A New Ramp Metering Control Algorithm for Optimizing Freeway Travel Times

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Statement of Authorship

Except where explicit reference is made in the text of the thesis, this thesis contains no material published elsewhere or extracted in whole or in part from a thesis by which I have qualified for or been awarded another degree or diploma. No other person's work has been relied upon or used without due acknowledgement in the main text and bibliography of the thesis.

Signed:_____________	Signed:_____________
Dated:_____________	Dated:_____________
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Table of Contents

Table of Figures

Abstract

In many cities around the world traffic congestion has been increasing faster than can be dealt with by new road construction. To resolve this problem traffic management devices and technology such as ramp meters are increasingly being utilized. Ramp meters are traffic signals used to control the number of vehicles merging onto a freeway at an on-ramp. Ramp meters have significantly reduced freeway travel times.

There are three main types of ramp meter control algorithm, open-loop occupancy, closed-loop occupancy and advanced traffic-responsive coordinated. Open-loop occupancy control algorithms match measured occupancy to a plot of historical traffic occupancy for each control period. Occupancy is defined as the time percentage that vehicles occupy the detector location. Occupancy and speed are both useful indicators of congestion levels. Closed-loop algorithms adjust the metering rate to match desired occupancy to actual occupancy. Advanced traffic-responsive coordinated control algorithms are considered the most suitable as they control and coordinate a number of ramp meters.

There are a large number of control algorithms operating with varying degrees of success. A common problem many of these algorithms have is their performance when dealing with ramp queues. Many algorithms fail to respond adequately to large ramp queues resulting in substantial ramp delays, or even spillback that affects traffic on the ramp feeder road. In determining ramp weightings ramp queues are usually measured by their length, which does not take varying amounts of ramp storage capacity into account. Some ramps may be dual lane with large amounts of storage while others may be single lane with smaller storage capacities; queue length in such comparisons is not meaningful. Ramp inflows may receive low priority, with higher weightings being given to mainline flows. The methodology in developing ramp weightings may be simplistic and inaccurate, failing to deal with large queues, and applying a blanket maximum metering rate to all meters that exceed a constant threshold. In using a constant for this threshold or ramp weighting these algorithms fail to deal with dynamic variability that occurs in a traffic system. In this thesis an advanced traffic-responsive coordinated control algorithm has

been developed to optimize freeway travel times using the linear programming and fuzzy logic approach. The model includes two fuzzy variables to deal with ramp weightings and estimated demand. Membership of these fuzzy variables is determined from a number of triangular fuzzy sets. The percentage of the ramp storage consumed by the queue is used to determine the weighting. The weighted sum of ramp flows is maximized and delay minimized. Ramp queue is dealt with as a constraint.

A traffic survey was undertaken at the Warrigal Road on-ramp to study the effectiveness of the existing closed-loop control algorithm in balancing the demands of on-ramp and mainline traffic. This survey found that at the 4.30pm peak significant spillback forms up Warrigal Road to the Waverley Road intersection. To rectify this problem the on-ramp needs to be given a higher weighting by the control algorithm. By optimizing the whole freeway, on-ramps and the mainline, the new algorithm will be able to better balance the demands of on-ramp and mainline traffic.

In this thesis a case study to test the ability of this algorithm to optimize freeway travel times using the Vissim traffic simulator was designed. The simulation model of the Monash freeway in Melbourne was modified to allow for an experiment on the sections from Warrigal Road to Ferntree Gully Road to be undertaken at Vicroads. The Monash freeway’s ramp meters use closed-loop algorithms that operate locally and are not coordinated. Impacts one ramp meter may have on another are not considered in this approach, nor is system-wide metering possible. Incidents are dealt with locally, and an operator is required to manually intervene to deal with them. The new algorithm offers the possibility for system-wide metering, with meters operating in a coordinated fashion and being able to respond to incidents and unusual traffic dynamics without the need for operator intervention.

A control condition experiment without the ramp meters operating was run. Future work to experiment with the new algorithm operating in the simulation model is recommended. This research would be useful in determining if the new algorithm is worthy of further investigation. As this work needs to be undertaken at Vicroads it is outside the scope of this thesis.

Chapter 1 - Introduction

Ramp meters are traffic signals used to control the number of vehicles merging onto a freeway at an on-ramp. Ramp metering was first started in 1963 in Chicago and simply involved a police officer controlling traffic at an on-ramp. Ramp meters restrict the number of vehicles allowed to enter a freeway from an on-ramp and incorporate a wait cycle that forces merging traffic to queue. The timing of the enter cycle and wait cycle is often determined by a control algorithm. This algorithm attempts to balance the demands of on-ramp traffic entering the freeway and mainline traffic traversing the freeway. Ramp meters have significantly reduced freeway travel times.

In the existing literature there are three main types of ramp meter control algorithm, open-loop occupancy, closed-loop occupancy and advanced traffic-responsive coordinated. Open-loop occupancy control algorithms match measured occupancy to a plot of historical traffic occupancy for each control period. Closed-loop algorithms adjust the metering rate to match desired occupancy to actual occupancy. Advanced traffic-responsive coordinated control algorithms are considered the most suitable as they control and coordinate a number of ramp meters creating a system-wide approach. In a system-wide approach all the ramp meters on the freeway system are controlled by one algorithm.

By applying information technology to transport infrastructure Intelligent Transport Systems (ITS) can be used as a tool for traffic management. Traffic management endeavours to control traffic in a way that minimizes chaos and maximizes efficiency and safety within the constraints of the road network.

An ITS architecture allows traffic management systems to connect with other ITS installations. Some examples of common traffic management systems are large-scale advanced traffic-responsive coordinated systems like Brisbane’s SWARM and STREAMS systems. Freeway ramp metering serves as a component of an optimized transport system.

In the second chapter of this thesis existing ramp meter control algorithms will be reviewed in order to discover the current state of research in the field and to develop a new traffic-responsive coordinated control algorithm for ramp meters that better optimizes mainline and on-ramp travel times.

There are a large number of control algorithms operating with varying degrees of success. A common problem with many existing algorithms is their unsatisfactory performance in dealing with ramp queues. Optimizing mainline flows is easy if ramp queues are allowed to grow. Balancing the travel times of vehicles entering the freeway via on-ramps and traversing the mainline is the key to optimizing travel time for the entire freeway system.

Ramps may receive low or inaccurate weightings while mainline flows attract high weightings. Many algorithms measure ramp queues by their length, which fails to take into consideration the amount of storage available in the ramp. A ramp with a lot of storage may have a 50 metre queue, while another ramp with a small amount of storage may have a 40 metre queue. Typically the 50 metre queue would get the higher weighting, failing to consider that the shorter queue may spillback and block traffic on the ramp feeder road. Ramp weightings need to be determined from the percentage of ramp storage capacity consumed by the queue.

Many algorithms use a constant for ramp weighting and estimated demand. This approach does not allow for dynamic variability. Should a particular ramp receive an unusual amount of demand the algorithm would not be able to adequately deal with this. Ramp weightings and estimated demand need to be fuzzy variables.

In this thesis a model to optimize freeway travel times using the linear programming and fuzzy logic approach will be developed. The model will include two fuzzy variables to deal with ramp weightings and demand. Ramp queue will be dealt with as a constraint. The weighted sum of ramp flows will be maximized and on-ramp and mainline delay minimized through a dynamic process of linear programming.

In chapter 5 a traffic survey shall be undertaken at the Warrigal Road on-ramp to determine the effectiveness of the existing closed-loop algorithm in maximizing ramp flows while minimizing delay. Ramp queue shall be used as a measure of ramp flow. A long ramp queue equates to inadequate ramp flows.

A case study to test the performance of this algorithm at Vicroads using the Vissim traffic simulator shall be designed. The simulation model of the Monash freeway in Melbourne will be modified to allow for an experiment on the sections from Warrigal Road to Ferntree Gully Road. The Origin-Destination matrices will be modified to suit the model and used to generate realistic traffic data for the experiment. This section of the Monash freeway operates four ramp meters that are controlled by closed-loop algorithms. These algorithms operate locally and are not coordinated, the impact one meter may have on the other is not considered. Incidents are dealt with by an operator manually intervening. The new algorithm offers the opportunity for a system-wide coordinated approach, with incidents and changes in the traffic dynamic being dealt with by the algorithm without the need for operator intervention.

Future work to conduct the case study with the new mathematical model controlling the ramp meters at Vicroads is recommended to determine if the new algorithm is worthy of further investigation and possible implementation on the Monash freeway.
However, this is beyond the scope of this thesis.

Figure 1.1 Typical Ramp Meter Layout

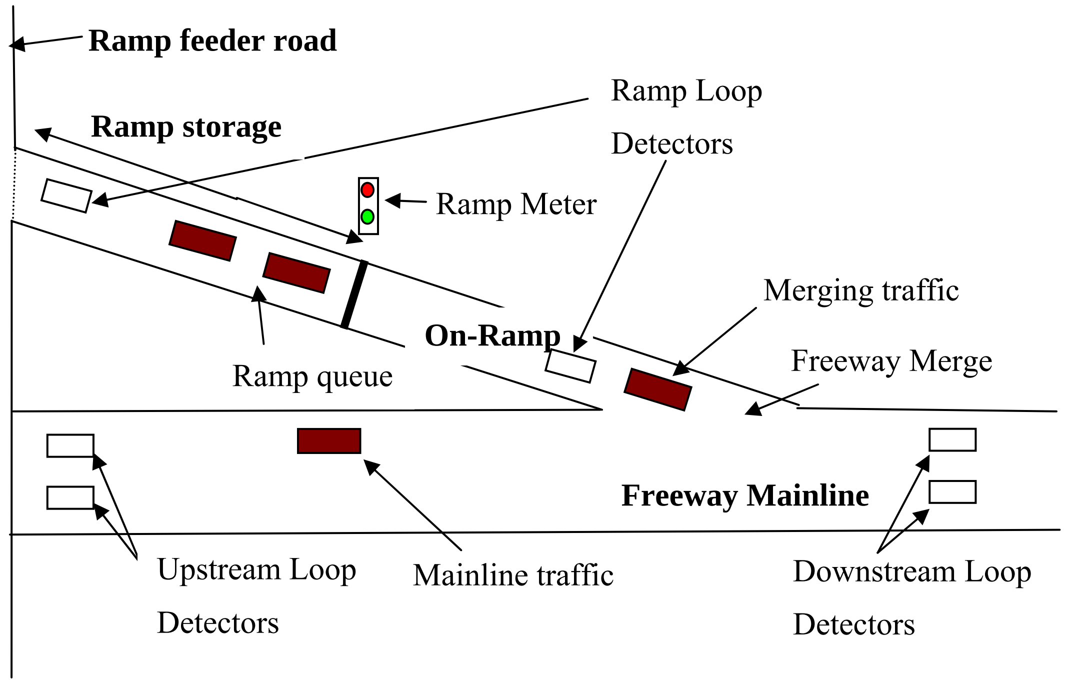

Figure 1.1 illustrates the typical layout of a freeway ramp meter. The ramp meter is located some distance along the on-ramp from the freeway merge and stops vehicles at some interval from entering the freeway mainline. If this stop interval is long enough a queue may form behind the ramp meter using up the available storage and spillback onto the ramp feeder road, affecting traffic flowing along the feeder road. More detail can be seen in figure 2.2.

Chapter 2 – Analysis of Existing Ramp Meter Control Algorithms

This chapter examines the need for ramp meters on congested urban freeways. An Intelligent Transport Systems' architecture for ramp meters is reviewed, which would allow ramp meters to fit into existing traffic control and telemetry systems and permit future expansion. The performance and equity of ramp meters is then assessed, with results from a number of studies presented. Ramp meters are controlled by algorithms, of which there are a number in the literature. The main ramp meter control algorithms are reviewed with the aim of developing a new algorithm to better optimize freeway travel times.

