (Papageorgiou and Papamichail, 2007)

### 2.3. Variable Speed Limits

A great deal of research works has been conducted in recent years to develop a number of VSL algorithms to improve motorway performance. These algorithms can be broadly classified into two control algorithms namely: reactive control algorithms and optimal control algorithms.
2.3.1. Reactive Control Algorithm

VSL algorithms under this category generally apply some threshold values for flow, occupancy, average speed or their combinations to determine speed limit values to be displayed in variable message signs (VMS). Based on what parameters they selected to determine speed limit values, it can be further subdivided as flow-based algorithms, occupancy-based algorithms, speed-based algorithms and multi-parameters based algorithms.

Flow-based Algorithms

In this category of algorithms, speed limits to be displayed in VSL displays are determined based on pre-specified flow thresholds. Such an algorithm is in operation in western quadrant of M25 motorway in United Kingdom since 1995. Depending on the motorway traffic conditions, the system posts 50 or 60 mph speed limits on VSL displays. UK Highways Agency (2004) conducted a business case to assess its effectiveness. It is reported that there is not much change in weekday journey times while off-peak journey times increased slightly compared to the previous year. The peak one-hour throughput remained unaffected. Nevertheless, the total throughputs increased by approximately 1.5% during the five-hour peak periods.

More recently, Habtemichael and Picado-Santos (2013) evaluated the performance of a flow based VSL algorithm under different traffic conditions and drivers’ compliance levels. They reported that for heavily congested traffic conditions, mobility benefit or loss caused by the VSL algorithm is not. While for lightly congested and uncongested traffic conditions, they recorded travel time savings of 16% and 6% respectively. They suggested that VSL controllers shall be turned on long before the peak hours. Although both of these studies indicated that there is no significant mobility gains using the flow based VSL algorithm, they observed its positive impacts on travel time savings under lightly congested traffic conditions.
**Occupancy-based Algorithms**

In this category of algorithms, speed limits to be displayed in VSL displays are determined based on pre-specified occupancy thresholds. Elefteriadou et al. (2012) reported implementation of this type of VSL algorithm in a 9-mile long portion of I-4 in Orlando, United States. Traffic conditions are classified as either free-flow, light congestion, or heavy congestion based on pre-defined occupancy thresholds to determine an appropriate speed limit for the respective traffic condition. Based on the investigation conducted using CORSIM micro-simulator for the eastbound direction of the road segment, they reported that the differences between the existing operations and no control scenario were not significant in terms of total travel time and traffic throughput.

**Speed-based Algorithms**

In this category of algorithms, speed limits to be displayed in VSL displays are determined based on pre-specified speed thresholds. Lee et al. (2004) employed a real-time crash prediction model integrated with a PARAMICS micro-simulator to evaluate a speed-based VSL algorithm on a 2.5 km long stretch of a sample motorway segment. They concluded that total crash potential was reduced at the expense of increase in total travel time. Detailed information of this algorithm is described below (Elefteriadou et al., 2012):

- Each VSL has an associated loop detector located adjacent to it
- Three signs are grouped together and data for these signs was averaged into one value
- If a crash potential threshold is reached the displayed speed is dropped at all signs using a set of criteria (all signs display the same speed)
  - 50 km/h if ave.speed ≤ 60 km/h,
  - 60 km/h if 60 < ave.speed ≤ 70 km/h,
➢ 70 km/h if 70 < ave. speed ≤ 80 km/h,
➢ 80 km/h if ave. speed > 80 km/h
➢ Reduced average total crash potential, especially at the bottleneck, but increased the overall travel time

More recently, Albania (2013) assessed a speed-based VSL algorithm for a section of E4 motorway in Stockholm, Sweden modeled using VISSIM micro-simulator. The author reported that the VSL algorithm resulted in a delayed onset of congestion, higher overall speeds and lower average travel times compared to the base case. These results contradict with those reported earlier by Lee et al. (2004).

**Multi-parameters based Algorithms**

In this category of algorithms, speed limits to be displayed in VSL displays are determined based on a combination of several parameters. Van den Hoogen and Shmulders (1994) reported on the implementation of such an algorithm on a 20 km long section of A2 motorway in Netherland. The VSL algorithm used a combination of the average speed and volume data across all lanes accumulated over every seconds time period to determine the speed limits. The authors reported reduction in speeds, speed difference between lanes and the severity of shockwaves. The displayed speed limits were determined based on 1-minute averages of speed and volume across all lanes. The authors concluded that VSL is not suitable to relieve congestion at bottlenecks as it does not increase capacity of bottlenecks.

Allaby et al. (2007) conducted a simulation based study on 8-km section of Queen Elizabeth Way in Toronto, Canada in eastbound direction. They used a logic tree based VSL algorithm with a combination of threshold values for flow, occupancy, and average speed. VSL displays were placed close to loop detectors. The display units are placed approximately 500–600 m apart to avoid an abrupt change of speed limits between signs. They reported that although
the proposed algorithm improved significantly safety, it also increased total travel time for all studied scenarios.

Papageorgiou et al. (2008) investigated the effects of VSL on the shape of the flow–occupancy diagram by using curve fitting methods. The flow and occupancy data were analyzed before and after VSL control on a European motorway that employs a rule-based VSL algorithm using average speed and volume thresholds. The authors reported that VSL declined the slope of flow-occupancy diagram at under-critical conditions and shifted the critical occupancy to a higher value. This allowed higher flows at the same occupancy values at overcritical conditions. However, the results regarding the impact of VSL on the capacity were not conclusive. The authors also suggested that using the real-time slope of the occupancy-flow curve as an indicator for VSL activation may enhance the performance of VSL control.

More recently, Hoogendoorn et al. (2013) reported on a trial conducted on A20 near Rotterdam, Netherland starting from June 28, 2011. They used a combination of smoothed values for average speed and flow data to determine the speed limits. The authors reported that the number of vehicle loss hours decreased by 20% with 4% increase in free flow capacity at the main bottleneck. This finding contradicts with the one reported earlier by Van den Hoogen and Shmulders (1994).

Kianfar et al. (2013) employed parametric curve fitting, non-parametric methods, and other statistical tests to examine the changes in traffic conditions before and after the implementation of VSL. The implemented VSL algorithm used a combination of average occupancy, speed and volume. The authors reported that changes in flow due to VSL were inconsistent across eight test sites. The maximum flows prior to and after the flow breakdown increased at some locations while decreased at other locations after using VSL.
Weikl et al. (2013) performed an empirical study on a 16.3 km section of autobahn 99 in German to investigate impacts of VSL on traffic flow. Their algorithm uses parameters including average speed, density, free flow speed and maximum density to compare with pre-specified threshold values to determine recommended speed and/or warning. The authors reported that there was no increase in capacity of the tested motorway section after implementation of the VSL system; instead the measured flow was decreased slightly.

Based on the findings reported in the literature, it is difficult to draw a conclusion on the impacts of the multi-parameters based VSL algorithms on total travel time or capacity of the bottleneck as they contradict each other. These contradictions might be due to the fact that these studies used different parameters and they were implemented in different locations under different traffic conditions.

2.3.2. Optimal Control Algorithms

A number of optimal control based VSL algorithms have been developed in recent years and most of them yielded significant improvements in traffic efficiency. Hegyi et al. (2005) proposed a model predictive control (MPC) method to suppress shockwaves at motorway bottlenecks. The objective of the MPC was to minimize travel time for each vehicle in the network. A general second-order traffic flow model METANET was modified to incorporate the influence of VSL into the calculation logic. The results showed that the MPC relieved shockwaves for all control cases and reduced total time spent (TTS) by approximately 21% compared to no-control case.

Popov et al. (2008) proposed an optimal control based VSL algorithm based on a distributed controller design. Different scenarios were simulated in the METANET environment. The authors reported that the proposed algorithm reduced TTS in the entire network by 20% compared to no-control case.
More recently, Hadiuzzaman et al. (2012) proposed a MPC algorithm based on a modified cell transmission model to dynamically control speed. The authors reported that total travel time, total travel distance and flow were improved by 15%, 6% and 7% respectively.

Islam et al. (2013) investigated safety and mobility effects of another MPC based VSL algorithm and reported that total travel time, total travel distance and flow were improved by approximately 32%, 3% and 3% respectively.

Yang et al. (2013) developed two models for proactive VSL control algorithm and assessed using a VISSIM micro-simulator for recurrently congested motorway segments. The authors reported 42.4% reduction in the number of vehicle stops and 17.6% reduction in the average travel time for two-hour study period.

The MPC based algorithms proposed in the literature seemed to achieve better control results than the reactive control algorithms. However due to the requirements for further predictions and complexity to the traffic operators, optimal control algorithms have been rarely implemented in the field. Most of the operational VSL systems still employ reactive control algorithms based on some threshold values for flow, occupancy, average speed or their combinations.

2.3.3. Discussion

The findings reported in the literature can be summarized as follows.

- The magnitude of mobility gains or losses due to VSL is inconsistent. Some studies observed no or negative impacts of VSL on total travel time, while some others reported a significant reduction in total travel time.
➢ No well-established consensus can be reached on capacity changes due to VSL. Even for the same motorway, changes in capacity due to VSL were inconsistent for different locations (Kianfar et al., 2013).

➢ The relationship between safety and mobility for VSL controlled segments are still not clear. Studies by Allaby et al. (2007) and Lee et al. (2003) showed that safety was improved at the expense of increase in travel time. However studies by Habtemichael and Picado-Santos (2013) and Islam et al. (2013) showed improvements in mobility as well as safety after implementation of VSL.

➢ There might be several reasons for the contradictory findings reported in the literature including different VSL algorithms applied in the literature for varying test networks, level of driver compliance, simulation environment and assessment methodology.

2.4. Combination of RM and VSL

Hegyi (2005) stated that RM strategies are useful only when the traffic demand from both the on-ramp and the mainline does not significantly exceed the downstream capacity. Applying VSL can partially address this issue and can enhance the efficiency of RM control. As shown in Figure 2.7, when mainline traffic is in state 1, it is unstable and even a small inflow from the entrance can lead to a breakdown. When VSL is implemented, it will shift from state 1 to somewhere between state 2 and 3, which will change the shape of the speed-density curve from the solid grey line to the dashed black line (Hegyi, 2005). Because the controlled flow is below the capacity of the motorway, there will be some space left to store the vehicles from the on-ramp and a breakdown is avoided. As a result, the mainline density remains low and the outflow remains high.
Alessandri et al., (1998) used a second order model for optimal VSL and RM control in addition to an extended Kalman filter for state estimation. The system was optimized by minimizing (or maximizing) an empirical mean cost function based on the Monte Carlo method.

Hegyi et al., (2003) designed a combined VSL and CRM method using MPC with a second order METANET model. It mainly considered how the coordinated control would work based on the fundamental diagram. The authors reported that RM was efficient only when the traffic demand was not too high. In the paper, the combined VSL and CRM method took into account mobility, safety, equity and driver acceptance instead of just safety as in most previous VSL practices. However, the results were sub-optimal from the overall system viewpoint.

Abdel-Aty and Dhindsa (2007) combined RM and VSL to reduce the risk of crash and improve operational parameters such as travel times and speeds. They suggested that RM and VSL are the two key solutions to influencing traffic conditions of congested motorways. Using micro-simulation, the authors showed the positive effect of VSL individual control. Preliminary micro-simulation work combining RM with VSL was reported. The simulation
model and the RM strategy adopted were rather simple and might not reflect actual motorway traffic dynamics and driver behavior, thus might not be able to address significant traffic uncertainties.

Caligris and Sacone (2007) defined an MPC scheme to control motorway traffic by combining RM and VSL. They refined the METANET model to take into account two different classes of vehicles (basically, cars and trucks).

Papamichail et al. (2008) investigated the impacts of VSL on traffic flow using a quantitative model and reported that VSL can significantly improve the efficiency of traffic flow especially when integrated together with CRM. The authors considered combining VSL and CRM with an optimal control approach. They claimed that the algorithm is feasible for large scale systems and showed by simulation that traffic flow significantly improved with combination of CRM and VSL compared to using each strategy individually.

Carlson et al. (2010) continued the work of Papamichail et al. (2008) using a similar method and reported that when implemented at upstream locations, VSL worked similarly to RM when the flow was regulated on the mainstream rather than at on-ramps. The results revealed that VSL reduced TTS by 15.3% and increased traffic flow by lessening the capacity drop at bottlenecks.

Lu et al. (2010) developed a combined VSL and CRM control to maximize the throughput of a recurrent bottleneck which can be modelled as a lane reduction. The proposed strategy can be described as:

- assume a known metering rate for each on-ramp;
- use finite time horizon model predictive control to design speed limits for each link;
- design speed limits based on a simplified second order METANET model with density (or occupancy) and mean speed as the state variables.
They performed the simulation in Matlab with several performance measures to assess the proposed strategy quantitatively. Though this approach is appealing theoretically, the nonlinear optimization requires frequent changes in speed limits, which may have some difficulties during implementation.

Lu et al., (2011) proposed another combined VSL and CRM approach for motorway traffic control. The idea of the approach was that if the section upstream of a bottleneck was congested, the bottleneck flow would drop below its capacity. Thus, a logical approach to maximize recurrent bottleneck flow was designed to create a discharge section immediately upstream of the bottleneck. They developed a control method for combining VSL and CRM to achieve this objective when the bottleneck could be represented as a lane reduction. The CRM could work as a standalone algorithm without VSL: the speed in the model was just the measured traffic speed estimation. In this way, the CRM system model was linearized. The CRM was then designed by an optimal control approach. The control problem was further simplified as a Finite Time Horizon Model Predictive Control. It resulted in a linear programming (LP) problem in each time step, which could be solved efficiently.