2.1 The Need for Ramp Meters

The 2004 Urban Mobility Report from the Texas Transportation Institute reports average delay per traveller in the United States (US) has increased 287% from 1982 to 2002 and congestion costs have increased 445% to US$63.2 billion over the same period [86]. Some research has put this figure as high as US$150 billion [97]. The report found US$6 billion or roughly 10% of total congestion costs have been saved by operational treatments such as ramp metering. The report warns that while major traffic infrastructure improvements can take 10 to 15 years to implement areas with medium levels of congestion now will have end up having major congestion problems. The authors recommend a balanced approach - to begin planning major projects or policy changes now while relieving bottlenecks and aggressively pursuing available minor capacity additions, operations improvements and demand management options. The report lists four operational improvements- freeway entrance ramp metering, freeway incident management programs, traffic signal coordination programs, and arterial street access management programs. In the study areas ramp metering reduced freeway delay by 5%. The delay saved by the other operational improvements was – incident management 7%, traffic signal coordination 1.5%, and arterial street access management

3.6%. Ramp metering is reported to have saved US$1.8 billion in congestion costs over the study period, with incident management representing the largest saving at US$3 billion [86]. In a recent study by Vicroads ramp metering was found to be the most effective of the congestion reduction methods employed on a test section of the Monash freeway in Melbourne, Australia [111].

The marginal external congestion cost per vehicle/km on freeways in Melbourne, Victoria, Australia is A$0.14 [97]. The New South Wales (NSW) Environment Protection Authority (EPA) in Australia reported the total daily congestion costs for Melbourne to be A$8,690,629 in 1992 [23]. Annualized per capita in A$ this is roughly triple that of the 2004 Mobility Report figures for the average of the 85 major urban centres studied in the US.

Research shows that a 5% reduction in traffic volumes on a congested highway can result in a 30% reduction in traffic delays, and as 20% of all driving and 80% of congestion costs occur during peak periods any operational improvement that can reduce traffic volumes during peak periods will have a significant impact on congestion costs [97].

An objective of ramp metering is to keep upstream demand below downstream supply to prevent flow breakdown from occurring. Another objective is to reduce accidents at the on-ramp merge, which can cause flow breakdown [27]. Ramp metering has the effect of preventing platoons of merging cars disrupting mainline traffic. By delaying merging traffic long enough ramp metering encourages drivers making short trips to either defer their trip till a less-congested period or to use an alternative route such as a parallel arterial [12].

Queensland also uses ramp meters as part of its STREAMS initiative [41, 110].
Texas, after removing its ramp meters has now been forced to reintroduce them due to significant congestion problems on its freeway system. As the volume of traffic using its on-ramps is now much higher (1200-1400 vehicles per hour (vph)) than when ramp meters were first installed it has been found that freeway on-ramps had to be redesigned to accommodate queues from ramp meters [12]. California and Texas have both introduced a design policy for new ramp meters that includes providing enough length in a new on-ramp to accommodate ramp meter queues and to allow enough distance

between the ramp meter and the freeway merge to permit vehicles to accelerate up to freeway speeds [91, 10].

Ramp metering is therefore a vital ingredient for producing an efficient freeway system that maximises throughput and minimizes delays.

2.2 Intelligent Transport Systems Architecture for Ramp Meters

In 1999 the ITS Joint Program Office of the US sponsored a major data collection study to track ITS deployment in the largest metropolitan areas in the US. The study looked at how the metropolitan infrastructure elements fitted into the National ITS Architecture [26].

The Minnesota Department of Transport (MnDOT) has developed a state-wide architecture for the implementation of Intelligent Transport Systems (ITS) called Polaris. Polaris is a tailored version of the US National ITS Architecture that is built around six project deliverables -

1. ITS Travellers wants and needs
2. ITS Transportation wants and needs
3. State-wide ITS as-is agency reports for Minnesota
4. ITS system specification
5. ITS component specification
6. ITS implementation plan

The purpose of the Polaris architecture is to define critical interfaces, illustrate how associated systems can be integrated to share resources and information, establish standards for communications and physical components so interoperability can be maintained as the system evolves and new technology is incorporated [51]. South Africa is also developing a national ITS architecture so new ITS developments are nationally consistent and interoperable [88].

The CENtral European Region TRansport Telematics Implementation CO-ordination Project (CENTRICO) is a European Commission (EC) initiative, which has ramp metering as a component. The Open Traffic data Access Protocol (OTAP) has been designed to allow CENTRICO countries to exchange real-time traffic data [25]. The EUropean Ramp metering Project (EURAMP) is another EC initiative that aims to consolidate ramp meter development in Europe and to allow interoperability with other ITS systems such as traffic signals [24, 35, 64, 65, 66]. Queensland through their SWARM and STREAMS systems integrate freeway and street systems together. Should an incident happen on the freeway STREAMS is able to shut down ramps in the affected area and initiate traffic re-routing [110].

2.3 The Performance of Ramp Metering

After a six-week shut-down of all 430 ramp meters in the Twin Cities in Minnesota there was a reported 22% increase in freeway travel times, a doubling of the unpredictability of travel times and a 26% increase in accidents. This produced a cost/benefit ratio for ramp metering of 1:5 [36]. A 10.6% reduction in average trip lengths with the deactivation of the ramp meters was also found [109]. See also [54] for more results of this study.

The Texas Department of Transportation (TxDOT) [53], after removing their original ramp meters reintroduced ramp metering to 100 ramps in Houston and found it was well accepted by the public. By designing their busy ramps (1200-1600 vph) for dual-lane, single entry like the Kingsgrove Road M5 on-ramp in Sydney [73], and their congested ramps (>1600 vph) for dual-lane, dual-entry the TxDOT overcame a lot of the public's concern about long delays at ramp meters. The TxDOT found single lane ramps could effectively deal with up to 800 vph, and platoon metering could serve up to 1050-1150 vph - where 2-3 vehicles per green are released [53]. As an additional measure the Ramp Meter Design Manual prepared by the Traffic Operations Program in California recommends using a Variable Message Sign (VMS) to display the different meter control regimes in use to ramp users, such as 'One Car Per Green' or for platoon metering 'Two Cars Per Green'.

Treiber and Helbing [93] found through an experiment using the Intelligent Driver Model (IDM) that ramp metering could benefit drivers delayed at the on-ramp because ramp metering can reduce total travel times.

Clark et al [19] found that many studies contradicted each other as to the benefits of ramp metering, with some showing a neutral or negative effect. This, Clark et al said, was the result of not understanding the costs and performance of ramp metering systems. Through their trade off curve the authors sought to overcome this deficiency and found that small initial investments could produce significant benefits but this suffered diminishing return with greater expenditures.

2.4 Equity and Ramp Metering

Equity is about Intelligent Transport Systems dealing fairly with all road users. The Transportation Equity Act for the 21st Century in the US (TEA-21) set the goal to develop an integrated ITS infrastructure, with ramp metering as an element of this [26]. Ramp metering sets out to achieve equity by optimizing flows on the mainline freeway, but to be truly equitable some delays on the mainline are necessary to limit delays at the on-ramp and prevent spillback affecting flows on the ramp feeder roads. Further, by forcing drivers making short trips to divert ramp meters can cause more congestion on local streets and parallel arterials [109]. Some transport professionals question whether ramp metering has any benefits at all [19] while others, such as Zhang and Levinson [108], believe by using a different objective function i.e. minimizing total weighted travel time, it is possible to provide equity for all.

Another issue with ramp meters is the ethics of letting high-occupancy vehicles (HOV's) and trucks bypass ramp meters. Because of their higher values of time some researchers have found that trucks and HOV's should be allowed to bypass ramp meters [59, 97].

Ramps in Texas are designed so that the maximum delay for ramp access to the freeway is 2 minutes. If a queue at a ramp meter exceeds a certain length as determined by the location of the queue tail-sensor the queue is flushed – the ramp meter stays green till the queue disappears [53]. The downside of this system is that the freeway may experience flow breakdown [89].

Initial ramp metering in Detroit operated in the outbound direction only so as not to disadvantage inner suburban traffic travelling into the city. Later the system was expanded to include inbound traffic with fewer objections. In New York City ramp metering is predominantly employed on the suburban ramps of a ring freeway. In Dallas, concerns over ramp metering favouring outer-suburban traffic over inner-suburban traffic was resolved through a traffic count, which showed approximately as many vehicles were exiting the freeway before they reached the city as were entering downstream of the adjacent suburbs [27].

Driver frustration over unexpected delays can be an issue [99]. Some ramp metering systems have flashing lights that notify drivers that a ramp meter is in operation, while others display the maximum wait time so that drivers can decide if they are going to use the ramp before getting caught in a queue [91].

2.5 Ramp Meter Control Algorithms

In this literature review the two main categories of control algorithms, isolated and coordinated are reviewed.

Isolated control algorithms comprise two main types, open-loop and closed loop occupancy. Open-loop occupancy control algorithms match the current measured occupancy to a plot of historical volume/occupancy data at each measurement location to select a metering rate for the next control period (usually 1 minute). Closed-loop occupancy control algorithms adjust the metering rate to bring the measured occupancy in-line with the desired occupancy [27].

Advanced, traffic-responsive coordinated ramp meter control algorithms attempt to deal with traffic congestion by coordinating a number of ramp meters together and responding on a system-wide level. Should downstream traffic detectors detect the signs of congestion forming upstream ramp meters would have their metering rates reduced in an intelligent way to attempt to prevent the congestion occurring. This approach of using a large number of ramp meters outside the immediate area of congestion, all controlled by one algorithm is called a system-wide approach. The rate for each meter would depend on a number of factors, such as the ramp queue occupancy, the estimated demand at the ramp over the control period, the contribution traffic from this ramp will have to downstream congestion and the current mainline flow conditions in the immediate vicinity of the ramp. Advanced, traffic-responsive coordinated ramp metering strategies are regarded as the most promising for the future, although they require extensive hardware (loop detectors and communication infrastructure) and control software that needs operational calibration [16]. Figure 2.1 illustrates the types of algorithms, figure 2.5 illustrates a typical ramp meter set-up including the terminology used in this chapter.