A number of studies have been devoted to the combination of RM and VSL. Nevertheless the methods proposed in the technical literature have not yet reached a sufficiently mature level for generic large-scale field implementation. The main reasons for this are:

- MPC scheme is used in the most of the proposed combined strategies, which is a relatively complex scheme for motorway operators; and
- the nonlinear optimization used in the proposed combined strategies might require frequent changes in speed limits, which is unlikely to be acceptable to drivers.
2.5. Efficiency versus Equity

Minimizing the overall travel cost for road users is overwhelmingly the most important goal for most motorway management systems. However, a newly designed or an updated control system would have two effects, namely, the “generative” effect and the “distributive” effect (Lakshmanan et al., 2001). The former refers to the net social welfare improvements resulting from the investment in transportation systems, while the latter occurs when some of the positive effects are compensated for by the negative ones. In traffic control systems, the generative effect and distributive effect are equivalent to the efficiency performance and the equity performance respectively. This section presents how both effects have been treated in transportation systems.

2.5.1. Equity

Litman (2007) proposed a generally accepted taxonomy for evaluation of equity issues in transportation systems. The author identified two general categories of equity:

- Horizontal equity is concerned with treating everybody equally; this means that public policies should avoid favoring certain individuals over the others.
- Vertical equity is concerned with the distribution of the gains or losses between individuals that differ in needs and abilities. If a policy favors the disadvantaged individuals, it is considered equitable since it compensates for the overall social inequities.

Litman (2007) concluded equity principles that can reflect the progress toward planning or operational objectives including

- treating everyone equally, unless the treatment is justified for special reasons;
- allocating the costs to individuals who impose them;
- being progressive regarding income;
benefiting transportation disadvantaged people (non-drivers, disabled, children, etc.);
- improving basic access: favors trips considered necessities rather than luxuries.

These principles and associated indexes have been employed to analyze various types of transportation policies such as parking restrictions, public transit subsidies and congestion pricing (Ma et al., 2005).

Kesten et al., (2013) mentioned that the indicators used in the literature to measure equity of traffic control strategies are mainly adapted from statistical or socio-economic models. The former examines the distribution of any variable in a given population while the latter is based on welfare economics and integrates equity concerns into a welfare function. Examples of statistical measures are: range, variance, measure of variation, log variance, Gini measure and Theil’s entropy measure. The axiomatic measures can be used to assess the inequality of any vector or distribution of observations. Table 2.3 shows a summary of equity index.

The efficiency of RM in improving motorway throughout, environmental quality and travel time reliability are verified by a number of experimental and simulation studies (e.g. Hasan et al., 2002; Papageorgiou et al., 1997). However, system-wide benefits of RM might be obtained at the cost of a portion of road user population, which lead to an inequitable distribution of benefits of RM.

The lack of consideration of the equity has adversely affected user acceptance and hindered wide applications of RM. The ramp meter shut-off experiment conducted in Twin Cities, Minnesota area concluded that ramp metering is a cost-effective investment of public funds, however the strategy should be adjusted to be more publicly acceptable and equitable (Levinson et al., 2002).
Some practical ways have been applied to reduce the inequality (Zhang and Levinson, 2003). In Detroit, the initial RM was applied only in the outbound direction to decrease urban-suburb equity issue. Although urban residents would argue that they were unable to directly access to the motorway, suburb residents could enter the motorway without the on-ramp delays. Once the benefits of the new system was released and established, it was extended with fewer objections. This modification may help to deploy the system; however it does not really address the equity issue among commuters.

Some other operational RM strategies (e.g. Bottleneck algorithm) have employed such a queue override control as well. Similarly, Stratified Zone algorithm has a maximum ramp delay constraint which ensures the delay of each vehicle is less than four minutes at the on-ramp and less than two minutes on motorway to motorway ramps. In fact, the minimum metering rates included in many RM strategies also make contribution to the equity. Nevertheless, their influence is not easy to determine in advance so a balancing process is obtained implicitly (Zhang and Levinson, 2003).

Kotsialos and Papageorgiou (2001) addressed the equity issue by imposing different on-ramp storage restrictions in their AMOC optimal control strategy. They observed that there is a trade-off between efficiency and fairness which the AMOC strategy addressed implicitly with consideration of the available on-ramp storage space. Such a queue override control has been used in some other practical RM strategies, e.g., Bottleneck strategy (Jacobson et al. 1989). Similarly, Stratified Zone strategy (MnDOT, 2003) exerts a maximum on-ramp delay constraint to ensure that delay per vehicle at on-ramps is less than four minutes. Though above discussed practical considerations can balance efficiency and equity to some degree, Zhang and Levinson (2003) pointed out that these impacts are difficult to determine in advance and the compromising process is implicit.
Zhang and Levinson (2005) proposed a new RM objective as minimizing total weighted travel time. The objective function can be used to balance efficiency and equity of RM control via weighting on-ramp delays non-linearly (i.e., longer delay is weighted more). Nevertheless, they acknowledged in their paper that it is difficult to find a meaningful weighting function for on-ramp delays.

**TABLE 2.3. A summary of equity index (Kesten et al., 2013)**

<table>
<thead>
<tr>
<th>Measure</th>
<th>Definition</th>
<th>Properties</th>
</tr>
</thead>
<tbody>
<tr>
<td>Range</td>
<td>$R = Y_{max} - Y_{min}$</td>
<td>$+ - -$</td>
</tr>
<tr>
<td>Variance</td>
<td>$V = \frac{1}{n} \sum_{i=1}^{n} (Y_i - \bar{Y})^2$</td>
<td>$+ + -$</td>
</tr>
<tr>
<td>Covariance</td>
<td>$c = \frac{\sqrt{V}}{\bar{Y}}$</td>
<td>$\pm + -$</td>
</tr>
<tr>
<td>Relative Mean Deviation</td>
<td>$M = \frac{1}{n} \sum_{i=1}^{n} \left</td>
<td>\frac{Y_i - \bar{Y}}{\bar{Y}} - 1 \right</td>
</tr>
<tr>
<td>Logarithmic Variance</td>
<td>$v = \frac{1}{n} \sum_{i=1}^{n} \left( \log \left( \frac{Y_i}{\bar{Y}} \right) \right)^2$</td>
<td>$- + -$</td>
</tr>
<tr>
<td>Variance of Logarithms</td>
<td>$v_i = \frac{1}{n} \sum_{i=1}^{n} \left( \log \left( \frac{Y_i}{\bar{Y}} \right) \right)^2$</td>
<td>$- + -$</td>
</tr>
<tr>
<td>Gini</td>
<td>$G = \frac{1}{2n^2 \bar{Y}} \sum_{i=1}^{n} \sum_{j=i+1}^{n}</td>
<td>Y_i - Y_j</td>
</tr>
<tr>
<td>Theil</td>
<td>$T = \frac{1}{N} \sum_{i=1}^{n} \frac{Y_i}{\bar{Y}} \log \left( \frac{Y_i}{\bar{Y}} \right)$</td>
<td>$+ + -$</td>
</tr>
<tr>
<td>Atkinson</td>
<td>$A_x = 1 - \frac{1}{n} \sum_{i=1}^{n} \left[ \frac{Y_i^{x+1}}{\bar{Y}^{x+1}} \right]^{1/x}$</td>
<td>$+ + -$</td>
</tr>
<tr>
<td>Kolm</td>
<td>$K_\alpha = \frac{1}{\alpha} \log \left( \frac{1}{N} \sum_{i=1}^{n} \exp \left( \alpha (\bar{Y} - Y_i) \right) \right)$</td>
<td>$+ + +$</td>
</tr>
</tbody>
</table>

Gini Coefficient (Gini, 1936) and the associated Lorenz Curve (Lorenz, 1905) have been borrowed in the field of RM to measure the inequity due to RM. Yin et al. (2000) used Gini
coefficients to analyze trip cost ratios before and after applying RM in a southern California corridor. In Twin Cities RM shut-off experiment (Levinson et al. 2002), the Lorenz Curve is plotted with the absolute terms of travel delay for motorway users. The trade-off between efficiency and equity is also confirmed in their study.

2.5.2. Efficiency

The efficiency performance of motorway systems has been studied through experimental and simulation-based studies (Kotsialos et al., 2001; Smaragdis and Papageorgiou, 2003; Hadi, 2005; Heygi et al., 2005; Papageorgiou et al., 2008; Papamichail et al., 2008; Carlson et al., 2010; Geroliminis et al, 2011). To assess the performance of motorway systems, the most commonly used efficiency measures are travel delay and travel time. Travel delay is the extra travel time beyond free flow conditions. When the road users do not switch routes, the minimization of travel delay is equivalent to the minimization of travel time; otherwise, travel time and travel delay are two different measures of the system efficiency in the motorway network.

The total travel time spent (TTT) by all vehicles is an important index to reflect the overview performance of the network. Less TTT in the motorway network indicates higher outflow, less delay and thus better traffic conditions. Other commonly used efficiency measures to evaluate the effectiveness of a control strategy include number of stops per vehicle, stop time, number of vehicles being delayed and total throughput.

2.5.3. Discussion

Minimizing the overall travel cost for road users is overwhelmingly the most important goal for most motorway management systems. Only recently equity aspect has become a concern. No holistic picture has ever been drawn to reveal the interaction between the two. Explicitly
or implicitly, the two aspects have been considered as competing criteria (Kotsialos and Papageorgiou, 2004). However, Yin et al. (2000) implied that balancing efficiency and equity in one motorway system is not necessarily a zero-sum game. Therefore, it is reasonable to adjust the existing strategy to be more publicly acceptable, equitable and efficient via a better design.

2.6. Simulation

It is widely accepted that simulation is a cost-effective technique that provides an experimental test to compare different control measures. Evaluation of the control measures in the field is not an option because costs are too high and the expected performance is unknown. Studies of the capabilities of specific simulation models as well as previous studies comparing models are reviewed in the following sections.

2.6.1. Simulation Models

AIMSUN

AIMSUN is capable of replicating various real traffic networks and conditions on a computer platform. The driver behavior models inside AIMSUN such as the gap-acceptance model, the lane changing model and the car-following model provide the behavior of individual vehicle during the entire simulation period (TSS, 2010). Because it is developed in the GETRAM simulation environment, users can develop the Application Programming Interface (API) in AIMSUN; this enables it to communicate with customized functions. The advantage of AIMSUN also includes the capability of simulating a traffic network in detail and recording a number of measures of effectiveness (MOEs). AIMSUN is an extensible software package
that provides all of the tools needed by transportation researchers and managers. At this moment, the environment consists of (TSS, 2010):

- A network editor for 2D and 3D visualizations.
- CAD files importer, GIS files importer/exporter and raster images importer.
- Third party traffic and transportation software importers.
- The microscopic simulator in AIMSUN.
- The mesoscopic simulator in AIMSUN.
- A macroscopic module that includes a static traffic assignment feature, a collection of O/D matrix manipulation functionalities (adjustment, traversal, balancing) and an optimal detector location calculation.
- An embedded pedestrian simulator from LEGION to be used in a microscopic simulation.
- Complete scripting using the Python programming language.
- Full extensibility and customization of the environment using C++ and the AIMSUN SDK (Software Development Kit).
- An API to connect externally to the micro simulator during the micro-simulation to get and set information about vehicles, demand, control, traffic management. The micro simulator API is offered both in C and in Python.
- A micro simulator SDK to modify the behavioral models of the desired vehicles. This micro simulator SDK is offered in C++.
- Planning software interfaces with Emme and SATURN.
- Signal optimization interfaces with TRANSYT-7F, TRANSYT/12 and SYNCHRO.

Barcelo (2001) presented a detailed description of the dynamic assignment capabilities of AIMSUN. The author explained the car-following and lane changing algorithms in AIMSUN and their relation to past methodologies. In the paper a case study was described that showed
the use of AIMSUN in analyzing ITS strategies such as RM and advanced traffic information systems. Barcelo (2003) described the AIMSUN model and its potential applications.

**VISSIM**

VISSIM is a time step and behavior based microscopic traffic simulation model to analyze the full range of functionally classified roadways and public transit operations (Hoyer and Fellendorf, 2007; Fellendorf, 2007). The simulation model consists of two primary components: the simulator and the signal state generator. The former is in charge of the movement of vehicles, and the latter models the signal status decision and then sends the signal status back to the traffic simulator (Bloomberg and Dale, 2000). The VISSIM model is capable of modeling various vehicle types for both motorways and arterials under different traffic conditions (Gao, 2008).

**PARAMICS**

PARAMICS is one of the earliest microscopic traffic simulation tool developed with ITS modeling capabilities. PARAMICS simulation software package is composed of six modules: Modeler, Processor, Analyzer, Monitor, Programmer and Estimator. The Modeler that is the core simulation engine is responsible for network representation, driver behavior, and traffic control. The Processor, Analyzer and Monitor assist users in batch simulation, post-simulation analysis of results, and pollution monitoring, respectively. Programmer offers the API for users to implement user-defined functions and to link with external software (Cheu et al., 2004).

**CORSIM**

CORSIM is one of the most commonly used micro-simulation software package for modeling vehicle traffic operations including the analysis of motorways, urban streets, and corridors.
and networks. CORSIM model consists of two predecessor models: FRESIM and NETSIM. The former is a motorway model that models uninterrupted facilities including grade separated expressways and interstate motorways; the latter is an arterial model that models arterials with at-grade intersections. CORSIM model is capable of modeling different intersection controls; a wide range of traffic flow conditions; and surface geometry (Gao, 2008).

Owen et al. (2000) presented an overview of the CORSIM model and its applications. They studied the ability of CROSIM to model special circumstances such as HOV facilities and real-time adaptive traffic control systems. Perrin et al. (2002) presented work on the ability of CORSIM to interface with and analyze adaptive traffic control operations.

**SimTraffic**

SimTraffic is a micro-simulation software package which employs the SYNCHRO program to model traffic networks. It was initially designed to model the arterial signal system timings. It can simulate motorways, surface street networks, pre-timed and actuated traffic signals, pedestrians, stop-controlled intersections, roundabouts, weaving sections and transit operations (Ratrout and Rahman, 2008). Sorenson and Collins (2000) presented an introduction to SimTraffic and its applications.