2.5.1 Algorithms by Name

Figure 2.1 –Ramp Meter Control Algorithms Assessed

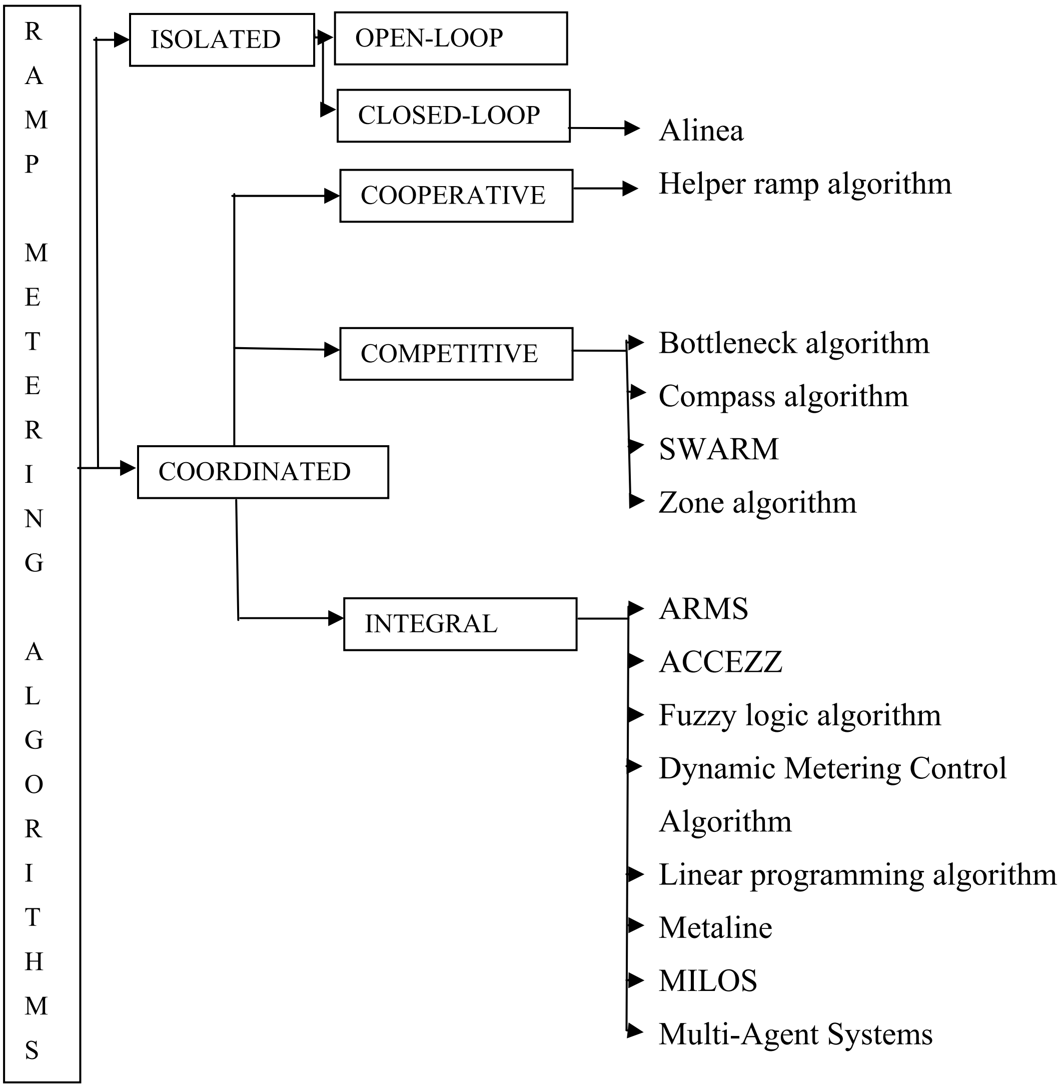

Figure 2.1 shows the categories of ramp meter control algorithms assessed.

2.5.1.1 ALINEA

Widely used, ALINEA is a discrete, closed-loop occupancy control algorithm based on feedback control theory [17]. The metering rate per iteration *R(l)* is determined by the sum of the measured volume of vehicles the ramp meter is allowing onto the freeway mainline *r* at the interval $l-\Delta t$ (computation iteration l minus the ramp meter update cycle Δt) and the product of the coefficient K_R with the difference between the desired downstream occupancy O_s and the measured occupancy per computation iteration $O_{out}(l)$. Shown by this formula

$$R(l) = r(l-\Delta t) + K_R(O_s - O_{out}(l))$$

Where:

l is the computation iteration;

R(l) is the metering rate per iteration;

$r(l-\Delta t)$ is the measured metering rate at interval $(l-\Delta t)$, where Δt is the update cycle of the metering rate;

O_s is a preset desired value of downstream occupancy;

$O_{out}(l)$ is measured occupancy per iteration;

K_R is a coefficient, normally set to 70 vph [16, 17].

The "gain" of the control loop is established by the coefficient K_R. As K_R is increased, the sensitivity and speed of response to changing inputs is increased. This tends to make the control more oscillatory and more sensitive to random variations and errors in the measured occupancy [27]. Although an effective algorithm in reducing congestion, Chu and Yang [17] advised that accurate implementation of ALINEA depends on correctly choosing three parameters; l, K_R, O_s and the location of the downstream detector. Kachroo and Krishen [46] note that as ALINEA was designed using linearization of the system dynamics it is valid only for the local region around equilibrium. They warned that as ALINEA does not explicitly take ramp queues into consideration it needs a feedback control law that incorporates queue length. Hasan [32] found that ALINEA performed worse at higher demand levels due to its inability to deal with downstream bottlenecks. Hasan also found that ALINEA's performance deteriorated at demand levels below 80% and ramp queues over 75% the length of the ramp. Bogenberger et al [3, 4] found ALINEA to be inferior to coordinated ramp metering in the case of an incident. Papageorgiou and Smaragdis [63] advised that modifications were needed so that ALINEA could use upstream instead of downstream measurements, flow-based rather than occupancy-based parameters, automatic real-time adaption of set values to optimize downstream flows and efficient ramp-queue control to avoid interference with ramp feeder roads. For more detail on ALINEA modifications as part of the Euramp project see [65] and [66].

2.5.1.2 Adaptive Coordinated Control of Entrance ramps with fuZZy logic (ACCEZZ)

Adaptive Coordinated Control of Entrance ramps with fuZZy logic (ACCEZZ) was developed to overcome the limitations of existing coordinated ramp metering algorithms. ACCEZZ is a genetic fuzzy logic controller with a special hybrid learning algorithm that learns the optimal control strategy for the next interval through a thousand epochs. The control action is determined every minute in a two-stage process. The first stage of meter coordination is embedded in the single fuzzy controller of each ramp as a specific input of the major downstream bottleneck and the corresponding rule. The second stage of coordination is included in the genetic algorithm that determines the optimal coordinated parameters of the fuzzy ramp metering controllers based on a macroscopic traffic system model. An optimal system is then determined and implemented. The integration of a traffic model, which evaluates the different overall strategies consisting of all the single fuzzy controllers for the metered freeway helps to find (as the result of the optimization procedure) the best system-wide strategy of all single traffic responsive ramp metering controllers. In a German study ACCEZZ was shown in simulations to substantially improve the traffic conditions for the freeway analysed and has since been implemented in Munich on the Olympic interchange of the Middle Ring Road [3]. See Chapter 3 for more details on ACCEZZ.

2.5.1.3 Advanced Real-time Metering (ARMS)

The Texas Transportation Institute developed Advanced Real-time Metering. It works on three levels. The first level is system-wide and attempts to maintain free-flow conditions. The total metering volume is determined by maximizing an objective function that includes throughput and the risk of congestion, which is distributed to each ramp using Origin-Destination (O-D) information. O-D information is data on the number of vehicles travelling from a particular origin to a particular destination – for instance from the first on-ramp to the last off-ramp. The second level attempts to predict congestion and flow breakdowns using a learning algorithm. The third level works to resolve congestion once it starts by minimizing the congestion clearance time and queues on the controlled ramps [44, 115]. The authors of [44] regarded this algorithm as very good due to its incorporation of a congestion risk factor and prediction of bottlenecks.

Figure 2.2 –ARMS Algorithm Operational Flowchart

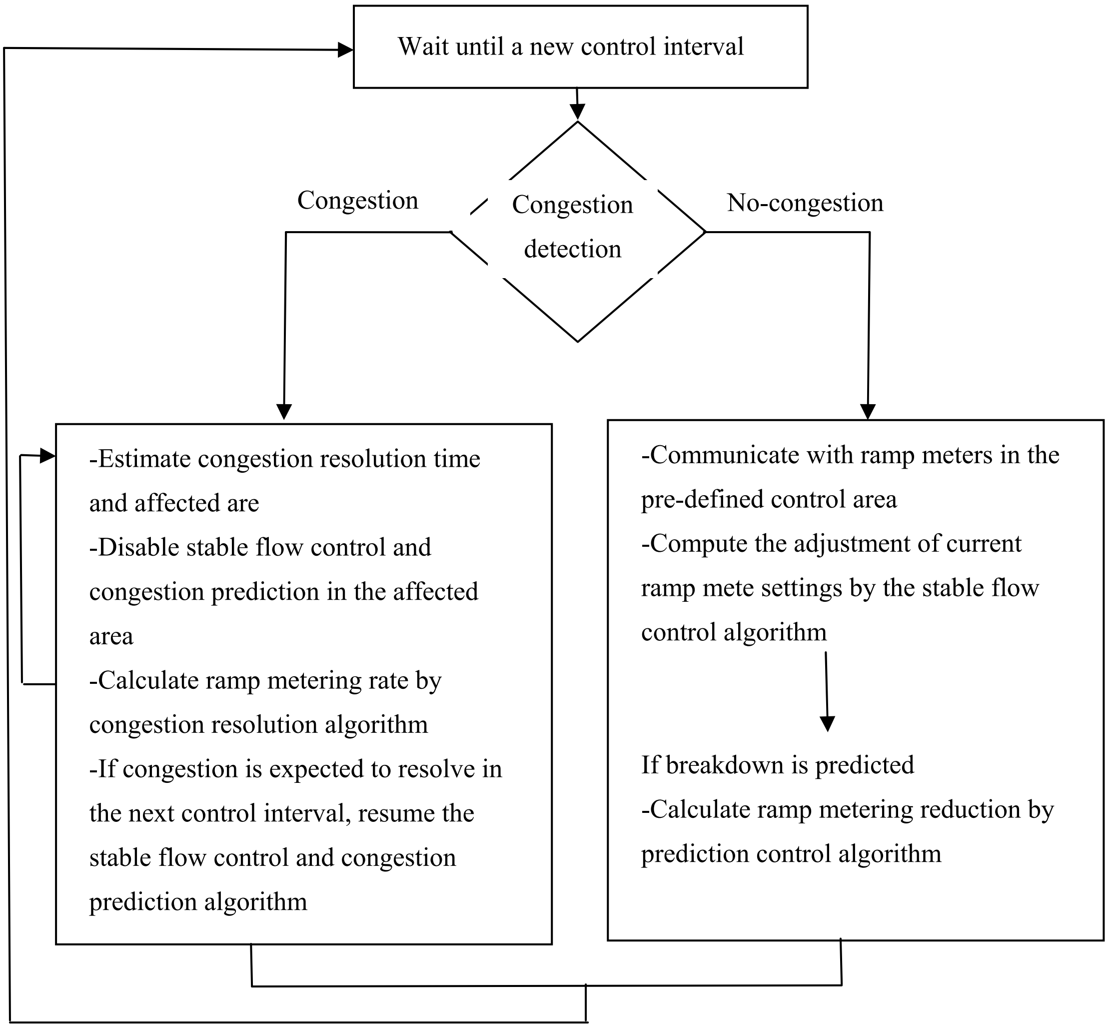

Figure 2.2 shows the operational flowchart for the ARMS algorithm.

2.5.1.4 Bottleneck

Bottleneck is a coordinated, competitive zonal algorithm like Zone (see 2.5.1.15) used to control ramp meters in Seattle, Washington State. It divides a freeway into zones, as defined by the location of adjacent detectors. Each section has an area of influence that includes several upstream on-ramps that are responsible for a traffic volume reduction in that section. Bottleneck uses a local-level metering rate selected from a lookup table matched to the detected upstream occupancy rate except when the following two conditions are met:

1. Capacity condition

$$O_d(h,t) \geq O_t(h)$$

Where:

$O_d(h,t)$ is the average occupancy for the downstream detectors of section *h* over the previous one-minute update period (*t*);

$O_t(h)$ is the occupancy threshold for the downstream detector of section *h* when it is near maximum capacity.

2. Vehicle storage condition

$$Q_{in}(h,t) + Q_{on}(h,t) \geq Q_{off}(h,t) + Q_{out}(h,t)$$

Where:

$Q_{in}(h,t)$ is the volume entering section *h* across the upstream detectors over the last minute (*t*);

$Q_{on}(h,t)$ is the volume entering section *h* from on-ramps during the last minute (*t*);

$Q_{off}(h,t)$ is the volume exiting section *h* from exit ramps during the last minute (*t*),

$Q_{out}(h,t)$ is the volume exiting section *h* over the downstream detectors in the last minute (*t*).