**INTEGRATION**

The INTEGRATION model was conceived during the mid 1980's as an integrated simulation and traffic assignment model (Van Aerde, 1985). This model is unique because it utilizes the same traffic flow logic to represent both motorway and signalized links and that both the simulation and traffic assignment components are also microscopic, integrated, and dynamic. In order to achieve these attributes, traffic flow is represented as a series of individual
vehicles that each follows pre-fixed macroscopic traffic flow and assignment relationships. The combined use of individual vehicles and macroscopic flow theory resulted in the model being considered mesoscopic by many practitioners (Van Aerde et al., 1996).

**TRANSYT**

TRANSYT is an off-line macroscopic simulation and optimization model that models traffic as cycle flow profiles (CFP), traces the flow of CFP from link to link throughout the network, and makes systematic changes to the cycle length, phase split, and offset of the traffic signals. It also models the associated traffic conditions to estimate a corresponding performance index (PI) that includes vehicle delay and number of vehicle stops. The simulation module within TRANSYT assesses the objective function that is to be minimized (Rakha and Van Aerde, 1996).

**WATSim**

WATSim is based on the NETSIM (Network Simulation) simulation model logic. WATSim, developed by KLD Associates, extends the functionality of NETSIM to incorporate both motorway and ramp operations. Its operational features include those in NETSIM plus path tracing, HOV configurations, RM, light-rail vehicles, toll plazas, and real-time simulation and animation (KLD Associates, 1996).

**2.6.2. Comparison of Simulation Models**

In the last two decades, a variety of studies have been performed to compare different traffic simulation packages and their ability to adequately model various test networks and transportation system configurations. A summary of key comparisons is presented in Table 2.4. The purpose of the review is not to summarize all work in this area, but rather to present representative findings relevant to this study.
<table>
<thead>
<tr>
<th>Reference</th>
<th>Packages</th>
<th>Main findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Middleton and Cooner, 1999</td>
<td>CORSIM, FREQ, INTEGRATION</td>
<td>Models were used to model congested motorway conditions. Although all models performed relatively well for uncongested conditions, they were inconsistent in their ability to accurately model congested conditions.</td>
</tr>
<tr>
<td>Prevedouros and Wang, 1999</td>
<td>CORSIM, INTEGRATION, WATSim</td>
<td>Field data for a large integrated (street and motorway) network were used as input and all three software programs were able to replicate field-measured volumes well. INTEGRATION required extensive modifications to approximate complex signal timing plans and WATSim needed the fewest modifications.</td>
</tr>
<tr>
<td>Bloomberg and Dale, 2000</td>
<td>CORSIM, VISSIM</td>
<td>The packages were assessed for use with congested arterials. The authors found that the tested models produced consistent results. They also reported that the packages are equally user friendly with respect to initial coding.</td>
</tr>
<tr>
<td>Boxill and Yu, 2000</td>
<td>CORSIM, AIMSUN, PARAMICS, INTEGRATION</td>
<td>The models were assessed for their ability to model ITS. The study concluded that AIMSUN and PARAMICS have significant potential for modeling ITS but that they require more calibration and validation efforts. CORSIM and INTEGRATION were reported to be the most probable for ITS applications because of familiarity and extensive calibration/validation.</td>
</tr>
<tr>
<td>Barrios et al., 2001</td>
<td>CORSIM, VISSIM, PARAMICS, SimTraffic</td>
<td>The packages were assessed based on their graphical presentation (animation) capabilities. The selected packages were to be used to model bus operations. Reviews of transit-related functions and visualization capabilities of each model are presented. Ultimately, VISSIM was selected due to its 3-D capabilities.</td>
</tr>
<tr>
<td>Trueblood, 2001</td>
<td>CORSIM, SimTraffic</td>
<td>The results revealed that the difference between two models for arterials with low to moderate traffic was not significant.</td>
</tr>
<tr>
<td>Choa et al., 2002</td>
<td>CORSIM, PARAMICS, VISSIM</td>
<td>The study compared the ability of models to accurately simulate a motorway interchange. The authors cited that the ability of CORSIM to compute control delay for individual approaches as an advantage. PARAMICS and VISSIM were determined to more closely reflect actual conditions. The 3-D capabilities of PARAMICS and VISSIM were cited as advantages.</td>
</tr>
<tr>
<td>Kaskeo, 2002</td>
<td>VISSIM, CORSIM, SimTraffic</td>
<td>The models were compared for three facility types including motorways, interchanges, and arterials with coordinated signals. The study concluded that 1) CORSIM was the most mature and widely used package; 2) VISSIM was the most powerful and versatile; and 3) SimTraffic was found to be the most straightforward to use.</td>
</tr>
</tbody>
</table>
Tian et al., 2002: CORSIM, SimTraffic, VISSIM. The models were evaluated for signalized arterials. The results showed that the outputs varied with link length and speed range in addition to volume levels.

Rakha and Crowther, 2003: FRESIM, INTEGRATION. The authors stated that the additional degree-of-freedom that is incorporated in the INTEGRATION steady-state car-following model overcomes the weaknesses of the current state-of-practice car-following and traffic stream models.

Bloomberg et al., 2003: CORSIM, INTEGRATION, PARAMICS, VISSIM, WATSim. All of the tested models were applied to signalized intersections and motorways. The authors reported that all of the models performed reasonably well and were fairly consistent.

Rakha and Van Aerde, 2007: INTEGRATION, TRANSYT. The authors concluded that the INTEGRATION model was able to simulate traffic-signalized networks as accurately as the TRANSYT model for static conditions. INTEGRATION was able to simulate important dynamic conditions that represented limitations to the current TRANSYT model.

2.6.3. Discussion

The selection of traffic simulation software for a particular issue relies on the nature of the issue. The most commonly used simulation software in New Zealand and Australia are AIMSUN, VISSIM and PARAMICS. AIMSUN simulation software package is selected for this research for following reasons:

- AIMSUN is capable of reproducing various traffic networks and conditions on a computer platform;
- AIMSUN offers the capability of modeling a motorway network in detail and producing a number of MOEs;
- the driver behavior models in AIMSUN provide the behavior of each vehicle during the entire simulation period; and
- in AIMSUN, users can implement various traffic management measures through developing an Application Programming Interface (API).
Chapter 3. METHODOLOGY

This chapter discusses the research methodology incorporating study framework, data collection, preliminary analysis and simulation model development.

3.1. Research Framework

Figure 3.1 presents the methodological framework of this study. After identifying research gap, traffic data of a critical bottleneck section on State Highway 1 of Auckland Motorway is collected. Then the traffic occupancy and volume data is analyzed to investigate traffic behavior in the vicinity of the bottleneck section. Based on data analysis results, AIMSUN model is developed for the test bed. Two existing RM algorithms are assessed namely: ALINEA and HERO. Then, a logic tree based VSL control algorithm is also assessed. The results revealed that the existing logic tree based VSL control algorithm cannot improve significantly mobility performance of motorway systems and is rather rough for the speed control. Thus two alternative VSL control algorithms are proposed namely: a modified logic tree based controller and a fuzzy logic based controller. Both utilize optimized control logics and detector-controller configurations. In the next step, an integrated RM and VSL control strategy is proposed to address the issues confronted by RM. The integrated method is aimed to preserve the traffic flow at bottlenecks close to their capacity and avoid excessive delays at on-ramps. Finally, this research investigates the relationship between efficiency and equity using a modified HERO strategy.
FIGURE 3.1. Research framework
3.2. Data Collection

The purpose of the data collection stage is to collect the attributes for model development. This research requires extensive data covering different traffic attributes from motorway network, which can be divided into two categories namely: static data and dynamic data.

3.2.1. Static Data

This category contains the physical and technical characteristics of the motorway network (e.g. the number of lanes, width, location of ramps and their control mechanism). This data can be obtained from GIS viewer provided by Auckland Council. A critical bottleneck section on State Highway 1 (SH1) of Auckland Motorway connecting Central Auckland with Northern Auckland is selected for this study. Figure 3.2 presents a layout of the study section, which has 5 on-ramps and 4 off-ramps in a direction towards Auckland city centre. Here O₁ represents on-ramp from Esmonde Road while O₅ represents on-ramp from Greville Road.

3.2.2. Dynamic Data

The traffic data used in this study is provided by New Zealand Transport Agency (NZTA) including loop detector measurements from the mainline, off-ramps and on-ramps and accumulated over a 30 seconds time period. Three months data is collected for the State Highway 1 starting from 5th of March 2012 to the 27th of May 2012.
3.3. Preliminary Analysis

The occupancy and volume data is analyzed to investigate traffic behavior in the vicinity of the bottleneck section D1. In this study a method proposed by Kianfar et al. (2013) is employed to identify the capacity and critical occupancy at the bottleneck section. Critical occupancies are determined using a two-step procedure. First, the scatter plots of flow versus occupancy data points are observed for any clear change in trends. The initial trend of increase in flow with increase in occupancy is observed. This trend reverses after the critical occupancy is reached. Nevertheless, the exact critical occupancy value is not easily discernible from the scatter plot. Thus, to determine the exact critical occupancy value, regression lines are fitted for free flow and congested regions for different possible critical occupancy values, and the root mean square error (RMSE) are calculated. The critical occupancy value that produces the least RMSE is selected. Then, the before breakdown flow and after breakdown flow values are obtained from best fit-lines at critical occupancies.
Data treatment is performed to validate the available data and remove data that is faulty or irrelevant for the current analysis. Daily data that provides little or no information regarding the effect of traffic congestion on traffic conditions is not taken into account in the analysis. This faulty or irrelevant data includes weekends, incidents and days with adverse weather. A total of 53 flow breakdown points are extracted for this particular location D1. Figure 3.3 presents a scatter plot of occupancy versus flow data points just before flow breakdowns for the bottleneck section. In this figure, a vertical line is drawn at an occupancy value of 17 that separates two different traffic flow conditions. Left side of the line represents cases with occupancy lower than 17% where flow breakdown points are distributed in a range from 2100 to 2400 veh/h/l with most of breakdown points located in a range from 2200 veh/h/l to 2300 veh/h/l. While right side of the line represents cases with occupancy greater than 17% where flow breakdown points are distributed evenly in a wider range from 2000 to 2350 veh/h/l.

![FIGURE 3.3. Breakdown points scatter plot for bottleneck](image-url)
Frequency distribution analysis is also performed for these flow breakdown points, which is presented in Figure 3.4 for flow and Figure 3.5 for occupancy data points just before flow breakdowns. Based on chi-square distribution test, both flow and occupancy data points just before flow breakdowns fit well in normal as well as lognormal distribution functions. For flow data points, the mean and standard deviation are recorded as 2228.5 veh/h/l and 75.8 veh/h/l; while chi-square values for normal and lognormal distribution functions are recorded as 6.9 and 7.4 respectively with a critical chi-square value of 14.1. For occupancy data points, the mean and standard deviation are recorded as 16.5 % and 1.5%; while chi-square values for normal and lognormal distribution functions are recorded as 12.9 and 11.5 respectively with a critical chi-square value of 22.4.

![Frequency distribution of flow data points just before flow breakdown](image)
3.4. Performance Measures

3.4.1. Total Travel Time

Total travel time (TTT) is commonly used to reflect overall performance of the network. A lower TTT represents lower delay and higher outflow and therefore better traffic conditions. TTT can be expressed as follows in vehicles times hours (veh*h):

\[ TTT = T \sum_{k=1}^{K} \sum_{i=1}^{N} \rho_i(k) \Delta_i \]  

(3.1)

where,

- \( \rho_i \) is density of a segment \( i \);
- \( T \) is measurement duration;
- \( \Delta_i \) is the distance between two measured stations \((i-I)\) and \((i)\);
- \( N \) is a number of measurement stations; and
- \( K \) is time horizon.
3.4.2. Gini Coefficient

Gini coefficient proposed by Gini (1936) is a widely accepted measure in economic studies to analyse the degree of inequality in income distribution. Figure 3.6 illustrates the concept of Gini coefficient. The Lorenz curve (Lorenz 1905) shows the proportion of X receiving a given proportion of Y. While 100% of the population receives 100% of the resource, the more unfortunate 50% may only receive 25% of the total resource. The Gini coefficient corresponding to this Lorenz curve can be computed as \( A_1/(A_1+ A_2) \) in this graph. A zero value for Gini coefficient indicates perfect equality, while 1 indicates perfect inequality. Gini coefficient can be expressed as follows:

\[
G = \frac{1}{2n^2} \sum_{i=1}^{n} \sum_{j=1}^{n} |\tau_i - \tau_j|
\]  

(3.2)

where,

- \( G \) is the Gini coefficient;
- \( \bar{\tau} \) is the average delay time of all on-ramps;
- \( i \) and \( j \) are the \( i \)th and \( j \)th on-ramp;
- \( \tau_i \) is the delay time on the \( i \)th on-ramp; and
- \( n \) is the number of on-ramps.

This study uses the QUARTET pollution emission model embedded in AIMSUN to calculate the pollution emissions for all the vehicles in the simulation. The vehicle state and speed/acceleration are used to compute the emission from each vehicle for each simulation step. This is done by referencing look-up tables for each pollutant.
3.5. Simulation in AIMSUN

3.5.1. Network Building

In order to precisely code the motorway geometry, an overlay of SH1 is needed. Using a single aerial for the overall network is not practical as it does not have a sufficient resolution to show all the details of SH1. Thus, several individual pieces of the aerial are collected from GIS viewer provided by Auckland Council and then gathered into one master file using the Adobe Photoshop program. Once the overall network is completed using individual pieces, they are overlaid against the low resolution image to make sure that the motorway alignment is correct and there are no errors with the individual components.

After determining the geometric overlay, the nodes and links are coded into the model. Information about the number of lanes and curvature of each link are also collected from Auckland GIS viewer. Once the links are created, the adjust points in the links are adjusted to
match the real network geometry. This step is essential to ensure that the modelled vehicles move freely between links without interruption. Then, these links are connected using nodes.