When these two conditions are met the system-wide bottleneck-metering rate is activated according to:

$$R(j,t) = Q_{on}(j,t-1) - MAX_{h=1}^{n}\left(Q_r(h,t) * \frac{(WF_j)_h}{\sum_j^n (WF_j)_h}\right)$$

Where:
R(j, t) is the bottleneck metering rate for ramp *j* over one minute (*t*);

$Q_{on}(j,t-1)$

is the entrance volume on ramp *j* during the past minute (*t*);

$(WF_j)_h$

is the weighting factor of ramp *j* within the area of influence for section *h*;

$Q_r(h,t) * \frac{(WF_j)_h}{\sum_j^n (WF_j)_h}$

is the volume reduction of ramp *j* because of section *h*;
n is the total sections in the network;

$MAX_{h=1}^{n}$

is the operator of selecting the maximum volume reduction if a ramp is inside of multiple areas of influences;

$Q_r(h,t)$

is the upstream ramp volume reduction which is equal to;

$Q_r(h,t) = (Q_u(h,t) + Q_{on}(h,t)) - (Q_{off}(h,t) + Q_d(h,t))$

is the number of vehicles stored in the section during the past minute (*t*).

O_u (*h, t)* is average occupancy for the upstream detectors of section *h* over the previous one-minute period (*t*) [16].

Further adjustments are made to the most restrictive ramp rate and bottleneck rate including queue adjustment, ramp volume adjustment and advanced queue override. The queue adjustment and advanced queue override are employed to prevent spillback onto the arterial road network. Ramp volume adjustment copes with the condition when more vehicles are entering the freeway than anticipated, such as (High Occupancy Vehicle) HOV bypass lanes and drivers disobeying the meter. The adjusted rate should be within the pre-specified minimum and maximum metering rates [16].

Figure 2.3 Bottleneck Algorithm Operational Flowchart

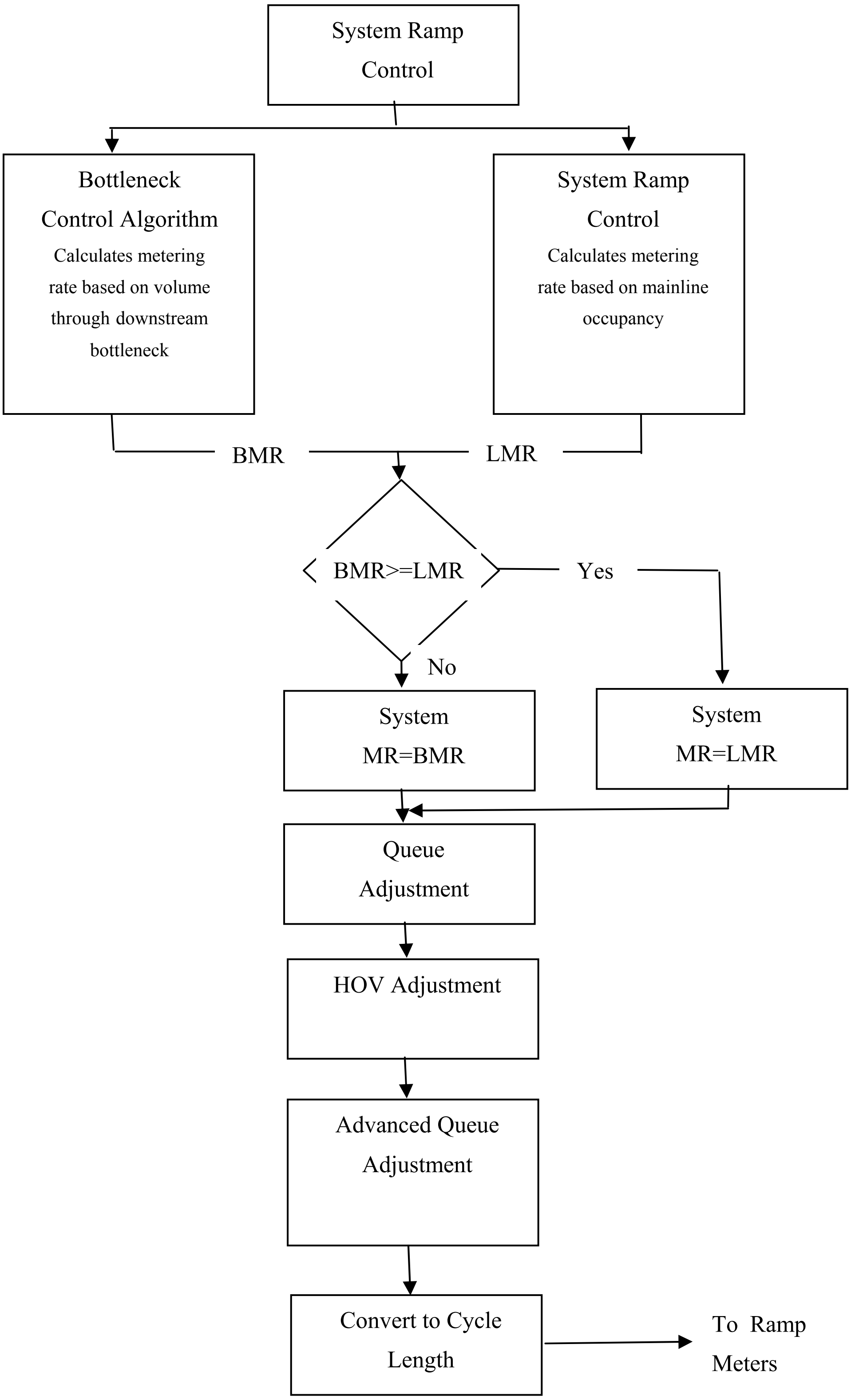

Figure 2.3 shows the operational flowchart for the Bottleneck algorithm.

Where BMR = Bottleneck Metered Rate, LMR = Local Metered Rate, MR =Metered

Rate.

2.5.1.5 Compass

Compass is a coordinated and competitive algorithm that was first implemented in the Toronto area in Canada in 1975. Compass determines the local metering rate from an ad-hoc lookup table, which has seventeen levels for each ramp. The rates are determined by the mainline occupancy, the downstream mainline occupancy, the upstream mainline volume as well as some predefined parameters that include thresholds for upstream volume and local and downstream occupancy. Coordinated control metering rates are determined by off-line optimization that uses system-wide information. The more restrictive of the two rates is used. Spillback is dealt with by overriding restrictive rates that increase the metering rate one level once the queue threshold is exceeded. The authors regarded Compass as a good, flexible algorithm that considers many constraints and is easy to implement. However, it has been criticized for not being robust due to its use of lookup tables and predetermined metering rates [44].

2.5.1.6 Dynamic Metering Control Algorithm

Developed by Chen, Hotz and Ben-Akiva [113] the dynamic metering model has four elements: local adaptive control, area-wide control, state estimation and O-D prediction. The local adaptive control algorithm ALINEA attempts to maintain conditions in the local region around the ramp meter matching the target conditions provided by the area-wide control. The area-wide control is a predictive optimal control algorithm that obtains metering rates by minimizing the total system travel time (including travel time on the mainline and delay on the ramps), subject to queue and demand-capacity constraints. To estimate future travel demand and traffic conditions a state-estimation and O-D prediction model are also included. The state estimation module processes the surveillance data (from loop detectors) and estimates the current network state.

The product of the coefficient K with the difference between the local mainline occupancy O_t and the occupancy set by the area-wide control algorithm O_k is subtracted from the metering rate set by the area-wide control algorithm R_k to determine the local area metering rate R_t. The two controls are combined as:

$$R_t = R_k - K(O_t - O_k)$$

Where:

K is a coefficient;

R_t and O_t are the local ramp metering rate and occupancy at time t;

R_k and O_k are the ramp metering rate and occupancy set by the area-wide control algorithm.

The authors regarded this algorithm as one of the most comprehensive and complex that they had reviewed and had a lot of the qualities of an ideal ramp metering algorithm – system-wide, adaptive, predictive and combining local and area-wide control. However, they did note that it relied heavily on the accuracy of its state estimation and O-D prediction models [44, 115].

Figure 2.4 Dynamic Metering Control Algorithm Operational Flowchart

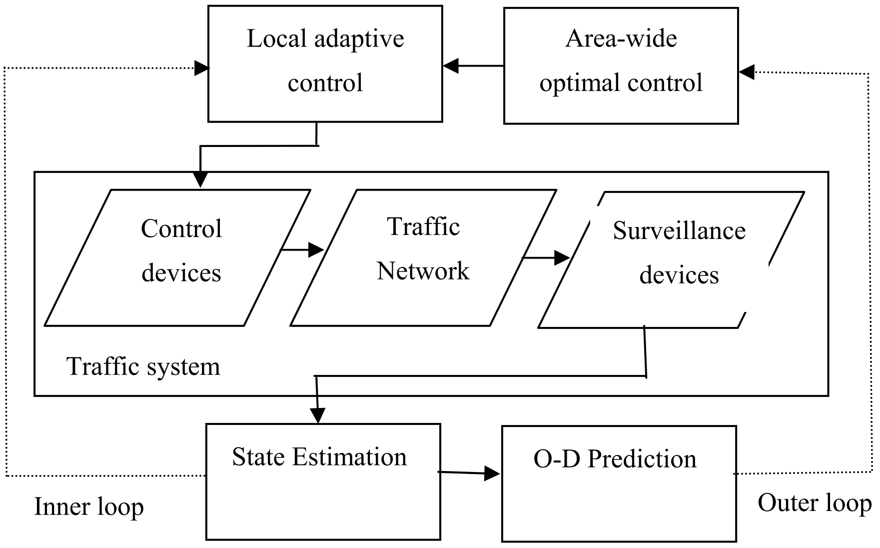

Figure 2.4 shows the operational flowchart for the Dynamic Metering Control algorithm.

2.5.1.7 Fuzzy Logic Algorithm –the Washington State DOT Algorithm

The University of Washington algorithm (see section 2.5.1.14), although improving flows over the pre-metered conditions, was found to have the following deficiencies. It required congestion to develop before it could start metering and it tended to oscillate between controlling freeway congestion and removing excessive ramp queues [27].

Taylor and Meldrum [79] describe a different fuzzy logic algorithm designed to address these deficiencies. Successfully implemented in Seattle and Holland on the A12 motorway [3], fuzzy logic is a coordinated and integral controller [44]. In the Dutch study the fuzzy logic controller produced 35% faster travel times and 5-6% greater bottleneck capacity than two other controllers trialled on the 11km test stretch [82]. In Seattle the largest speed improvements (up to 75%) were in the morning peak, with some negative effects in the afternoon peak [95]. Fuzzy logic has the ability to address multiple objectives by weighing the rules that implement these objectives and to implement the tuning process in a more user-friendly fashion through the use of linguistic rather than numerical variables. Rule groups used by the algorithm include local mainline speed and occupancy, downstream speed and occupancy, ramp queue occupancy and the quality of the ramp merge [27]. Taylor and Meldrum [79] claim fuzzy logic is a superior ramp metering algorithm to conventional algorithms as it can adapt to changes in traffic from incidents, weather etc. smoother and more effectively while requiring less manual tuning.

The fuzzy logic controller (FLC) takes six inputs. These include speed and occupancy from the mainline and downstream detector stations, the queue occupancy detector and the advanced queue occupancy detector (at the upstream end of the ramp storage location). Through fuzzification each numerical input is translated into a set of fuzzy classes. For local occupancy and local speed, the fuzzy classes used are very small (VS), small (S), medium (M), big (B), and very big (VB). The degree of activation indicates how true that class is on a scale of 0 to 1. For example, if the local occupancy were 20%, the M class would be true to a degree of 0.3, and the B class would be true to a degree of 0.8, while the remaining classes would be zero. The downstream occupancy only uses the VB class, which begins activating at 11%, and reaches full activation at 25%. The downstream speed uses the VS class, which begins activating at 64.4 km/hr and reaches full activation at 88.5 km/hr. The queue occupancy and advanced queue occupancy use the VB class. For ramps with proper placement of ramp detectors, the parameter defaults for activation begin at 12%, and reach full activation at 30%. For each input at each location, the dynamic range, distribution and shape of these fuzzy classes can be tuned [27].

Taylor and Meldrum [80] noted that a deficiency of the algorithm was its inability to estimate ramp queue delays. Presumably because of this, Taylor and Meldrum have only provided a queue flushing rule in their fuzzy rules that applies a VB metering rate should the queue be VB [78]. To be more effective a more measured response with corresponding weightings depending on various queue sizes is desirable. Inclusion of a maximum ramp meter delay rule would fit in with current US legislation such as the maximum delay of 4 minutes set out in some US states. Kingery [48] reviewed the University of Washington fuzzy logic algorithm for the Florida DOT. In this review, Kingery advised the Florida DOT against using the University of Washington code as although very effective it contained several dependencies on the Washington State DOT code that may not be obtainable. He noted that a lot of the code seemed specific to the site in Washington State that it was built around.

Figure 2.5 –Ramp Meter and Freeway Layout

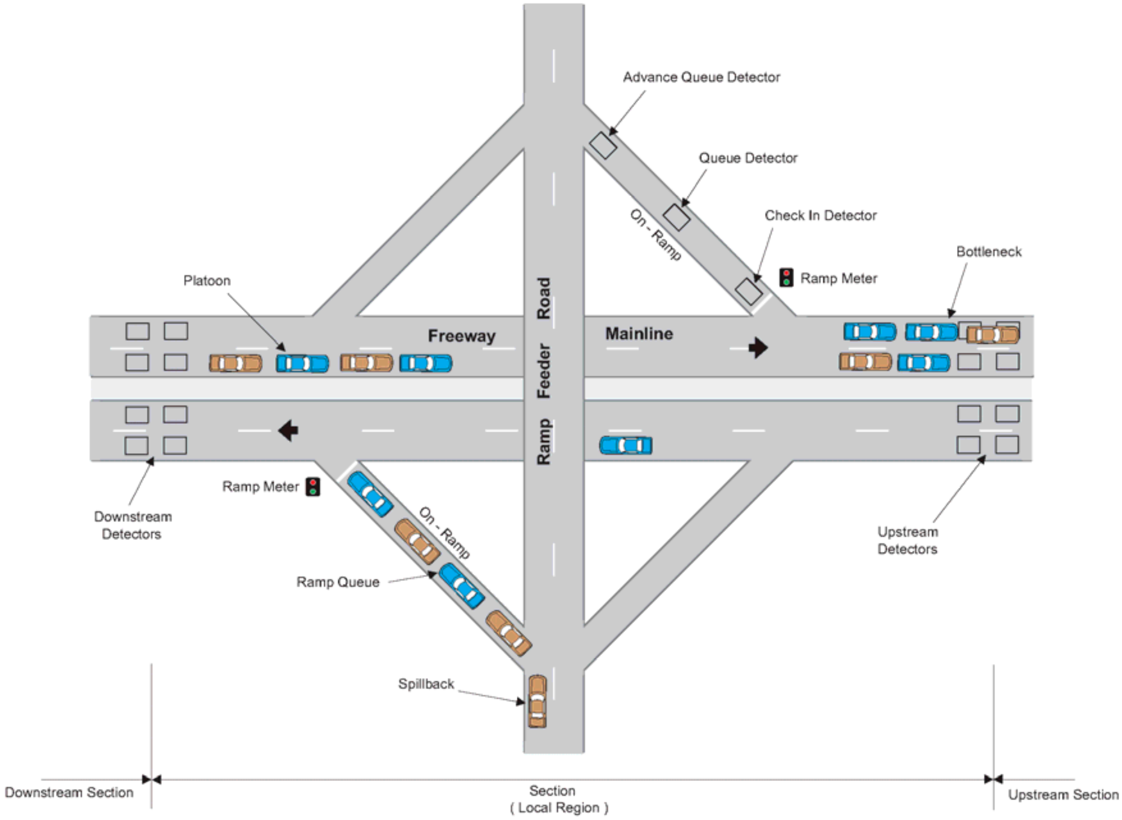

Figure 2.5 shows the typical layout of a freeway and its on-ramps, showing the different terminology used in this chapter.

2.5.1.8 Helper

Helper is a coordinated, cooperative ramp metering algorithm used in Denver, Colorado. Bogenberger, Keller and Ritchie claim Helper [3, 4] is designed to deal primarily with the first ramp next to the detected bottleneck. In their study of the effectiveness of Helper compared to ACCEZZ the authors found that HELPER would perform worse when dealing with more than this situation [3].

Helper consists of a local traffic-responsive metering algorithm that selects one of six available metering rates based on local upstream mainline occupancy. Ramp queue detection is also used, increasing the metering rate one level at a time to clear ramp queues in danger of causing spillback. An exponential smoothing function is used to prevent wild fluctuations in the metering rates.

Data is collected every 20 seconds from the loop detectors in the freeway and the on-ramps and fed into a coordinated centralised control algorithm. This centralised algorithm overrides local upstream ramp control should a ramp queue reach a critical stage reducing the next upstream ramp one metering rate level at a time. This process is continued each time interval, moving to the next upstream ramp until the situation is remedied [115].

2.5.1.9 Linear Programming Algorithm

Among the oldest in research and practice linear programming algorithms were widely used in time-of-day metering before automatic control and dynamic algorithms were developed. The linear programming algorithm that is described here was developed in Japan [105, 115]. It maximizes the weighted sum of ramp flows, with the weights selected by the user depending on the users' perception of the importance of each ramp. A real-time capacity for each segment is then calculated which allows the algorithm to work under congested road conditions. Ramp queue length and metering bound constraints are easily incorporated. Although mathematically very complicated the problem can be solved efficiently using canned linear programming solvers. The main limitation of this algorithm is its dependence on accurate O-D data, close spacing of loop detectors and its neglect of the variation in travel time in its computation of metering rates [44]. There is more on this type of algorithm in chapter 3.

2.5.1.10 Metaline

A coordinated ramp meter control algorithm, Metaline is an extension of the ALINEA local control algorithm. It has been implemented on some freeways in France, the Netherlands and the US. Metaline uses proportional-integral state feedback for its control logic. The metering rate of each ramp (*R(l)* at time step *l*) is computed based on the change in measured occupancy of each controlled freeway segment, and the deviation of occupancy from critical occupancy for each segment that has a controlled on-ramp, according to:

$$R(l) = R(l-1) - K_1\{\, O(l) - O(l-1) \,\} - K_2\{\, O(l) - O^C \,\}$$

Where:

R is the vector $[R_1 \ldots R_m]^T$ of metering rates for the m controlled ramps at time step l or l-1;

l is the current time interval;

$O(l-1)$, $(O(l)-O^c)$ are respectively the measured and desired occupancy vectors $[O_1 \ldots O_m]^T$ and $[O_1 \ldots O_m]^T$ downstream of m controlled ramps;

O^c is the vector $\left[O_1^c \ldots\ldots O_m^c\right]^T$ of m corresponding maximum capacity values for all locations defined in the O vector;

$K_1 \in R^{mxn}$, $K_2 \in R^{mxn}$ are two gain matrices (tuneable weighting factors for each ramp location defined by r vectors).

Correctly choosing the control matrices K_1, K_2 and the target occupancy vector O^c is critical to the algorithms success. The authors [44] note that the algorithm does not directly consider queue overflow, HOV/bus priority, and bottleneck effects, although these constraints could be partially addressed by adjusting the metering rate.

2.5.1.11 Multi-objective Integrated Large-scale and Optimized System (MILOS)

Multi-objective Integrated Large-scale and Optimized System (MILOS) is a coordinated, real-time multi-objective adaptive ramp metering controller. In a simulation of a 7-mile segment of the I-10 in Phoenix, [18] reported MILOS' performance was excellent, achieving drastically improved freeway flow and travel times.

Figure 2.6 –The MILOS Control Algorithm Operational Flowchart

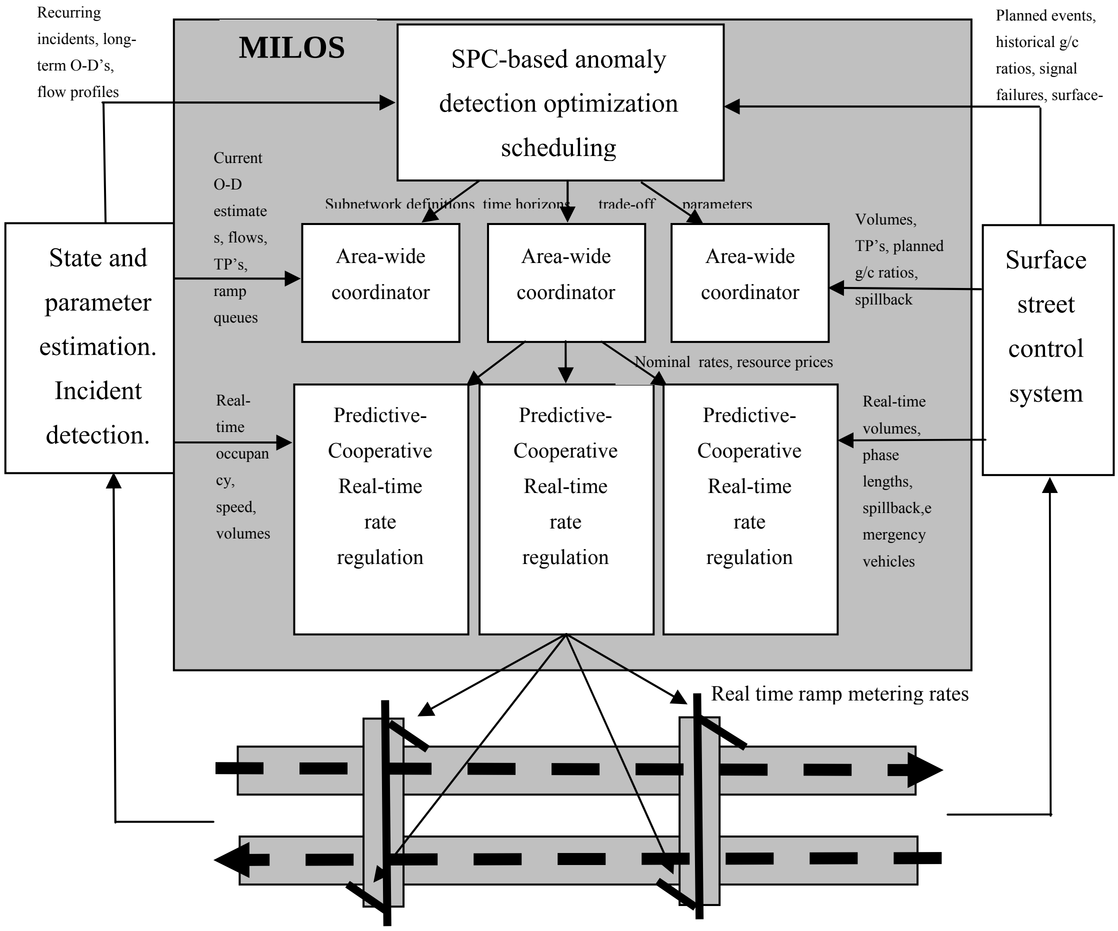

Figure 2.6 shows the operational flowchart for the Multi-objective Integrated Large-scale and Optimized System Control algorithm.