3.5.2. Model Calibration and Validation

Model calibration is an iterative process in which proper model parameters are adjusted so as to obtain an acceptable match between simulated results and the corresponding field data given that they have the same boundary conditions (Xiao et al., 2005). Earlier studies (Hourdakis and Michalopoulos, 2002; Hourdakis et al., 2003; Xiao et al., 2005) suggested that the calibration process should be performed in two trial and error stages, namely volume-based and speed-based calibration. However the loop detectors installed in Auckland Motorway system is unable to capture the traffic speed data directly. Thus this research only performs the volume-based calibration that aims to obtain simulated volumes as close as possible to the actual volumes.

The first phase in the calibration procedure involves the adjustment of global parameters including simulation step, driver reaction time and reaction time at stop, acceleration and deceleration, give way time, and headway. After calibration of the above parameters, local parameters that are defined at the section level and applied locally to vehicles while they are travelling along a section are calibrated. These include section gradients and Distance Zone 1 and Distance Zone 2. The latter is important in regulating the lane change behavior along sections of the motorway.

The model is calibrated against the data collected on Monday, 12th March, 2012 and then validated against the data collected on Friday 9th March 2012. The data collected in these two days provides relatively complete information and typical traffic conditions on SH 1 of Auckland Motorway. GEH statistic (Dowling et al., 2004) is used for the volume calibration.
as well as validation criteria based on volume data collected from 14 loop detectors. The GEH statistic can be obtained as follows:

$$GEH = \sqrt{\frac{(E-V)^2}{(E+V)/2}}$$

\begin{equation}
(3.3)
\end{equation}

where,

- \(E\) is estimated volume by model; and
- \(V\) is field count.

It is required that:

- Flow < 700 veh/h: within 100 veh/h of field flow for > 85% of time points
- Flow from 700 to 2,700 veh/h: within 15% of field flow for > 85% of time points
- Flow > 2,700 veh/h: within 400 veh/h of field flow for > 85% of time points

The New Zealand Transport Agency (NZTA) Economic Evaluation Manual (EEM) provides guidelines for the validation/calibration of transport models. A model is considered to be acceptable by the criteria if the GEH values for more than 85% of the observed detectors remain below 5 and that is the case in this study for both calibration and validation as shown in Table 3.1. Hence the model is accepted for further analysis to test different scenarios presented in the following sections.

### TABLE 3.1. Calibration and validation results for study area

<table>
<thead>
<tr>
<th>Detector location</th>
<th>D1</th>
<th>D2</th>
<th>D3</th>
<th>D4</th>
<th>D5</th>
<th>D6</th>
<th>D7</th>
<th>D8</th>
<th>D9</th>
<th>D10</th>
<th>D11</th>
<th>D12</th>
<th>D13</th>
<th>D14</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>% GEH&lt;5 (Calibration)</td>
<td>93</td>
<td>93</td>
<td>87</td>
<td>100</td>
<td>100</td>
<td>93</td>
<td>87</td>
<td>87</td>
<td>93</td>
<td>87</td>
<td>93</td>
<td>87</td>
<td>100</td>
<td>93</td>
<td></td>
</tr>
<tr>
<td>% GEH&lt;5 (Validation)</td>
<td>87</td>
<td>87</td>
<td>87</td>
<td>100</td>
<td>100</td>
<td>93</td>
<td>87</td>
<td>87</td>
<td>93</td>
<td>93</td>
<td>93</td>
<td>93</td>
<td>87</td>
<td>80</td>
<td>87</td>
</tr>
</tbody>
</table>
Chapter 4. ASSESSING EXISTING RM AND VSL CONTROL METHODS

This chapter presents details of the study conducted on assessing two RM strategies namely ALINEA and HERO and a logic tree based VSL control algorithm. The RM and VSL control algorithms are evaluated for a critical bottleneck section of Auckland Motorway using AIMSUN micro-simulation based on two important performance indicators namely total travel time and Gini coefficient representing the efficiency and equity of the motorway system respectively.

4.1. Simulation in AIMSUN

4.1.1. Implementation of RM

ALINEA strategy is realized in AIMSUN using an internal ALINEA control module. For HERO, an Application Programming Interface (API) is developed in AIMSUN to implement and verify the performance of HERO strategy for the study area. Figure 4.1 illustrates HERO control process that is used in AIMSUN software. ALINEA ramp meters installed at each on-ramp receive occupancy and flow data from AIMSUN model and calculate their individual metering rates locally and autonomously. Once HERO control strategy is activated due to detection of “master” on-ramp, the current queue lengths data from each on-ramp are transmitted to HERO API. Based on this information, HERO API determines and assigns minimum queue lengths at each “slave” on-ramps. The related control actions and minimum queue lengths are updated at each control time interval $T_c$. It shall be noted that queue lengths
at each on-ramps (aggregating all vehicle types) can be automatically obtained in AIMSUN. However, HERO coordination software (Papamichail and Papageorgiou, 2008) employs a queue estimation module proposed by Vigos et al. (2008) which is a Kalman filter based estimator.

![HERO API Diagram](image1)

**FIGURE 4.1. Implementation of HERO strategy in AIMSUN**

### 4.1.2. Implementation of Variable Speed Limits in AIMSUN

The detector location for the logic tree VSL algorithm tested in this research is similar to the one proposed by Allaby et al. (2007), where the VSL display unit is connected to loop detectors nearby on the upstream side of the bottleneck section as illustrated in Figure 4.2.

![Detector Location Diagram](image2)

**FIGURE 4.2. Detector location**
The speed limits to be displayed in VSL display units are determined based on traffic volume, mean speed, and occupancy measurements from the loop detectors and a set of pre-specified threshold values as illustrated in Figure 4.3.

All control actions related to VSL are realized in AIMSUN using “strategies” functions. During each control time interval $T_c$, traffic volume information received from the mainline detectors immediately upstream side of the on-ramp is compared against activation threshold value. When the relative flows reach or exceed the activation threshold value, then certain “triggers” will be launched and related VSL “strategies” which are pre-defined in “strategies” function will be activated. “Speed change” function exerts speed limits on the respective control segments. Figure 4.4 presents a conceptual diagram of VSL implementation at each on-ramp.

**FIGURE 4.3.** VSL control logic proposed by Allaby et al. (2007)
4.2. Analysis Results

In this section, analysis results of four different control scenarios including no control scenario, logic tree VSL algorithm, ALINEA and HERO are presented. Here “no control” scenario is used as a reference to measure improvements achieved by other control scenarios in terms of efficiency and equity of the motorway system.

4.2.1. Traffic Flow Conditions in Bottleneck Section

Figure 4.5 presents scatter plots of occupancy versus flow data points collected from the bottleneck section for different scenarios. It can be observed that flow breakdown occurs only in the first three scenarios that is no control, VSL and ALINEA while for HERO scenario, there are no flow breakdown points, which are represented by dark (red) points. In VSL case, speed limits applied at under-critical occupancies have the impact of decreasing the slope of the flow–occupancy diagram when compared with no-control case. This finding is in agreement with those of Hegyi et al. (2005) and Papamichail et al. (2008). For VSL and
ALINEA there is reduction in the number of flow breakdowns compared to the no control case.

A method proposed by Kianfar et al. (2013) is employed to compute the capacity and critical occupancy values of the bottleneck section for different control scenarios, as shown in Table 4.1. The results show that both VSL and ALINEA contribute positively to improve capacity of the bottleneck section though such improvements remain far from being significant (less than 1 %). The capacity for the HERO scenario cannot be computed as no flow breakdown points are observed for this scenario. However, from Figure 4.5 it can be observed that HERO strategy seems to yield higher bottleneck capacity than other scenarios.

![Flow-occupancy plots for the studied bottleneck under different scenarios](image)

FIGURE 4.5. Flow-occupancy plots for the studied bottleneck under different scenarios
4.2.2. System-wide Performance

Table 4.2 presents performance measures computed for the entire study area of the motorway network under different control scenarios. VSL records an improvement close to 6% in TTT compared with no control case. ALINEA strategy records over 12% improvement in TTT when compared with no control scenario. HERO strategy scenario outperforms all other control scenarios for TTT, producing the highest improvement of 17.6%. For emissions, ALINEA scenario produces the highest improvement among all the control scenarios.

F-test and T-test are performed to check how significant the differences in the TTT values are under different control scenarios and the results are presented in Table 4.3. On F-test results, the cells highlighted with a dark background represent cases of significant difference in the variance. On T-test results, the cells highlighted with a dark background represent cases of significant difference in the mean representing significant improvement in TTT when compared with the other scenarios. Based on these results, it can be concluded that the network controlled by HERO outperforms the one controlled by VSL. The difference between ALINEA case and VSL case is not statistically significant.
Figure 4.6 presents a time series of total travel time (TTT) for the entire study section under different control scenarios. It can be observed that improvements contributed by VSL and RM are mainly during the peak periods in this case from around 6:45 to 8:15.

### TABLE 4.2. Measures of effectiveness for different scenarios

<table>
<thead>
<tr>
<th>MoEs</th>
<th>No control</th>
<th>VSL</th>
<th>ALINEA</th>
<th>HERO</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>%Impr.*</td>
<td>Value</td>
<td>%Impr.*</td>
</tr>
<tr>
<td>Total travel time (in veh-h)</td>
<td>1719</td>
<td>1622</td>
<td>5.64</td>
<td>1504</td>
</tr>
<tr>
<td>CO₂ (in gm/km)</td>
<td>1.4×10⁶</td>
<td>1.3×10⁶</td>
<td>3.29</td>
<td>1.3×10⁶</td>
</tr>
<tr>
<td>CO (in gm/km)</td>
<td>786.86</td>
<td>752.89</td>
<td>4.32</td>
<td>726.31</td>
</tr>
<tr>
<td>NOₓ (in gm/km)</td>
<td>3060</td>
<td>3010</td>
<td>1.63</td>
<td>2984</td>
</tr>
</tbody>
</table>

* Compared to No-control option

### TABLE 4.3. Results of F-test and T-test for TTT under different scenarios

<table>
<thead>
<tr>
<th></th>
<th>No control</th>
<th>VSL</th>
<th>ALINEA</th>
<th>HERO</th>
</tr>
</thead>
<tbody>
<tr>
<td>T-Test Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td>F-Test Results</td>
<td>1.28</td>
<td>2.07</td>
<td>3.06</td>
</tr>
<tr>
<td>VSL</td>
<td>1.35</td>
<td>1.32</td>
<td>2.16</td>
<td></td>
</tr>
<tr>
<td>ALINEA</td>
<td>1.76</td>
<td>1.37</td>
<td>1.06</td>
<td></td>
</tr>
<tr>
<td>HERO</td>
<td>2.42</td>
<td>1.68</td>
<td>1.37</td>
<td></td>
</tr>
</tbody>
</table>

F critical = 1.39
T critical = 1.97
NOTE: Grey background is used for the values exceeding critical values indicating significant difference.
Figure 4.7 presents speed contour plots under different control scenarios. It can be observed that traffic congestion mainly occurs on the first three merging areas in no-control and VSL scenarios. The red and yellow spots (representing slow moving traffic) reduce significantly for ALINEA scenario when compared with no control and VSL scenarios, representing significant improvement in speed environment near the merging areas. A minimal number of red and yellow spots are left in HERO scenario when compared with ALINEA scenario representing further improvement in speed environment contributing to even lower TTT.

Figure 4.8 presents queue length profile at the five on-ramps under different control scenarios. For the first two scenarios namely no-control and VSL scenarios, most of the delays occur near on-ramps O₁ and O₂. This is mainly due to the formation of bottleneck on the mainline near the on-ramp O₁ due to heavy traffic demand and then propagation of the congestion to the immediate upstream on-ramp location, which is O₂. For other two scenarios, there is significant increase in queue length at the on-ramps. This is obviously because of metering applied to the on-ramps creating longer queues and longer delays under those scenarios. HERO case creates longer queue lengths and delays at the last four on-ramps (slaves).
compared with ALINEA case while it slightly improves on the average on-ramp delay for the master on-ramp O1.

FIGURE 4.7. Speed contour plots under different control scenarios
FIGURE 4.8. On-ramp queue length profile under different control scenario
4.2.3. Equity Aspect

As observed in Figure 4.8, huge delay occurs at the on-ramp O₁. It might be unfair for the drivers using the on-ramp O₁ to experience such an excessively long delay. Figure 4.9 presents a plot of Gini coefficient values under different control scenarios as a measure of inequalities among motorway users. ALINEA produces the highest Gini coefficient value when compared with all other scenarios; representing the least equitable system. While HERO produced the lowest Gini coefficient value compared with all other scenarios representing the most equitable system. This improved equity performance of HERO strategy can be attributed the concept to distribute queue lengths to the successive “slave” on-ramps, which also helps to distributes delays among the on-ramps.

![Gini Coefficient Values](image)

FIGURE 4.9. Gini coefficient values under different control scenarios

4.3. Summary

A number of existing motorway traffic management tools are assessed including logic tree based VSL control algorithm and RM control algorithms namely ALINEA and HERO. They
are assessed for a critical bottleneck section on Auckland Motorway using AIMSUN microsimulator based on two performance measures namely efficiency and equity. The former is represented by total travel time and the latter is represented by Gini coefficient.

For the logic tree based VSL control algorithm proposed by Allaby et al. (2007), the bottleneck capacity and critical occupancy value are increased marginally by 0.3% and 0.8% while TTT and Gini coefficient value are decreased by 5.6% and 4.7% respectively when compared with no control case. For ALINEA LRM control algorithm, the bottleneck capacity and critical occupancy value are increased by 0.8% and 7% respectively while TTT is decreased by 12.5% and Gini coefficient (representing inequity) is increased 4.7% when compared with no control case. For HERO CRM control algorithm, improvements in the bottleneck capacity and critical occupancy value could not be analysed as the flow did not reach the capacity. While TTT and Gini coefficient value is decreased by 17.6% and 41.4% respectively when compared with no control case. The T-test and F-test results show that the improvement in efficiency using the logic tree based VSL control algorithm is not that significant while those using ALINEA and HERO control algorithms are significant when compared with no control case. Among the three control measures assessed, HERO CRM algorithm yields the most efficient and equitable motorway system. It assigns queue lengths in a more balanced way among a group of successive on-ramps, which contributes to improve the equity performance for the motorway system.
Chapter 5. A MODIFIED LOGIC TREE BASED VSL CONTROLLER

This chapter presents some modifications to detector location and control logic for the logic tree based VSL control algorithm proposed by Allaby et al. (2007). These modifications are systematically organized into three different scenarios to assess mobility benefits for the proposed modifications compared to no control case.