Area wide coordinator

The area-wide coordinator sets ramp metering rates for the medium-term (10 – 20 minutes) to maximize mainline flow, balance ramp queue growth rates and minimize ramp queue spillback. It is based on a rolling horizon implementation of a multiple-criteria, quadratic programming optimization problem. A mathematical description of the area-wide coordination optimization problem is listed here:

$$\max r \in R \sum_{i=1}^{N} \left(1 + 2\beta\gamma c_i d_i\right) r_i \; - \beta\gamma c_i r_i^2 - \beta_2 \gamma c_i z_i^2$$

subject to

$$\sum_{i=1}^{j} A_{i,j} r_j \leq CAP_j \quad \forall j$$

$$(d_i - r_i)T - z_i \leq Q_i \quad \forall i$$

$$r_{MIN} \leq r_i \leq r_{MAX} \quad \forall i$$

$$c_i = \frac{\sum_{m=1}^{M} \frac{V_{m,i}}{C_{m,i}}}{\max_i(c_i)} \quad \forall i \qquad \gamma = \frac{\left(\sum_{i=1}^{N} d_i\right)}{\sum_{i=1}^{N} c_i \left(d_i - r_{i,MIN}\right)^2}$$

$$d_i = \rho_{R,NB} d_{NB} + \rho_{L.SB}\left(1 - \rho_{R,SB}\right) d_{SB} + \rho_{T,EB} d_{EB} + \frac{q_i(0)}{T} \quad \forall i$$

Where:

N is the number of on-ramps;

M is the number of off-ramps;

d_i is the demand (vph) at ramp *i;*

r_i is the ramp metering rate (vph) at ramp *i;*

ß is a weighting factor. Setting *ß* large will increase the importance of balancing ramp queues and setting *ß* to small will decrease the importance of balancing ramp queues and increase the importance of maximizing freeway throughput;

c_i is a congestion weighting factor for interchange *i;*

s_i is the saturation flow rate of ramp *i;*

CAP_j is the maximum mainline capacity for section *j;*

$A_{i,j}$ is the proportion of the flow entering at ramp *i* that continues through section *j* en-route to its destination;

$r_{i,MAX} = \min(d_i, s_i)$. $r_{i,MIN}$;

$r_{i,MIN}$ is the slowest ramp metering rate acceptable to drivers, which could be as low as zero if the ramp was allowed to be and/or capable of being fully closed;

$C_{m,i}$ is the maximum capacity of the mainline in phase *m* at ramp *i;*

$V_{m,i}$ is the offered volume of the mainline in phase *m* at ramp *i;*

$q_i(0)$ is the queue length at the ramp when the optimization begins;

$\rho_{R,NB}$, $\rho_{L,SB}$ and $\rho_{T,EB}$ are the current probabilities of turning right, left and through, respectively at each of the approaches to the interchange feeding ramp *i;*

d_{NB}, d_{SB} and d_{EB} are the demands on the northbound, southbound and eastbound approaches to interchange *i,* respectively. These definitions assume an eastbound freeway for demonstration;

z_i is the extra capacity allocated at each ramp queue *i* to accommodate the flow at that ramp;

T is the optimization time horizon [18].

The goals of the area-wide coordinator are to:

1. plan coordinated metering rates for recurrent congestion
2. identify short-term flow fluctuations that require re-solution of the area-wide and real-time optimization problems.
3. react to changes in the relative congestion levels of the interchanges
4. balance queue growth rates in the network
5. respond to non-recurrent congestion generated by crashes

Predictive-cooperative real-time control

The area-wide coordinator provides a table of metering rates and desired freeway states (occupancy, speed etc.) to the predictive-cooperative real-time controller (PC-RT) at each ramp. To maximize the time savings produced by the area-wide coordinator the PC-RT solves optimization problems based on a linearized description of the effects on freeway flow by the ramp metering rates. At any time *k* the PC-RT metering rate algorithm tries to take advantage of the excess local capacity of the freeway and ramps $\rho_j(k) \triangleleft \rho_{j,N}$ and $q_i(k) \triangleleft q_{i,N}(k)$ by reacting to predicted ramp demand and upstream freeway flow in the following ways:

1. increase the metering rate when the freeway density is lower than the nominal density and the ramp demand is higher than nominal,
2. decrease the rate when the ramp demand is lower than nominal and freeway density is higher than nominal,
3. increase the rate when ramp demand is lower than nominal and freeway density is lower than nominal
4. increase or decrease the metering rate according to a trade-off solution when ramp demand is higher than nominal and freeway density is higher than nominal.

How much the ramp metering rate $r_i(k)$ of ramp *i* at time *k* is increased or decreased from the nominal setting $r_{i,N}$ is determined by the results of a linear programming (LP) problem. The LP is formulated using a linearized description of the freeway flow equations about the nominal freeway flow state ($\rho_{j,N}, V_{j,N}, r_{i,N}$) and a linear description of ramp queue growth about the nominal queue-growth trajectory $q_{i,N}(k)$.

The cost function of this LP optimization problem is a weighted sum of travel-time savings in each section of the freeway and on the on-ramps.

The PC-RT ramp meter rate regulation algorithm can be described as:

1. Given that a significant deviation from the upstream freeway or ramp demand nominal flow is detected, predict several possible subsequent flows to the ramp and the upstream freeway segment,
2. Given these predicted possible future scenarios, solve the LP optimization problem for each predicted scenario that reduces queuing time on the ramp and/or reduces the possibility for congestion on the freeway over the next few minutes, and
3. In the next optimization interval, collect the actual upstream freeway flow and ramp demand, compare the actual flow to the predicted scenarios, and apply the appropriate metering rate for the scenario that best matches the actual flow [18].

2.5.1.12 Multi-Agent Systems

The characteristics of Multi-Agent Systems are that (1) each agent has incomplete information or capabilities for solving the problem and, thus, has a limited viewpoint; (2) there is no system global control; (3) data are decentralized; and (4) computation is asynchronous [116]. This makes Multi-Agent Systems well suited

Multi-agents are capable of replicating emergent intelligence as arises from the interaction of several entities, each having different goals and objectives. Agents solve problems based on their own goals and the actions of other agents. Hierarchical design allows conflicts to be resolved by higher-agents that may be more focused on meta-issues. As an example of such a system, Decentralized Adaptive Agent for contRol of Traffic Signals (DAARTS) is a hierarchical multi-agent system used for controlling signalized urban intersections based on distributed collaborative problem-solving, dynamic resource allocation and optimization. A study [46] is being undertaken by the University of Queensland into determining the effectiveness of a multi-agent system on a simulation of a Brisbane street scheme. The simulation shall be calibrated using reaction times, travel speeds, travel times and behaviour obtained from traffic surveys.

2.5.1.13 System-Wide Adaptive Ramp metering Algorithm (SWARM1)

A heuristic, coordinated and competitive ramp metering algorithm used in Orange County, California, the System-Wide Adaptive Ramp Metering algorithm (SWARM) attempts to predict the onset of congestion and then to apportion-ramp metering rates system-wide. As a substitute for density occupancy is measured at each loop-detector. Metering rates at a number of upstream ramps are altered to manage density at the control point - defined by the detector that a Kalman Filter predicts is approaching critical density [27]. SWARM1 has a built-in failure management module to clean faulty input from its traffic detectors and allows further adjustment to accommodate spillback. These features enhance its robustness. SWARM1 uses a predictor to anticipate traffic congestion problems, making it efficient, however its efficiency depends on the quality of its prediction models and O-D information [44]. SWARM consists of two individual algorithms operating independently, with the more restrictive being implemented each time interval. SWARM1 is a forecasting and system-wide algorithm, while SWARM2 is a local traffic-responsive algorithm like ALINEA [115].

SWARM1 optimizes traffic density, with the goal of maintaining density below the maximum capacity for each section of freeway. Using linear regression and a Kalman filter applied to detector data from the prior interval a density trend is forecast for each detector location for the next 30 second time interval. From this forecast an excess density, or a density above the maximum density for the section is calculated. When the excess density for each detector has been determined the target density for each detector is calculated as follows:

[Target Density = Current Density – (1/Tcrit) * Excess Density]

The volume reduction required at each detector is then calculated as follows:

[Volume Reduction = (Local Density – Target Density) * (# of Lanes) * (Distance to next Station)]

This volume reduction is distributed over the upstream on-ramps using weighting factors at each ramp based on ramp demand and queue storage capacity to determine how much of the volume reduction is borne by each specific ramp [115].

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Figure 2.7 – SWARM1 Algorithm Operational Flowchart

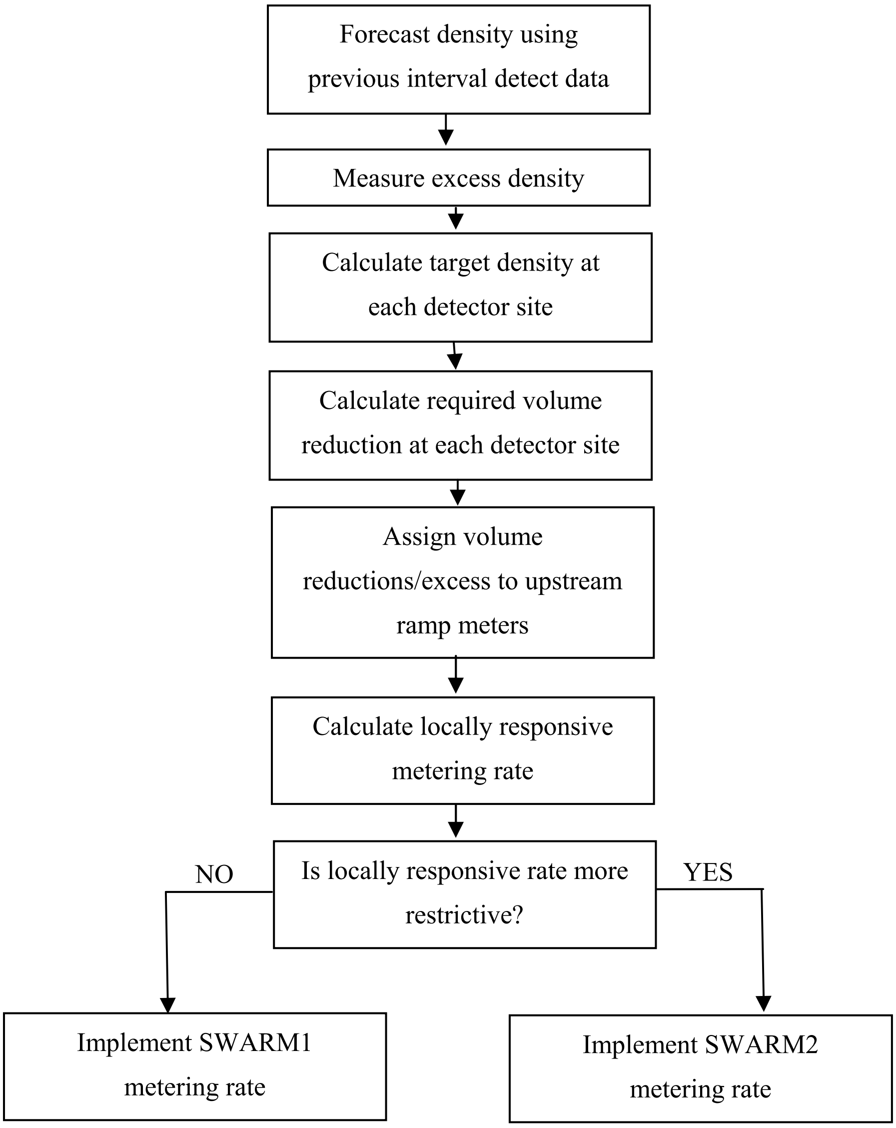

Figure 2.7 shows the operational flowchart for the SWARM1 algorithm.

Figure 2.8 – SWARM General Concept

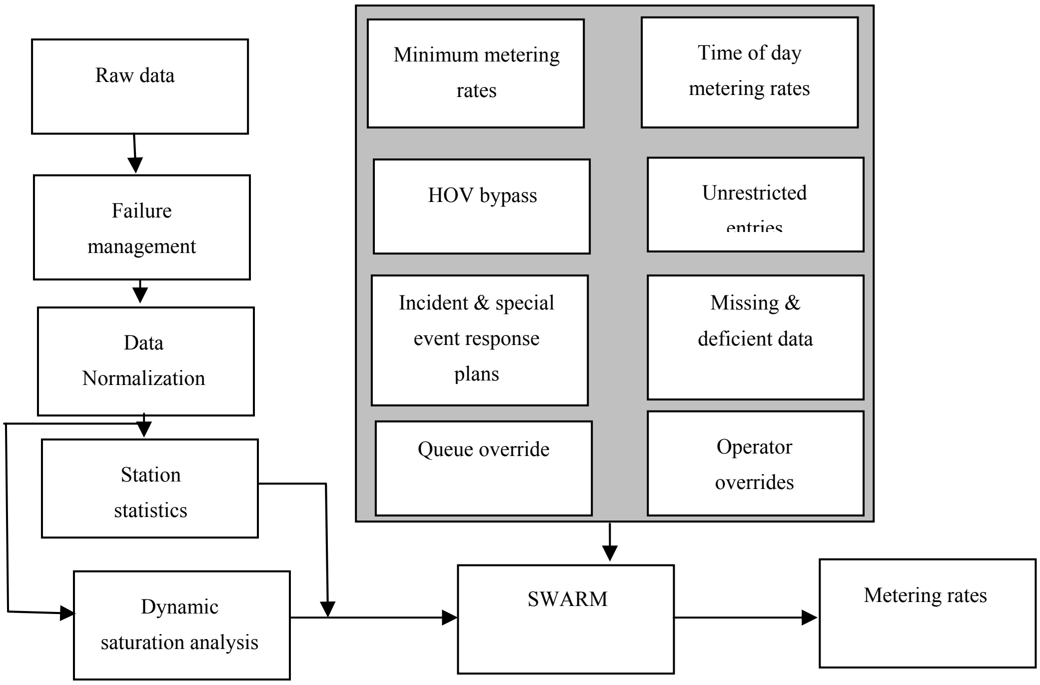

Figure 2.8 shows the general operational concept for the SWARM algorithm.

Raw occupancy data from the detectors is run through failure management and data normalisation to deal with inaccurate or non-functioning detectors. Data is checked against historical trends to identify failures and data noise [115].

2.5.1.14 University of Washington Algorithm

The Washington State DOT implemented a system-wide ramp metering regime with an algorithm developed by the University of Washington based on metering for bottleneck conditions. The system and local demand constraints are used to select metering rates. A bottleneck system metering rate is also calculated, and the most restrictive rate used.

Sections are defined on the freeway between pairs of detectors. Each section is checked in every iteration of the algorithm. If the vehicles begin to be stored or threshold occupancy is exceeded in any section a bottleneck is declared. Incident conditions are automatically responded to:

$$Q_h(t+1) = (Q_{in}(h,t) + Q_{on}(h,t)) - (Q_{out}(h,t) - Q_{off}(h,t))$$

This equation represents the rate at which vehicles are being stored.

Where:

$Q_{h}(t+1)$ is the upstream ramp volume reduction for section *h* required in next metering interval $(t+1)$;

$Q_{in}(h,t)$ is the volume entering section *h* across the upstream detector station during the past minute *t*;

$Q_{on}(h,t)$ is the volume entering section *h* during the past minute *t* from the entry ramp;

$Q_{out}(h,t)$ is the volume exiting section *h* across the downstream detector station during the past minute *t*;

$Q_{off}(h,t)$ is the volume exiting section *h* during the past minute *t* on the exit ramp. See figure 2.9 for the meaning of these parameters.

A group of ramps upstream of the bottleneck section is defined as an area of influence. Ramps within this area are collectively metered to reduce the volume entering the freeway by $Q_{h}(t+1)$. The amount of this volume reduction is determined by assignable weighting factors and apportioned among the upstream ramps within the area of influence.

A key feature of this algorithm is that the bottleneck identification and upstream volume reduction computations do not require direct knowledge of the bottleneck capacity. There are also a number of adjustments that may be made to the calculated metering rates [44]. For comments on the deficiencies of this algorithm see section 2.5.1.7.

Figure 2.9 – University of Washington and Zone Algorithms – Meaning of the Parameters

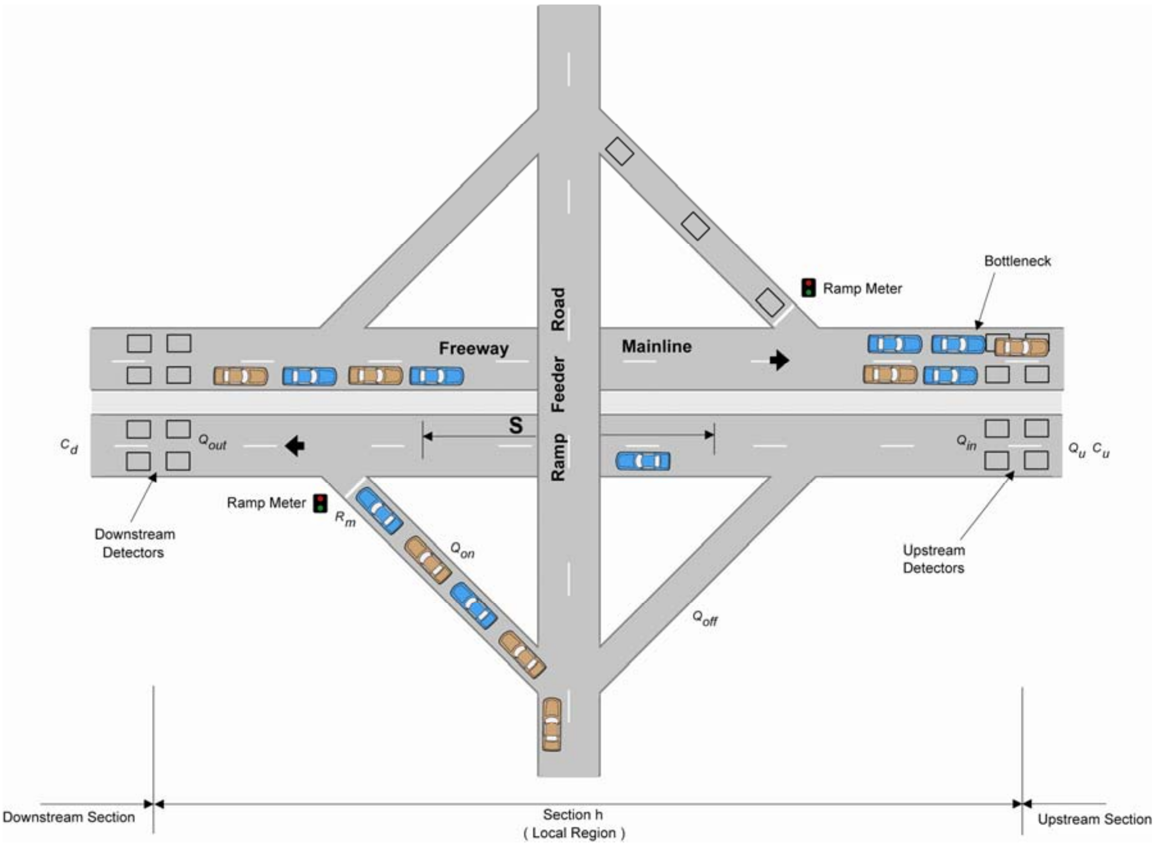

Figure 2.9 shows the meaning of the parameters for the University of Washington and Zone algorithms.

2.5.1.15 Zone

The Minnesota stratified zone algorithm is a coordinated algorithm like Bottleneck that aims to balance the inflow volume into a zone (designated as the area between two detectors) with the outflow volume from the zone.

The algorithm works on the principle that the total volume of traffic allowed to enter the freeway through the zone's ramp meters R_m combined with the maximum upstream capacity of the freeway C_u and the actual volume measured at the nearest upstream detector Q_u must be less than or equal to the sum of maximum downstream capacity of the freeway C_d, the total volume of traffic exiting the freeway from the zone's downstream off-ramps Q_{off} and the estimated space available within the zone *S*. This is modeled in the equation:

$$R_m + C_u + Q_u \leq C_d + Q_{off} + S$$

Therefore the metering rate R_m is determined by

$$R_m < C_d + Q_{off} + S - C_u - Q_u$$

Where:

R_m is the total metered ramp volume permitted to pass through the zone between the upstream detector and downstream detector;

Q_u is the upstream volume measured at the nearest upstream detector;

Q_{off} is the total measured off-ramp volume;

C_d is the downstream bottleneck volume at capacity – normally set to 185 vehicles per lane per 5 minutes;

C_u is the upstream bottleneck volume at capacity;

S is the space available within the zone calculated from measured occupancy values of the freeway detectors using an experimental formula (untested).

The key of stratified zone metering is to disperse the volume R_m depending on the demand D on the metered entrance ramps in the zone.

This equation gives the proposed rate for every meter depending on the demand according to a percentage of R_m:

$$R_n = \frac{(R_m * D_n)}{D}$$

Where:

R_n is the proposed rate for meter *n* within the zone;

D is the demand for all meters within the zone;

D_n is demand for the meter *n* [44]. See figure 2.8 for the meaning of these parameters.

2.6 Incident Detection Algorithms

Due to the importance of incident detection for any freeway flow-optimization model a new two-stage incident detection algorithm based on advanced wavelet analysis and pattern recognition is listed here. For more information on this algorithm see [47]. In their study (see 2.5.1.12), Kachroo and Krishen [46] investigate the possible use of agents in incident detection .

2.7 Fuzzy Logic

Fuzzy logic is derived from fuzzy set theory dealing with reasoning that is approximate rather than precisely deduced from classical predicate logic. It can be thought of as the application side of fuzzy set theory dealing with well thought out real world expert values for a complex problem.

Degrees of truth are often confused with probabilities. However, they are conceptually distinct; fuzzy truth represents membership in vaguely defined sets, not likelihood of some event or condition. For example, if a 100-ml glass contains 30 ml of water, then, for two fuzzy sets, Empty and Full, one might define the glass as being 0.7 empty and 0.3 full. Note that the concept of emptiness would be subjective and thus would depend on the observer or designer. Another designer might equally well design a set membership function where the glass would be considered full for all values down to 50 ml. A probabilistic setting would first define a scalar variable for the fullness of the glass, and second, conditional distributions describing the probability that someone would call the glass full given a specific fullness level. Note that the conditioning can be achieved by having a specific observer that randomly selects the label for the glass, a distribution over deterministic observers, or both. While fuzzy logic avoids talking about randomness in this context, this simplification at the same time obscures what is exactly meant by the statement the 'glass is 0.3 full'.

Fuzzy logic allows for set membership values to range (inclusively) between 0 and 1, and in its linguistic form, imprecise concepts like "slightly", "quite" and "very". Specifically, it allows partial membership in a set. It is related to fuzzy sets and possibility theory. It was introduced in 1965 by Lotfi Zadeh at the University of California, Berkeley.

Fuzzy logic is controversial in some circles and is rejected by some control engineers and by most statisticians who hold that probability is the only rigorous mathematical description of uncertainty. Critics also argue that it cannot be a superset of ordinary set theory since membership functions are defined in terms of conventional sets.

2.7.1 Applications

Fuzzy logic can be used to control household appliances such as washing machines (which sense load size and detergent concentration and adjust their wash cycles accordingly) and refrigerators.

A basic application might characterize sub-ranges of a continuous variable. For instance, a temperature measurement for anti-lock brakes might have several separate membership functions defining particular temperature ranges needed to control the brakes properly. Each function maps the same temperature value to a truth value in the 0 to 1 range. These truth values can then be used to determine how the brakes should be controlled.

2.7.2 How Fuzzy Logic is Applied

Fuzzy Set Theory defines Fuzzy Operators on Fuzzy Sets. The problem in applying this is that the appropriate Fuzzy Operator may not be known. For this reason, Fuzzy logic usually uses IF/THEN rules, or constructs that are equivalent, such as fuzzy associative matrices.