5.1. Existing Logic Tree based Algorithm and Proposed Modifications

Scenario 1- Existing Logic Tree Based Algorithm with Upstream Detectors

The detector location for this scenario is similar to the one proposed by Allaby et al. (2007) where the VSL display unit is connected to loop detectors nearby on the upstream side of the bottleneck section as illustrated in Figure 4.2 in Chapter 4. The speed limits to be displayed in VSL display units are determined based on traffic volume, mean speed, and occupancy measurements from the loop detectors and a set of pre-defined threshold values based on the method proposed by Allaby et al. (2007) as illustrated in Figure 4.3 in Chapter 4.

Scenario 2- Existing Logic Tree Based Algorithm with Detectors at Bottleneck

In this scenario, the data from the detectors located at the bottleneck section instead of the ones close to the VSL display units is used, as shown in Figure 5.1. This enables the VSL controllers to respond quickly to any changes in traffic conditions at the bottleneck section.
For VSL control algorithm, the same existing logic tree based algorithm is used. This scenario is useful to analyze the effects of change in detectors’ location.

**Scenario 3 – A Modified Logic Tree Algorithm with Detectors at Bottleneck**

Based on the results of the preliminary data analysis conducted in Chapter 3 and a number of different combinations tested in AIMSUN, the logic tree based VSL algorithm is modified as shown in Figure 5.2. The modified logic tree based VSL algorithm selects appropriate speed limit values through checking pre-specified volume and occupancy threshold values. This is the combination that yield the lowest total travel time (TTT). Based on improved results for scenario 2 which will be discussed in the next section, for this case, the data from the loop detectors placed at the bottleneck section is used as shown in Figure 5.1.

**FIGURE 5.1.** Detector location for scenario 2 and scenario 3

![Detector location diagram](image)

**FIGURE 5.2.** Modified VSL control logic

![Modified VSL logic diagram](image)
5.2. Analysis Results

The results are presented under two subheadings: traffic flow conditions in the bottleneck section and system-wide performance. The former is important to understand the influence of the VSL algorithms on capacity of the bottleneck while the latter summarizes the impacts of the VSL algorithms on different MOEs for the entire study section.

5.2.1. Traffic Flow Conditions in Bottleneck Section

Figure 5.3 presents scatter plots of occupancy versus flow data points collected from the bottleneck section for different scenarios including no control scenario that represents a case without VSL controller. It can be observed that flow breakdowns occur with occupancy ranging from 15% to 18% for all scenarios. The critical occupancy values before flow breakdown is located around 16% for the first three cases while for scenario 3, it is located around 17%. It can also be observed that after breakdown point are less in number for scenario 3 and flow values are slightly higher than other scenarios for both before and after breakdown.

To investigate this further, a method proposed by Kianfar et al. (2007) is used to identify the critical occupancy and capacity at the bottleneck section. The occupancy value that results in the lowest root mean square error (RMSE) is selected as the critical occupancy. Then using a curve fitting technique and the data points representing under-critical conditions, the capacity of the bottleneck section is determined for each scenario as presented in Table 5.1. The results show no significant difference among critical occupancy and capacity values for the first three scenarios. However for scenario 3, the capacity is increased to 2312 veh/h/l, which is around 6% improvement compared to no-control case with a capacity value of 2178 veh/h/l. Meanwhile the critical occupancy is also shifted from 16.13% for no control case to 17.38% for scenario 3. Scenario 3 outperforms scenario 1 that is tested as the existing logic tree based
algorithm, witnessing 5% and 7% improvements in capacity and critical occupancy values respectively.

**FIGURE 5.3.** Flow-occupancy plots for the studied bottleneck

**TABLE 5.1.** Capacities and critical occupancies of the studied bottleneck

<table>
<thead>
<tr>
<th></th>
<th>No control</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>% change</td>
<td>Value</td>
<td>% change</td>
</tr>
<tr>
<td>Capacity (veh/h/l)</td>
<td>2178</td>
<td>+0.28</td>
<td>2199</td>
<td>+0.96</td>
</tr>
<tr>
<td>Critical occupancy (%)</td>
<td>16.13</td>
<td>+0.77</td>
<td>16.25</td>
<td>+0.77</td>
</tr>
</tbody>
</table>
5.2.2. System-wide Performance

Table 5.2 shows a summary of simulation results for the entire study section under different control scenarios. The results reveal that the magnitude of the efficiency benefits is highly dependent on the level of driver’s compliance to VSL – higher levels of compliance result in lower TTT in three VSL cases. For 100% driver compliance rate, the existing VSL algorithm tested as scenario 1 witnesses 5.6% improvement in TTT compared to no control scenario, which is further improved to nearly 8% by the change in location of the loop detectors to the bottleneck section in scenario 2. Scenario 3 outperforms all other control scenarios tested in this study, producing the lowest TTT (improved by 11%). For environmental related MOEs also, there are reasonable improvements witnessed in this study. These improvements might be due to decrease in stop-start driving conditions with the application of VSL algorithms.

<table>
<thead>
<tr>
<th>MoEs</th>
<th>No control</th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
</tr>
</thead>
<tbody>
<tr>
<td>TTT (in veh-h)</td>
<td>100% compliance</td>
<td>1719</td>
<td>1622</td>
<td>5.64</td>
</tr>
<tr>
<td>TTT (in veh-h)</td>
<td>80% compliance</td>
<td>1719</td>
<td>1639</td>
<td>4.65</td>
</tr>
<tr>
<td>TTT (in veh-h)</td>
<td>60% compliance</td>
<td>1719</td>
<td>1660</td>
<td>3.43</td>
</tr>
<tr>
<td>CO₂ (in gm/km)</td>
<td></td>
<td>1.37×10⁶</td>
<td>1.35×10⁶</td>
<td>1.46</td>
</tr>
<tr>
<td>CO (in gm/km)</td>
<td></td>
<td>786.86</td>
<td>752.89</td>
<td>4.32</td>
</tr>
<tr>
<td>NOₓ (in gm/km)</td>
<td></td>
<td>3060</td>
<td>3010</td>
<td>1.63</td>
</tr>
</tbody>
</table>

* Compared to No-control option
Figure 5.4 presents a time series of TTT for the entire study area of the motorway network under different control scenarios. It is observed that the amelioration of TTT contributed by VSL mainly occurred during the peak periods in this case from around 6:45 to 8:15 AM.

Figure 5.4. Time series of TTT under different control scenarios

Figure 5.5 presents changes in the average delay contributed by different VSL control scenarios separately for on-ramp and mainstream compared to no control scenario. The results clearly show that VSL is effective in reducing on-ramp delay time. This contributes mainly to improve TTT. This finding is agreement with those of Carlson et al. (2010) that when VSL is implemented on the upstream side of on-ramps, it can work similar to RM by controlling the flow on the mainstream rather than at on-ramps. A slight increase in the average delay on the mainline is observed. However these increases are sufficiently compensated by delay time savings at on-ramps. Here also scenario 3 outperforms all other scenarios as it witnesses the minimum increase in the mainline delay and the maximum decrease in the on-ramp delay.
In this chapter, a logic tree based VSL algorithm is modified in terms of detector location and the governing VSL controller logic to achieve higher mobility gains. Following conclusions can be drawn based on the results presented in the previous section:

- Modified logic tree based VSL algorithm is effective to achieve significant mobility gains and reduction in emissions from the existing motorway infrastructure.
- Modified logic tree based VSL algorithm outperforms the existing algorithm in terms of capacity, total travel time and environmental related MOEs.
- The performance of VSL is highly influenced by the governing VSL controller logic and location of the detectors.
- VSL has got potential to contribute to manage recurrently congested bottlenecks in motorway systems.

**FIGURE 5.5. Improvement of average delay in VSLs control scenarios**

<table>
<thead>
<tr>
<th>Scenario</th>
<th>Mainline</th>
<th>On-ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>Scenario 1</td>
<td>-1.77%</td>
<td>50.75%</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>-1.13%</td>
<td>61.26%</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>-1.02%</td>
<td>74.99%</td>
</tr>
</tbody>
</table>
Chapter 6. A FUZZY LOGIC BASED VSL CONTROLLER

This chapter presents a fuzzy logic based VSL control algorithm as an alternative to the existing VSL control algorithms. The proposed algorithm is assessed for the test bed and verified against the logic tree based VSL algorithm proposed by Allaby et al. (2007).

6.1. Fuzzy Logic Algorithm

The term "fuzzy logic" was first introduced in 1965 by Zadeh (1965). Compared to traditional binary sets, fuzzy logic variables have a truth value that ranges in degree between 0 and 1. In a crisp classification, the membership degree of the example equals a value of 1 as shown in Figure 6.1a. Thus, the size of a subset equals counts of examples belonging to the subset. In a fuzzy classification, the number of examples of a subset is computed by aggregating the membership degree of examples that belong to a fuzzy set. Figure 6.1b illustrates that the degree of class membership of the example, \( Occ \) indicates the extent to what an example belongs to the fuzzy set. The basic structure of a fuzzy logic VSL controller consists of three components, namely, fuzzification of the input variables, construct rule base, and defuzzification of the output variable membership function.
6.1.1. Fuzzification

The first stage inside the fuzzy VSL controller is fuzzification which converts crisp input values into a set of fuzzy variables defined by membership functions. Fuzzification determines how well the condition of each rule matches the particular input. In this study there are two inputs into the fuzzy VSL controller, namely, downstream occupancy and flow which are measured immediately downstream of the on-ramp merge. Downstream flow is from 1900 to 2500 veh/h/l and described as three Gaussian set “low”, “medium” and “high” as depicted in Figure 6.2.

The Product Limit Method (PLM) is employed to generate a plot of the probability of breakdown under different occupancy levels based on the results of the preliminary data analysis conducted in Chapter 3. After examining different distributions to determine which
one best fits the PLM plot, a polynomial regression is applied to the PLM plot allowing the data to be more readily usable as illustrated in Figure 6.3.

![Figure 6.2: Fuzzy sets for downstream flow](image-url)

**FIGURE 6.2.** Fuzzy sets for downstream flow

![Figure 6.3: Fuzzy set for downstream occupancy](image-url)

**FIGURE 6.3.** Fuzzy set for downstream occupancy

Speed limits, as the output of fuzzy algorithm, are also converted to fuzzy set. Three triangular set “low”, “medium” and “high” are assigned to speed limits as shown in Figure
6.4. Note that above described membership functions are fine-tuned based on simulation results. Different combinations of centroid values in traffic flow and speed limit membership functions are tested in Micro-simulator AIMSUN; the one that yields the lowest total travel time (TTT) is selected for this study.

![Figure 6.4. Fuzzy set for speed limits](image)

**6.1.2. Inference**

At the heart of the controller the rules, sometimes called the knowledge base, are designed based on operator experience, expert opinions, and system knowledge. Basically the rules that belong to a linguistic controller are expressed in the following format:

\[
\text{IF } \text{premise} \text{ THEN } \text{consequent}
\]

There is also the possibility to combine several premises with operators:

\[
\text{IF } \text{premise 1} \text{ AND/OR } \text{premise 2} \text{ AND/OR } \text{premise 3} \ldots \text{ THEN } \text{consequent}
\]
In this study all rules are evaluated in parallel based on fuzzy set theory that describes interpretation of the logical operations such as the complement, intersection, and union of sets. The consequent of each rule assigns an entire fuzzy set to the outputs. The fuzzy set is represented by a membership function to indicate the qualities of the consequent. Thus every rule has a nonzero degree overlapping with other rules. The aggregation method is chosen to combine the inference results of these rules. The rule base for speed limits is stated in Table 6.1. The purpose of rules No.1 through 3 is to form a complete rule base. In other words, at least one of these rules will always fire before or during heavy congestion since the entire volume range is covered. These rules are to prevent the formation of downstream congestion rather than simply react to it. The rule No.4 is selected to release traffic congestion. This rule uses the premise that high downstream occupancy indicates bottleneck formation, calling for a more restrict speed control. The rule weight is to stress the priority of each rule. The higher weighting of rules No.3 and 4 emphasize that these are the chief means by which VSL is effective. Note that the weight factor values are also optimized based on simulation results. The combination producing the lowest TTT is chosen in this study.

**TABLE 6.1. Rule base for fuzzy VSL algorithm**

<table>
<thead>
<tr>
<th>No. of Rule</th>
<th>Weight</th>
<th>Premise</th>
<th>Consequent</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.0</td>
<td>IF downstream flow is low</td>
<td>THEN speed limit is high</td>
</tr>
<tr>
<td>2</td>
<td>1.0</td>
<td>IF downstream flow is medium</td>
<td>THEN speed limit is medium</td>
</tr>
<tr>
<td>3</td>
<td>2.0</td>
<td>IF downstream flow is high</td>
<td>THEN speed limit is low</td>
</tr>
<tr>
<td>4</td>
<td>2.0</td>
<td>IF downstream occupancy is high</td>
<td>THEN speed limit is low</td>
</tr>
</tbody>
</table>
6.1.3. Defuzzification

The defuzzification process is to convert each fuzzy output variable into a crisp (non-fuzzy) form (speed limits). The centroid method is commonly used in the defuzzification process. The equation of centroid gravity method is shown below:

\[ \frac{\int x f(x) \, dx}{\int f(x) \, dx} \quad (6.1) \]

In practice, a discrete fuzzy centroid equation is used since it is easier to calculate than the above continuous centroid equation. The discrete centroid equation is expressed as follows:

\[ \frac{\sum_{i=1}^{N} w_i c_i I_i}{\sum_{i=1}^{N} w_i} \quad (6.2) \]

where,

- \( N \) is the number of the output classes;
- \( c_i \) is the centroid of the \( i^{th} \) output class;
- \( w_i \) is the results of the aggregation of rules at the \( i^{th} \) output class; and
- \( I_i \) is the area of the \( i^{th} \) output class.

6.2. Simulation in AIMSUN

An Application Programming Interface (API) program is developed in AIMSUN to implement and verify the performance of fuzzy logic control (FLC) VSL algorithm for the critical section of Auckland Motorway. Figure 6.5 illustrates the proposed algorithm implemented in AIMSUN. During each control interval, FLC API receives traffic information including traffic flow and occupancy data collected from the mainline detectors. Then, FLC API converts real-time traffic information to speed limit values through the three
fuzzy steps, namely, fuzzification, inference and defuzzification. Finally, FLC API assigns the determined speed limit values to each VSL controller.

6.3. Analysis Results

This section presents assessment results of three different control scenarios for the study section including no control, logic tree algorithm and FLC algorithm. The “no control scenario” is chosen as a reference to measure improvements offered by other control scenarios.
6.3.1 Traffic Conditions in Bottleneck Section

Figure 6.6 presents scatter plots of occupancy versus flow data points collected from the bottleneck section for different scenarios. The initial trend of increase in occupancy with increase in flow is observed while this trend reverses after the capacity is reached. It can be observed that this change in trend occurs within occupancy ranging from 15% to 18% for all scenarios. The critical occupancy values before flow breakdown is located around 16% for the first two cases while for FLC case, it is located around 17%. Nevertheless, the exact critical occupancy and capacity values are not clear in the scatter plots.

FIGURE 6.6. Flow-occupancy plots for the studied bottleneck under different scenarios
To investigate this further, a method proposed by Kianfar et al. (2013) is employed to compute the capacity and critical occupancy at the bottleneck section. As presented in Table 6.2, there is not much difference in the critical occupancy and bottleneck capacity values for the first two scenarios that are no control case and logic tree algorithm case. For FLC case, the capacity is increased to 2318 veh/h/l, which is around 6% improvement compared to no-control case with a capacity value of 2178 veh/h/l. Meanwhile the critical occupancy is also shifted from 16.13% for no control case to 17.38% for FLC case.

TABLE 6.2. Capacities and critical occupancies of the studied bottleneck

<table>
<thead>
<tr>
<th></th>
<th>No control</th>
<th>Logic Tree</th>
<th>Fuzzy Logic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>% change</td>
<td>Value</td>
</tr>
<tr>
<td>Capacity (veh/h/l)</td>
<td>2178</td>
<td>+0.28</td>
<td>2318</td>
</tr>
<tr>
<td>Critical occupancy (%)</td>
<td>16.125</td>
<td>+0.77</td>
<td>17.38</td>
</tr>
</tbody>
</table>

6.3.2. System-wide Performance

Table 6.3 presents the values of MOEs computed for the entire study area of the motorway network under different control scenarios. Logic tree algorithm records 5.6% improvement in TTT when compared to no control scenario. FLC case outperforms other control scenarios for TTT, witnessing an improvement around 12% in TTT. Meanwhile, speed limitations resulted in reasonable emission reductions in this study; this amelioration might be contributed by decrease in stop-start driving conditions with the tested measures. Figure 6.7 presents a time series of TTT for the entire study area under different control scenarios. It can be observed that improvements contributed by VSL mainly occurred during the peak period. Here also the proposed FLC algorithm produces the lowest TTT for the most of time.
TABLE 6.3. Measurements of effectiveness for different control scenarios

<table>
<thead>
<tr>
<th>MoEs</th>
<th>No control</th>
<th>Logic tree algorithm</th>
<th>FLC algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>%change*</td>
<td>Value</td>
</tr>
<tr>
<td>TTT (in veh-h)</td>
<td>1719</td>
<td>1622</td>
<td>5.64</td>
</tr>
<tr>
<td>CO₂ (in gm/km)</td>
<td>1.37×10⁶</td>
<td>1.35×10⁶</td>
<td>1.46</td>
</tr>
<tr>
<td>CO (in gm/km)</td>
<td>786.86</td>
<td>752.89</td>
<td>4.32</td>
</tr>
<tr>
<td>NOₓ (in gm/km)</td>
<td>3060</td>
<td>3010</td>
<td>1.63</td>
</tr>
</tbody>
</table>

* Compared to No-control option

FIGURE 6.7. Time series of TTT under different control scenarios

To assess the impact of driver compliance on mobility benefits of the system for studied measures, each scenario is further analyzed by considering three levels of driver compliances including 60%, 80% and 100% as presented in Table 6.4. It can be observed that the mobility benefit of VSL is at its highest level with 100% driver compliance (that is a case of strictly
enforced VSL). Then TTT values increase with reduction in driver compliance rates. T-test is performed to check how significant the differences in the TTT values are under different driver compliance levels. The cells highlighted with a dark background represent cases of significant difference in the mean representing significant improvement in TTT when compared with the other scenarios. For FLC case, T-value computed using 100% driver compliance rate exceeds the critical T-value when compared with no control case, while for all other cases no statistically significant differences are observed among them.

**TABLE 6.4. TTT for different control scenarios with different compliance levels**

<table>
<thead>
<tr>
<th>Driver compliance</th>
<th>No control</th>
<th>Logic tree algorithm</th>
<th>FLC algorithm</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>%-Impr.</td>
<td>T-value</td>
</tr>
<tr>
<td>100%</td>
<td>1719</td>
<td>1622</td>
<td>5.64</td>
</tr>
<tr>
<td>80%</td>
<td>1719</td>
<td>1639</td>
<td>4.65</td>
</tr>
<tr>
<td>60%</td>
<td>1719</td>
<td>1660</td>
<td>3.43</td>
</tr>
</tbody>
</table>

\[ F\text{-critical} = 1.39 \]

\[ ^a \text{Compared to No-control option} \]

\[ ^b \text{Compared to corresponding 100\% driver compliance rate} \]

**6.4. Summary**

This chapter proposes a fuzzy logic approach to enhance the performance of VSL controllers. The performance of studied algorithms is measured by total travel time and emission levels with different driver compliance rates. The main conclusions drawn of this study are as follows:

- FLC algorithm offers an effective solution to improve mobility gains as well as emission reductions. The proposed algorithm dramatically improves the efficiency of
the infrastructure and outperforms all other studied measures in terms of total travel time and environmental related MOEs.

- The mobility benefit of VSL is at its highest level with 100% drivel compliance.
  With an increase in rates of driver compliance, travel time savings increase.
Chapter 7. AN INTEGRATED RM AND VSL CONTROLLER

In this chapter, a new method to integrate RM and VSL is proposed to preserve the traffic flow close to its capacity at bottlenecks, and to avoid excessive delays at on-ramps. This can be materialized through the deployment of VSL control on the motorway mainline immediately on the upstream side of on-ramps, so as to create some merging space for the traffic entering the mainline from on-ramps. The proposed method is implemented for two RM strategies namely ALINEA and HERO.

7.1. Integrated Method

Figure 7.1 presents a flowchart of integration between RM and VSL control logics proposed to enhance motorway performance. At each control interval $T$, the RM controller receives a queue length data from the queue detector placed at the on-ramp. When the queue length $w(k)$ exceeds a pre-selected threshold value $act(j)$, the corresponding metering rate $r'(k)$ is calculated using a formulation used in $X$-ALINEA/Q (Smaragdis and Papageorgiou, 2003)

$$r'(k) = \frac{1}{T} [\hat{w} - w(k)] + d(k - 1) \quad (7.1)$$

where,

- $T$ is the time interval;
- $w(k)$ is the current queue length;
- $\hat{w}$ is the desired queue length; and
- $d(k-1)$ is the demand flow entering the on-ramp.
The calculated $r'(k)$ is then compared with the metering rate $r(k)$ determined using Eq. (2.3) which is originally used to calculate metering rate in ALINEA strategy as described in Chapter 2. If $r(k)>r'(k)$, the metering rate remains the same that is $r(k)$ and no further integrated control need to be launched. In the case of $r(k)<r'(k)$, the new metering rate that is $r'(k)$ will be applied for the next time interval. In such cases, the existing speed limit will be replaced with an adjusted speed limit $v'(k)$ that will be displayed in the VSL display units to compensate an increased on-ramp inflow rate $r'(k)$. Once the relative queue length drops below the pre-specified deactivation threshold value $deact(j)$, the integrated control algorithm is deactivated and RM and VSL starts to operate individually again. The calculation steps for the adjusted speed limit $v'(k)$ is summarised in the follow

Eq. (2.3) can be modified as follows:

$$q_{in}(k) = q_{in}(k-1) + K_R[\hat{O} - O_{out}(k)] \tag{7.2}$$

where $q_{in}(k)$ is flow in the mainline at time step $k$ that enters the bottleneck section from the upstream VSL controlled segment; and $K_R$ is a regulator parameter with a recommended value of 70veh/h.

It shall be noted that queue lengths at each on-ramps (aggregating all vehicle types) can be automatically obtained in AIMSUN. For field application, queue length estimators, e.g., Kalman filter based estimator (Vigos et al., 2008), can be employed to measure on-ramp queue lengths. The mainline density for the upstream VSL controlled segment $\hat{p}(k)$ can be approximated as follows:

$$\hat{p}(k) = \frac{Q(k) \times 1000}{\Gamma} \tag{7.3}$$
where $O(k)$ is the upstream occupancy; and $\bar{l}$ is the effective vehicle length which is a sum of actual vehicle length and detectable length of the loop detector in meters.

Since the application of VSL unavoidably changes the density of the upstream VSL controlled segment, which in turn impacts the speed limit calculation process in Eq. (7.5). It is necessary to take into account density change due to VSL which is calculated via

$$\Delta \rho = T (q_u - q_{in})/L$$

(7.4)

where,

$T$ is control interval;

$q_u$ is the upstream flow entering the VSL controlled segment form the upstream section; and

$L$ is the length of VSL controlled segment.

The adjusted speed limit at time step $k$ that is $v^\prime (k)$ to be displayed on VSL display units is computed as follows:

$$v_{in}^\prime (k) = q_{in} (k)/(\bar{\rho}(k) + a \Delta \rho)$$

(7.5)

where $a$ is a control parameter ranging from 0 to 1. In this study, $a=0.4$ and $a=0.5$ which yield the lowest total travel time are selected for ALINEA+VSL and HERO+VSL scenarios respectively. The speed limits produced by Eq. (7.5) are directly applied to VSL display units without further discretization.
7.2. Simulation in AIMSUN

An Application Programming Interface (API) program is developed in AIMSUN micro-simulator to implement and verify the performance of integrated control for the critical section of Auckland Motorway. The integrated control API receives the required traffic information from the loop detectors during each control interval as illustrated in Figure 7.2. The measured on-ramp queue length is compared against the pre-specified activation threshold value. When it exceeds the activation threshold value, the integrated control logic is launched. The metering rate and the adjusted speed limit are calculated by the integrated control API autonomously, which are then applied in the respective controllers. As shown in Chapter 5 and Chapter 6, the magnitude of the efficiency benefits due to VSL are highly dependent on the level of driver’s compliance to VSL – higher levels of compliance results in better performance of the network. The following section presents the results obtained under
100% driver compliance rate representing a strictly enforced VSL system where the efficiency of VSL is at its highest level.

Figure 7.2. Implementation of integrated method strategy in AIMSUN

7.3. Analysis Results

Six different control scenarios are systematically assessed for the study section including no control, the modified logic tree algorithm, ALINEA, ALINEA+VSL, HERO and HERO+VSL. The “no control scenario” is used as a reference to measure improvements offered by other control scenarios in terms of efficiency and equity of the motorway system. The results are presented under three subheadings: traffic flow conditions in the bottleneck section, system-wide performance and equity aspects.

7.3.1. Traffic Flow Conditions in Bottleneck Section

Figure 7.3 presents scatter plots of occupancy versus flow data points collected from the bottleneck section for different scenarios. It can be observed that flow breakdown occurs only in the first three scenarios that is no control, VSL and ALINEA while for the last three scenarios including ALINEA+VSL, HERO and HERO+VSL, there is no flow breakdown...
points, which are represented by dark (red) points. In VSL case, speed limits applied at under-critical occupancies have the impact of decreasing the slope of the flow–occupancy diagram when compared with no-control case. This finding is in agreement with those of Hegyi et al. (2005) and Papamichail et al. (2008). For VSL and ALINEA there is reduction in the number of flow breakdown points compared to no control case.

7.3.2. System-wide Performance

Table 7.1 presents the values of performance measures computed for each control scenarios for the entire study section. The highest improvements are highlighted with a dark background. HERO+VSL scenario outperforms all other control scenarios for TTT, producing the highest improvement of 22.6%. The cases representing integrated combination of RM with VSL yield relatively lower TTT values compared against RM individual cases. For emissions, only VSL scenario produces the highest improvements. The amelioration of emission reduction might be due to decrease in stop-start driving conditions with the application of VSL.

F-test and T-test are conducted to check how significant the differences in the TTT values are under different control scenarios and the results are presented in Table 7.2. On F-test results, the cells highlighted with a dark background represent cases of significant difference in the variance and is treated the same when computing the T-test results. On T-test results, the cells highlighted with a dark background represent cases of significant difference in the mean representing significant improvement in TTT when compared with the other scenarios. Based on these results, it can be concluded that the network controlled by HERO outperforms those controlled by VSL or ALINEA.
FIGURE 7.3. Flow-occupancy plots for the studied bottleneck under different scenarios
### TABLE 7.1. Measures of effectiveness for different scenarios

<table>
<thead>
<tr>
<th>MoEs</th>
<th>No control</th>
<th>VSL</th>
<th>ALINEA</th>
<th>ALINEA+VSL</th>
<th>HERO</th>
<th>HERO+VSL</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Value</td>
<td>%Impr.*</td>
<td>Value</td>
<td>%Impr.*</td>
<td>Value</td>
<td>%Impr.*</td>
</tr>
<tr>
<td>TTT (in veh-h)</td>
<td>1719</td>
<td>1531</td>
<td>10.94</td>
<td>1504</td>
<td>12.51</td>
<td>1416</td>
</tr>
<tr>
<td>CO₂ (in gm/km)}</td>
<td>1.4×10⁶</td>
<td>1.3×10⁶</td>
<td>3.29</td>
<td>1.3×10⁶</td>
<td>3.29</td>
<td>1.3×10⁶</td>
</tr>
<tr>
<td>CO (in gm/km)</td>
<td>786.86</td>
<td>719.69</td>
<td>8.54</td>
<td>726.31</td>
<td>7.7</td>
<td>723.52</td>
</tr>
<tr>
<td>NOₓ (in gm/km)</td>
<td>3060</td>
<td>2974</td>
<td>2.81</td>
<td>2984</td>
<td>2.48</td>
<td>2978</td>
</tr>
</tbody>
</table>

* Compared to No-control option

### TABLE 7.2. Results of F-test and T-test for TTT under different scenarios

<table>
<thead>
<tr>
<th>MoEs</th>
<th>No control</th>
<th>VSL</th>
<th>ALINEA</th>
<th>ALINEA+VSL</th>
<th>HERO</th>
<th>HERO+VSL</th>
</tr>
</thead>
<tbody>
<tr>
<td>F-test Results</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>No control</td>
<td></td>
<td>1.78</td>
<td>2.07</td>
<td>2.86</td>
<td>3.06</td>
<td>4.07</td>
</tr>
<tr>
<td>VSL</td>
<td>1.65</td>
<td></td>
<td>0.38</td>
<td>1.16</td>
<td>1.37</td>
<td>2.50</td>
</tr>
<tr>
<td>ALINEA</td>
<td>1.76</td>
<td>1.07</td>
<td></td>
<td>0.85</td>
<td>1.06</td>
<td>2.20</td>
</tr>
<tr>
<td>ALINEA+VSL</td>
<td>2.28</td>
<td>1.38</td>
<td>1.29</td>
<td></td>
<td>0.22</td>
<td>1.40</td>
</tr>
<tr>
<td>HERO</td>
<td>2.42</td>
<td>1.47</td>
<td>1.37</td>
<td>1.06</td>
<td></td>
<td>1.18</td>
</tr>
<tr>
<td>HERO+VSL</td>
<td>3.32</td>
<td>2.01</td>
<td>1.88</td>
<td>1.45</td>
<td>1.37</td>
<td></td>
</tr>
</tbody>
</table>

F critical = 1.39
T critical = 1.97

NOTE: Grey background is used for the values exceeding critical values indicating significant difference.
Figure 7.4 presents a time series of TTT for the entire study area under different control scenarios. It can be observed that improvements contributed by studied control measures are mainly during the peak periods in this case from around 6:45 to 8:15 AM. Here also HERO+VSL scenario produces the lowest TTT for the most of time.

Figure 7.5 presents the average queue lengths at each of the five on-ramps. The queue’s formation mainly occurs in on-ramps O₁ and O₂. This is because of the formation of bottleneck on the mainline near the on-ramp O₁ and then propagation of the congestion to the immediate upstream on-ramp location, which is O₂. Only VSL scenario produces the minimal queue lengths at the on-ramps followed by no-control scenario. While for all other scenarios that include RM, there is significant increase in queue length at the on-ramps. This is contributed by metering applied to the on-ramps creating longer queues under those scenarios. Among them also the scenarios representing integrated combination of RM with VSL produce relatively lower queue lengths compared to RM only scenarios that is ALINEA and HERO scenarios.

Figure 7.6 presents the average speed profile along the entire study section for each control scenario. As expected there is no increase in the average speed using the VSL algorithm, which well serves the purpose of VSL as it mainly harmonizes the traffic flow by controlling speed variation among vehicles in the control segment. The scenario using HERO produces the minimum speed drops represented by dark (red) lines.
FIGURE 7.4. Time series of TTT under different control scenarios

FIGURE 7.5. Average on-ramp queue length under different control scenarios
7.3.3 Equity Aspect

Figure 7.7 presents a plot of Gini coefficient values under different control scenarios as a measure of equalities among motorway users. ALINEA yields the highest Gini coefficient value among all of the tested scenarios; representing the least equitable motorway system.
While HERO+VSL produces the lowest Gini coefficient compared with all other scenarios; representing the most equitable motorway system. This improved equity performance of HERO strategy might be due to the concept of distributing queue lengths to the successive “slave” on-ramps, which also helps to distributes delays among the on-ramps. The significant reduction of queue length at the on-ramp O1 due to the integrated VSL also contributes to improving equity performance of the integrated control scenarios that is ALINEA+VSL and HERO+VSL when compared with the respective RM only scenarios that is ALINEA and HERO scenarios.

![Figure 7.7: Gini coefficient values under different control scenarios](image)

<table>
<thead>
<tr>
<th>Control Scenario</th>
<th>Gini Coefficient (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Control</td>
<td>67.26</td>
</tr>
<tr>
<td>VSL</td>
<td>53.88</td>
</tr>
<tr>
<td>ALINEA</td>
<td>70.39</td>
</tr>
<tr>
<td>ALINEA +VSL</td>
<td>48.18</td>
</tr>
<tr>
<td>HERO</td>
<td>39.41</td>
</tr>
<tr>
<td>HERO +VSL</td>
<td>22.25</td>
</tr>
</tbody>
</table>

**FIGURE 7.7.** Gini coefficient values under different control scenarios

### 7.4. Summary

This chapter presents a new method to integrate prudently RM with VSL controllers to achieve an efficient and equitable motorway system. The proposed method is used to combine a local and a coordinated RM strategy namely ALINEA and HERO with VSL. The
outcome performance is assessed in terms of efficiency and equity of the motorway system.

The main conclusions drawn of this study are as follows:

- An integrated RM and VSL system presents a promising intelligent transportation system measure to improve the performance of motorways in terms of efficiency and equity.

- The proposed method to integrate RM with VSL enables to demonstrate the prospects of the improvements that can be attained.

- The modified VSL only control scenario outperforms all other control scenarios in terms of improving vehicular emissions; this might be because of the harmonization of the traffic flow and shorter duration of stops.

- The HERO+VSL control scenario outperforms all other control scenarios in terms of the total travel time and the equity measured by the Gini coefficient. The equity improvements might be because of two reasons: (i) the concept implemented in HERO, to distribute queue lengths to the successive “slave” on-ramps, which manages to distribute delays more evenly among the on-ramps, and (ii) an integrated use of the RM and VSL results in a significant reduction of queue length at the first on-ramp O₁ which is next to the main bottleneck.
Chapter 8. RELATIONSHIP BETWEEN EFFICIENCY AND EQUITY

This chapter proposes a new CRM strategy aimed at reducing the inequity among motorway users using different on-ramps and investigates trade-offs between efficiency and equity for the proposed strategy. A combined index is proposed incorporating TTT and Gini coefficient to serve as an objective function to solve the bi-objective control design problem. The performance of the proposed strategy is verified by comparing against HERO strategy for the test bed.

8.1. Modified HERO Strategy

As described earlier in Chapter 2, HERO assigns the minimum queue length to each upstream on-ramp in a proportion of the maximum admissible queue length of the respective on-ramp using Eq. (2.11), which can lead to unfair distribution of delays for different on-ramp users. To address the equity issue, Eq. (2.11) is replaced with the following equations that will ensure more fair distribution of delays among different on-ramp users:

\[
W_{\text{min}}(k) = \min \{ W_1(k), W_2(k) \} \tag{8.1}
\]

\[
W_1(k) = \frac{\text{Sum}_w(i)}{N} \tag{8.2}
\]

\[
W_2(k) = W_{\text{max}}(k) \times a \tag{8.3}
\]
where,

\[ W_{\text{max}}(k) \] is the maximum admissible queue length of the respective on-ramp, \\
\[ a \] is a control parameter ranging from 0 to 1, \\
\[ \text{Sum}_W(i) \] is a sum of current queue lengths at each on-ramps within the coordination control string, and \\
\[ N \] is the number of on-ramps within the coordination control string.

Here, \( W_1(k) \) maintains the relative queue lengths at each on-ramps close to each other while \( W_2(k) \) prevents queues at on-ramps from interfering with the adjacent street traffic. By selecting the minimum of the two values, the minimum desired queue length at each on-ramp is determined.

Figure 8.1 presents a flowchart of the proposed strategy, which works in three different steps. In the first step, a “master” on-ramp is detected once the observed queue length exceeds a pre-specified queue length threshold. This step is related to the working principle #2 of HERO strategy as described in Section 2.2.3. The second step is to define dissolution of the coordination string, which is related to the working principle #5 of HERO strategy. In the third step, the minimum queue length is determined for each “slave” on-ramps using Eq. (8.1), which is related to the working principle #4 of HERO strategy. The minimum queue length computed using Eq. (8.1) is maintained at each “slave” on-ramp using the following formulation.

If \( w(k) > W_{\text{min}}(k) \) Then,

\[ R(k) = r^{'}(k) \quad (8.4) \]

Otherwise,

\[ R(k) = \min\{ r(k), r^{'}(k) \} \quad (8.5) \]
\[ r'(k) = \frac{1}{T} \{ w(k) - W_{\text{min}}(k) \} + d(k - 1) \]  

(8.6)

where,

- \( R(k) \) is the metering rate to be applied at the time step \( k \),
- \( r(k) \) is the metering rate determined by ALINEA strategy,
- \( T \) is the time interval,
- \( w(k) \) is the current queue length,
- \( d(k-1) \) is the demand flow entering the on-ramp.

Eq. (8.4) and Eq. (8.5) will help to maintain the on-ramp queue length close to the desired minimum queue length \( W_{\text{min}}(k) \) assigned by the proposed CRM strategy to each “slave” on-ramps. Eq. (8.6) will yield a lower \( r'(k) \) value (that is releasing lower number of vehicles from on-ramp and hence more strict ramp metering) when the current on-ramp queue length \( w(k) \) is lower than the desired minimum queue length to increase the on-ramp queue length closer to the desired minimum value. The same equation will yield higher \( r'(k) \) when the current on-ramp queue length \( w(k) \) is higher than the desired minimum queue length to reduce the on-ramp queue length closer to the desired minimum value. When \( W(k) \) is equal to \( W_{\text{min}}(k) \), Eq. (8.6) will yield \( r'(k) \) equals to \( d(k-1) \), which is to maintain the existing queue length. 30% and 15% of the maximum queue length are used as activation and deactivation threshold values respectively for the proposed control strategy. Note that this research only presents the results for values ranging from 50 to 90% for the maximum admissible queue length (\( a \) parameter value). The results for cases with \( a < 50\% \) are not presented because the modified HERO algorithm with low \( a \) value is unable to effectively regulate the on-ramp traffic; this is opposite to the purpose of RM that improves the traffic flow conditions on a motorway mainline by limiting the inflow of vehicles from on-ramps. The results for cases
with \( a > 95\% \) is not presented as the on-ramp traffic interfered with the adjacent street traffic, resulting in imprecise simulation results.

![Flowchart](image)

**FIGURE 8.1.** A flowchart of modified HERO strategy

### 8.2. Combined Index

A motorway system with the minimal TTT is considered to be the most efficient while the one with the minimal Gini coefficient is considered to be the most equitable. Thus, with the
same set of constraints, optimization based on Eq. (8.4) or Eq. (8.5) as the objective function to be minimized will result in an efficient or equitable motorway system respectively. Hence it will address only one aspect of its performance. To achieve a balanced efficiency and equity gain, it might be useful to propose a combined single index incorporating both TTT and Gini coefficient into a single objective function. The combined index can be expressed as follows

\[
\text{Combined Index} = E_1 \times G + E_2 \frac{TTT_t}{TTT_{\text{non}}}
\]  

(8.7)

where,

- \(G\) is Gini coefficient value computed using tested measure,
- \(TTT_t\) is TTT value computed using tested measure,
- \(TTT_{\text{non}}\) is TTT value computed using no control,
- \(E_1, E_2\) are weight factors to stress the priority of each control objective

### 8.3. Analysis Results

Table 8.1 presents TTT and Gini coefficient values computed for different control scenarios including no control, HERO and nine different scenarios for the proposed algorithm with the parameter \(a\) value ranging from 50% to 90%. Here no-control scenario represents a case of motorway without any type of ramp control. The highest improvements are highlighted with a dark background. HERO and all of the nine different control scenarios for the proposed algorithm yield substantial improvements compared to the no-control scenario in terms of both efficiency and equity. HERO strategy yields a system-wide efficiency gain of 17.63% (measured by TTT) and records an equity gain of 40% (measured by Gini coefficient) compared to the no-control scenario. For the proposed strategy, the efficiency and equity
gains are sensitive towards the value of $a$. Here, higher value of $a$ represents a longer desired queue length. It can be observed that the efficiency of the motorway system improves (that is TTT value decreases) as the value of parameter $a$ increases. The efficiency improvement reaches its highest level (TTT value reduced by 16.70%) when $a$ value is set at 90%. Meanwhile, the Gini coefficient value decreases with increase in parameter $a$ value, which shows that in this case improvements in efficiency and equity is not conflicting as they follow similar trend with only one exception where Gini coefficient increases from 34.95 to 35.09 when $a$ value increases from 60 to 65%. The Gini coefficient value is at its lowest (26.23%) when $a$ value is equal to 90%, resulting in 61% improvement compared to no-control scenario while TTT value remains close to that of HERO (1432 veh-h, an improvement of 16.7% compared to no-control scenario).

These improvements in equity performance can be attributed to a relatively fair management of queues at different on-ramps in the proposed CRM algorithm. This finding is in agreement with that of Kotsialos and Papageorgiou (2001) that the storage capacity of on-ramps provided by motorways should be used to the highest degree as it seriously improves both efficiency and equity properties of the RM strategy. From the observations discussed earlier, it is clear that the amelioration of TTT and Gini coefficient values is highly dependent on the storage capacity of on-ramp. More particularly, the shortest one is the most critical for the proposed strategy.

To further investigate trade-offs between TTT and Gini coefficient values, Figure 8.2 presents a scatter plot of the two variables for different $a$ values ranging from 0.5 to 0.9. The percentile improvements for Gini coefficient are distributed in a range from 40% to 60%. The same for TTT are distributed more evenly in a range from 10% to 20%. The improvement rate is positive for both variables with increasing value of $a$ while Gini coefficient has steeper average trend than the one for TTT. Figure 8.3 presents a scatter plot of Gini coefficient
versus TTT for different $a$ values. The data points show a strong correlation between the two variables in this case with a $R^2$ value of 0.91 and follow a non-linear (parabolic) pattern.

TABLE 8.1. TTT and Gini coefficient values for different scenarios

<table>
<thead>
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<th>No control</th>
<th>Total travel time (veh-h)</th>
<th>Gini coefficient (%)</th>
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</thead>
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<tr>
<td></td>
<td>Value</td>
<td>% Improvement</td>
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<tr>
<td>HERO</td>
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<td>Modified HERO ($a =50%$)</td>
<td>1560</td>
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<td>Modified HERO ($a =80%$)</td>
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</tr>
<tr>
<td>Modified HERO ($a =90%$)</td>
<td>1432</td>
<td>16.70</td>
</tr>
</tbody>
</table>

*Compared to no control scenario
Figure 8.2 presents percentile improvements in TTT and Gini for different $\alpha$ values.

Figure 8.3. Scatter plots of TTT and Gini coefficient for different $\alpha$ values.

Figure 8.4 presents contour plots of queue lengths built at all of the five on-ramps for four control scenarios including no-control, HERO and the proposed strategy with parameter $\alpha$ taking values of 0.5 and 0.9. For no-control scenario, queues build at only the first two on-ramps $O_1$ and $O_2$. With HERO strategy, queue length is distributed to other successive on-
ramps O₂ to O₅ with the longest queue at O₁. For the proposed strategy with a value of 0.5, the queue is distributed more evenly among O₂, O₃ and O₅. However, O₁ and O₄ are experiencing longer queue length. For the proposed strategy with a value of 0.9, the queue length developed at O₂ and O₃ are comparable while the queue length developed at O₄ and O₅ are also comparable. Queue length at O₁ (the master on-ramp) remains higher than others as it is the closest to the critical bottleneck and has the longest on-ramp length compared to other on-ramps. Similarly, the shortest queue length witnessed at on-ramps O₂ and O₃ is due to the fact that these on-ramps have shortest length (storage capacity). Based on these observations, it can be concluded that the proposed strategy with a value of 0.9 yields more evenly distributed queue length compared with the other three control scenarios.

Figure 8.5 presents the average delay at the five on-ramps under different control scenarios. O₁ (the master on-ramp), which is the closest to the critical bottleneck experiences the longest delay and O₅, which is the farthest from the critical bottleneck, experiences the minimum delay. Although the queue length formed at O₂ and O₃ discussed earlier are shorter than O₄ and O₅, the average delay is comparable at these on-ramps. Higher a value yields lower average delay for the first three on-ramps while the results are opposite for the last two on-ramps O₄ and O₅. No control scenario yields the lowest average delay among all the scenarios; this might be due to the absence of RM control. For HERO control strategy, the average on-ramp delay is less spread than the proposed strategy cases, representing a less equitable system.
FIGURE 8.4. Queue length profile for different control scenarios
Figure 8.6 presents the values of combined index computed for tested scenarios using $E_1 = 1$ and $E_2 = 1$. Here no-control scenario witnesses the highest combined index value of 1.67, representing its worst performance in terms of both efficiency and equity among all the tested control scenarios. The proposed control strategies with $a$ value ranging from 70% to 90% outperform HERO strategy in terms of a balanced efficiency and equity gain. The proposed control strategy with $a$ value of 0.9 (or 90%) yields the lowest combined index value, representing the most efficient-equitable motorway system among all the tested control scenarios.
8.4. Summary

This chapter proposes a CRM algorithm to achieve an efficient as well as equitable motorway system. Total travel time is used to measure efficiency while Gini coefficient is used to measure equity. The main conclusions drawn of this study are as follows:

- The proposed CRM algorithm shows prospects to improve significantly the equity performance of the motorway system while maintaining nearly the same level of efficiency to that of HERO strategy.
- The proposed combined index can be useful to measure a balanced efficiency and equity gain for the motorway system.
Chapter 9. CONCLUSIONS AND RECOMMENDATIONS

This chapter summarizes the main findings of this research to address the knowledge gaps specified in Chapter 1. The following section provides an overview of the motorway traffic management tools proposed in this research and the main findings. Finally, some recommendations regarding future research directions are made in the last section.

9.1. Conclusions

9.1.1. Assess the Existing Methods for RM and VSL Control

A number of existing motorway traffic management tools are assessed including a logic tree based VSL control algorithm and RM control algorithms namely ALINEA and HERO. They are assessed for a critical bottleneck section on Auckland Motorway using AIMSUN micro-simulator based on two performance measures namely efficiency and inequity. The former is represented by total travel time and emissions and the latter is represented by Gini coefficient. Following conclusions can be drawn based on the results presented in Chapter 4:

- For the logic tree based VSL control algorithm proposed by Allaby et al. (2007), the bottleneck capacity and critical occupancy value are increased marginally by 0.3% and 0.8% while TTT and Gini coefficient value are decreased by 5.6% and 4.7% respectively when compared with no control case.
- For ALINEA LRM control algorithm, the bottleneck capacity and critical occupancy value are increased by 0.8% and 7% respectively while TTT is decreased by 12.5%
and Gini coefficient (representing equity) is increased 4.7% when compared with no control case.

- For HERO CRM control algorithm, improvements in the bottleneck capacity and critical occupancy value cannot be analysed as the flow does not reach the capacity. While TTT and Gini coefficient value is decreased by 17.6% and 41.4% respectively when compared with no control case.

- The T-test and F-test results show that the improvement in efficiency using the logic tree based VSL control algorithm is not that significant while those using ALINEA and HERO control algorithms are significant when compared with no control case.

- Among the three control measures assessed, HERO CRM algorithm yields the most efficient and equitable motorway system. It assigns queue lengths in a more balanced way among a group of successive on-ramps, which contributes to improve the equity performance for the motorway system.

9.1.2. A Modified Logic Tree Based VSL Controller

It is quite clear from the results presented in the previous section that the existing logic tree based VSL control algorithm is unable to improve significantly the efficiency performance of the motorway system. Consequently, the logic tree based VSL control algorithm is modified to improve its efficiency performance by optimizing its control logics and detector-controller configurations. The proposed modified logic tree based VSL control algorithm is assessed for the same bottleneck section of Auckland Motorway using AIMSUN micro-simulator. Following conclusions can be drawn based on the results presented in Chapter 5:

- The proposed modified logic tree based VSL control algorithm increases the bottleneck capacity and critical occupancy value by 6.2% and 7.8% when compared with no control case.
➢ TTT is decreased by 10.9% for a case with 100% drivers’ compliance rate when compared with no control case.

➢ CO₂, CO and NOₓ emissions are reduced by 3.3, 8.5 and 2.8% (these values stand at 1.5, 4.3, and 1.6 % for the existing method) respectively when compared with no control case.

➢ The average delay for vehicles on on-ramp is reduced by 75.0% (stands at 50.8% for the existing method) however the average delay for mainline traffic is increased by 1.0% (stands at 1.8% for the existing method) when compared with no control case.

➢ For the modified logic tree based VSL control algorithm, the bottleneck capacity and critical occupancy value are increased by 5.9% and 7% while TTT is decreased by 5.6% when compared with the existing logic tree based VSL control algorithm.

➢ These results show that VSL has got potential to improve efficiency performance of motorway systems. The proposed VSL control algorithm is more effective than the existing one in terms of mobility gains and reduction in emissions.

9.1.3. A Fuzzy Logic Based VSL Controller

Rule-based VSL control algorithms dynamically change speed limits whenever the traffic measurement exceeds or drops below a certain threshold value, which may lead to oscillations in traffic flow. A fuzzy logic control (FLC) based approach can be useful to deal with the sensitivity issues confronted by the existing rule-based VSL algorithms. It uses fuzzy sets instead of crisp sets to allow the separation of attribute domains into several overlapping intervals. A new VSL control algorithm is developed based on fuzzy logic to overcome some of the weaknesses of the traditional rule-based VSL control algorithms. The proposed algorithm is assessed for the same bottleneck section of Auckland Motorway using AIMSUN.
micro-simulator. Following conclusions can be drawn based on the results presented in Chapter 6:

- The proposed FLC based VSL control algorithm increases the bottleneck capacity and critical occupancy value by 6.4% and 7.8% when compared with no control case, which is marginally better than the modified logic tree based VSL control algorithm presented in the previous section.
- TTT is decreased by 12.4% for a case with 100% drivers’ compliance rate when compared with no control case.
- CO₂, CO and NOₓ emissions are reduced by 3.7, 9.2 and 3.6% respectively when compared with no control case.
- The proposed FLC based VSL control algorithm performs significantly better than the existing logic tree based VSL control algorithm in terms of efficiency gains with 100% drivers’ compliance rate while it performs marginally better than the modified logic tree based VSL control algorithm presented in the previous section.

9.1.4. An Integrated RM and VSL Controller

An integrated RM and VSL control algorithm is proposed in this research to exploit the synergy between the two ITS measures. The proposed algorithm aims to preserve the mainline traffic flow at the critical bottleneck close to its capacity, and to avoid excessive delays at on-ramps. This is materialized through the deployment of VSL controllers on the motorway mainline immediately on the upstream side of on-ramps, so as to create some merging space for the traffic entering the mainline from on-ramps. The proposed algorithm is implemented to integrate VSL with ALINEA and HERO, which are RM control algorithms. The proposed algorithm is assessed for the same bottleneck section of Auckland Motorway using AIMSUN micro-simulator. Six different scenarios are assessed that includes no control,
only VSL, only ALINEA, ALINEA+VSL, HERO, and HERO+VSL. Following conclusions can be drawn based on the results presented in Chapter 7:

- The proposed integrated RM with VSL control algorithm demonstrates prospects to improve efficiency and equity performance of the motorway system.
- TTT for ALINEA+VSL and HERO+VSL are decreased by 16.6 and 22.6% respectively for a case with 100% drivers’ compliance rate when compared with no control case.
- The modified VSL yields the best performance (compared with other scenarios tested in Chapter 7) in terms of improvement in emissions yielding CO₂, CO and NOₓ emissions reduced by 3.3, 8.5 and 2.8% respectively when compared with no control case.
- The T-test and F-test results show that TTT for all the tested scenarios are significantly different from the one for no control scenario except for the case of the modified VSL control algorithm.
- HERO+VSL algorithm yields the lowest Gini coefficient value of 22.3%, giving an improvement of 66.9% when compared with no control case.
- Based on the results discussed in the previous paragraphs, VSL integrated with HERO outperforms all other cases in terms of efficiency and equity improvements.
- The equity improvements might be because of two reasons: (i) the concept implemented in HERO, to distribute queue lengths to the successive “slave” on-ramps, which manages to distribute delays more evenly among the on-ramps, and (ii) an integrated use of the RM and VSL results in a significant reduction of queue length at the first on-ramp O₁ which is next to the main bottleneck.
9.1.5. Relationship between Efficiency and Equity

A modified HERO strategy is proposed to improve equity performance of the CRM controller. The proposed strategy is used to explore the relationship between efficiency and equity with an aim to achieve a balanced gain for the motorway system. An index combining Gini coefficient and total travel time is proposed to serve as an objective function to solve the bi-objective control design problem. The proposed algorithm is assessed for the same bottleneck section of Auckland Motorway using AIMSUN micro-simulator. Following conclusions can be drawn based on the results presented in Chapter 8:

- The proposed CRM algorithm shows prospects to improve significantly the equity performance of the motorway system while maintaining nearly the same level of efficiency to that of HERO strategy.
- The proposed combined index can be useful to measure a balanced efficiency and equity gain for the motorway system.

9.2. Recommendations for Future Research

The findings in this research are limited in scope as they are based on a particular bottleneck section of Auckland motorway modelled in AIMSUN micro-simulation. A model can have its own limitations to represent real-world traffic conditions. It is recommended to conduct similar investigation under a range of different traffic conditions and for a range of motorway networks before generalizing any such findings.

Several rule-based RM and VSL algorithms are assessed in this research. Although none of optimal control based algorithms are applied and operated in the field due to their complexity, these algorithms that provide the best possible results can be used as a reference case for the
assessment of other simpler methods. It would be useful to comprehensively analyses optimal control based algorithms in terms of efficiency and equity.

Various levels of compliances to VSL are tested in this research using micro-simulation. It is still worth to investigate 1) what level of compliance can practically be achieved in the field; and 2) which enforcement mechanism should be used to achieve the best performance of the system. Comprehensive and detailed driver behaviors studies would provide better understanding of drivers’ reaction to displayed VSL. Developing and applying appropriate enforcement strategy would be useful to homogenize the driving behavior and eliminate aberrant driving behavior.

In this study, all the parameters in the proposed fuzzy logic VSL algorithm are optimized manually for the test bed in Auckland. However, the proposed fuzzy algorithm requires tedious and time-consuming retuning if applied to other location. Besides, the fuzzy controller with the pre-specified setting parameters cannot adequately deal with the disturbances (such as inconsistent traffic demand pattern) and changes in traffic system (weather condition, incidents or road maintenance). It would be useful to use Genetic Algorithm (GA) based optimization method to adaptively tune the fuzzy sets parameters for application in other motorway networks.

All of the VSL algorithms proposed in this research are mobility-oriented. Since VSL was originally designed to improve the safety of motorway systems. It is important to analyze the magnitude of the safety benefits achieved by these algorithms and examine the relationship between safety and efficiency of the system.
APPENDICES

Appendix A: Layout and Detector Location of State Highway 1

[Diagram of State Highway 1 layout and detector locations]
Appendix B: NZTA Data Format

**Volume data**

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**Occupancy Data**

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