Rules are usually expressed in the form:
IF *variable* IS *set* THEN *action*

For example, an extremely simple temperature regulator that uses a fan might look like this:
IF temperature IS very cold THEN stop fan
IF temperature IS cold THEN turn down fan

IF temperature IS normal THEN maintain level
IF temperature IS hot THEN speed up fan

Notice there is no "ELSE". All of the rules are evaluated, because the temperature might be "cold" and "normal" at the same time to differing degrees.

The AND, OR, and NOT operators of boolean logic exist in fuzzy logic, usually defined as the minimum, maximum, and complement; when they are defined this way, they are called the *Zadeh operators*, because they were first defined as such in Zadeh's original papers. So for the fuzzy variables x and y:

NOT x = (1 - truth(x))

x AND y = minimum(truth(x), truth(y))

x OR y = maximum(truth(x), truth(y))

There are also other operators, more linguistic in nature, called *hedges* that can be applied. These are generally adverbs such as "very", or "somewhat", which modify the meaning of a set using a mathematical formula.

In application, the programming language Prolog is well geared to implementing fuzzy logic with its facilities to set up a database of "rules" which are queried to deduct logic. This sort of programming is known as logic programming.

2.7.3 Formal Fuzzy Logic

A fuzzy set is a pair (A,m) where A is a set and . For each , $m(x)$ is the **grade** of membership of x. . If $A = \{x_1,...,x_n\}$ the fuzzy set (A,m) can be denoted $\{m(z_1) / z_1,...,m(z_n) / z_n\}$.

An element mapping to the value 0 means that the member is not included in the fuzzy set, 1 describes a fully included member. Values strictly between 0 and 1 characterize the fuzzy members.

As an extension of the case of multi-valued logic, valuations () of propositional variables (V_o) into a set of membership degrees (W) can be thought of as membership functions mapping predicates into fuzzy sets (or more formally, into an ordered set of fuzzy pairs, called a fuzzy relation). With these valuations, many-valued logic can be extended to allow for fuzzy premises from which graded conclusions may be drawn.

This extension is sometimes called "fuzzy logic in the narrow sense" as opposed to "fuzzy logic in the wider sense," which originated in the engineering fields of automated control and knowledge engineering, and which encompasses many topics involving fuzzy sets and "approximated reasoning."

Industrial applications of fuzzy sets in the context of "fuzzy logic in the wider sense" can be found at fuzzy logic.

A **fuzzy number** is a convex, normalized fuzzy set whose membership function is at least segmentally continuous and has the functional value $\mu_A(x) = 1$ at precisely one element. This can be likened to the funfair game "guess your weight," where someone guesses the contestants weight, with closer guesses being more correct, and where the guesser "wins" if they guess near enough to the contestant's weight, with the actual weight being completely correct (mapping to 1 by the membership function).

A **fuzzy interval** is an uncertain set with a mean interval whose elements possess the membership function value $\mu_A(x) = 1$. As in fuzzy numbers, the membership function must be convex, normalized, at least segmentally continuous.

2.7.4 Defuzzification

Defuzzification is the process of producing a quantifiable result in fuzzy logic. Typically, a fuzzy system will have a number of rules that transform a number of variables into a "fuzzy" result, that is, the result is described in terms of membership in fuzzy sets. For example, rules designed to decide how much pressure to apply might result in "Decrease Pressure (15%), Maintain Pressure (34%), Increase Pressure (72%)". Defuzzification would transform this result into a single number indicating the change in pressure. The simplest but least useful defuzzification method is to choose the set with the highest membership, in this case, "Increase Pressure" since it has a 72% membership, and ignore the others, and convert this 72% to some number. The problem with this approach is that it loses information. The rules that called for decreasing or maintaining pressure might as well have not been there in this case.

A useful defuzzification technique must first add the results of the rules together in some way. The most typical fuzzy set membership function has the graph of a triangle. Now, if this triangle were to be cut in a straight horizontal line somewhere between the top and the bottom, and the top portion were to be removed, the remaining portion forms a trapezoid. The first step of defuzzification typically "chops off" parts of the graphs to form trapezoids (or other shapes if the initial shapes were not triangles). For example, if the output has "Decrease Pressure (15%)", then this triangle will be cut 15% the way up from the bottom. In the most common technique, all of these trapezoids are then superimposed one upon another, forming a single geometric shape. Then, the centroid of this shape, called the *fuzzy centroid*, is calculated. The *x* coordinate of the centroid is the defuzzified value.

2.8 Expert Systems

An **expert system**, also known as a **knowledge based** system, is a computer program that contains some of the subject-specific knowledge, and contains the knowledge and analytical skills of one or more human experts.

An expert system is a system that incorporates concepts derived from experts in a field and uses their knowledge to provide problem analysis through programs available to clinical practitioners.

The most common form of expert systems is a program made up of a set of rules that analyze information (usually supplied by the user of the system) about a specific class of problems, as well as providing mathematical analysis of the problem(s), and, *depending upon their design*, recommend a course of user action in order to implement corrections. It is a system that utilizes what appear to be reasoning capabilities to reach conclusions.

2.8.1 Knowledge Representation

Knowledge representation is an issue that arises in both cognitive science and artificial intelligence. In cognitive science, it is concerned with how people store and process information. In artificial intelligence (AI) the primary aim is to store knowledge so that programs can process it and achieve the verisimilitude of human intelligence. AI researchers have borrowed representation theories from cognitive science. Thus there are representation techniques such as frames, rules and semantic networks which have originated from theories of human information processing. Since knowledge is used to achieve intelligent behavior, the fundamental goal of knowledge representation is to represent knowledge in a manner as to facilitate

2.8.2 Application of Expert Systems

Expert systems are designed and created to facilitate tasks in the fields of accounting, medicine, process control, financial service, production, human resources etc. Indeed, the foundation of a successful expert system depends on a series of technical procedures and development that may be designed by certain technicians and related experts. When a corporation begins to develop and implement an expert system project, it will use self-sourcing, in-sourcing and/or outsourcing techniques.

While expert systems have distinguished themselves in AI research in finding practical application, their application has been limited. Expert systems are notoriously narrow in their domain of knowledge—as an amusing example, a researcher used the "skin disease" expert system to diagnose his rust bucket car as likely to have developed measles—and the systems were thus prone to making errors that humans would easily spot. Additionally, once some of the mystique had worn off, most programmers realized that simple expert systems were essentially just slightly more elaborate versions of the decision logic they had already been using. Therefore, some of the techniques of expert systems can now be found in most complex programs without any fuss about them.

An example and a good demonstration of the limitations of an expert system used by many people is the Microsoft Windows operating system troubleshooting software located in the "help" section in the taskbar menu. Obtaining expert / technical operating system support is often difficult for individuals not closely involved with the development of the operating system. Microsoft has designed their expert system to provide solutions, advice, and suggestions to common errors encountered throughout using the operating systems.

Another 1970s and 1980s application of expert systems — which we today would simply call AI — was in computer games. For example, the computer baseball games Earl Weaver Baseball and Tony La Russa Baseball each had highly detailed simulations of the game strategies of those two baseball managers. When a human played the game against the computer, the computer queried the Earl Weaver or Tony La Russa Expert

System for a decision on what strategy to follow. Even those choices where some randomness was part of the natural system (such as when to throw a surprise pitch-out to try to trick a runner trying to steal a base) were decided based on probabilities supplied by Weaver or La Russa. Today we would simply say that "the game's AI provided the opposing manager's strategy."

2.8.3 Advantages and Disadvantages

Advantages

- Provide consistent answers for repetitive decisions, processes and tasks
- Hold and maintain significant levels of information
- Reduces creating entry barriers to competitors
- Review transactions that human experts may overlook

Disadvantages

- The lack of human common sense needed in some decision makings
- The creative responses human experts can respond to in unusual circumstances
- Domain experts not always being able to explain their logic and reasoning
- The challenges of automating complex processes
- The lack of flexibility and ability to adapt to changing environments as questions are standard and cannot be changed
- Not being able to recognize when no answer is available

Chapter 3 – An Integrated Methodology

From the algorithms reviewed in the chapter two the advanced traffic-responsive coordinated class of algorithm was found to be the most suitable for optimizing freeway travel times. However the algorithms of this class do not adequately deal with ramp queues, so to overcome this limitation a new mathematical model based on the linear programming and fuzzy logic approach is developed. From this mathematical model a new algorithm to better optimize freeway travel times is produced. This algorithm reflects an integrated methodology taking the best parts from the existing algorithms studied in Chapter 2.

3.1 A Basic Linear Programming Algorithm

A study conducted by Tsuyoshi Yoshino et al [105, 115] shall be used as an example. The study looked at the automated traffic control system used on the Hanshin Expressway in Osaka-Kobe, Japan which uses a linear programming solution to optimize freeway flows through a mixture of ramp meters and traffic information systems. The Osaka-Kobe area is the second most populated area in Japan with a freeway network of over 200 kilometres serving more than 1,000,000 vehicles per day. For political reasons the algorithm controls the toll gates allowing vehicles onto the freeway, not ramp meters. The logic of the system is, however, essentially the same as that for a ramp metered system.

The control algorithm has two phases, one to control natural congestion when traffic flows around the network at a steady rate and an emergency control phase to eliminate the effects of an accident as quickly as possible. The first phase has two sub phases, of which ramp meter control is the first. This sub phase aims to maximize the flows onto the freeway while minimizing flow disruptions on the mainline and preventing spillback from affecting the surrounding arterial roads. To set the metering-rate the system solves a set of linear programming problems once every five minutes using real-time data such as volume, time occupancy, and speed obtained from traffic detectors. This is called the Linear Programming Control. Traffic parameters determined from off-line analyses are also included in determining LP Control. LP Control goes into effect if on-ramp volumes exceed certain parameters and flow fluctuations are within predetermined ranges as per the following mathematical formulae.

This equation represents the rate at which vehicles are being stored:

$$Z = a_1 u_{t,1} + a_2 u_{t,2} + \ldots a_k u_{t,k}$$

Subject to the constraints

$$X_1 = Q_{1,1} u_{t,1} + Q_{2,1} u_{t,2} + \ldots Q_{k,1} u_{t,k} \leq C_1$$

$$X_2 = Q_{1,2} u_{t,1} + Q_{2,2} u_{t,2} + \ldots Q_{k,2} u_{t,k} \leq C_2$$

$$X_m = Q_{1,m} u_{t,1} + Q_{2,m} u_{t,2} + \ldots Q_{k,m} u_{t,k} \leq C_m$$

And:

$$0 \leq u_{t,i} \leq N_{t,i} + u^d_{t,i} \quad i = 1,2,\ldots k$$

$$N_{t,i} + u^d_{t,i} - u_{t,i} \leq L_i \quad i = 1,2,\ldots k$$

Where:

$u_{t,i}$ is the allowable inflow between *t* and *t* + *dt* in the *i*-th ramp (vph);

$N_{t,i}$ is the queue length between *t* and *t* + *dt* in the *i*-th ramp *i* at time *t*;

$u^d_{t,i}$ is the estimated demand of inflow through ramp *i* (*i* = 1, 2, ... k) between time *t* and *t* + *dt* (vph);

d_t is the control cycle, 5 minutes for the control system of the Hanshin Expressway;

L_i is the maximum number of vehicles allowed to wait at ramp *i;*

X_h is the volume estimated to flow at section *h* of the freeway, *h* =1, 2, ...m (vph);

C_h is the capacity of section *h;*

a_i is a tunable weighting factor which is pre-defined for each ramp as part of the objective function to allow for weighting ramp inflows. This weighting factor is used to give preference to or discourage the use of specific ramps in the system;

k is the number of entrance ramps under consideration;

m is the number of sections;

$\boldsymbol{Q}_{i,h}$ is the ratio of the volume that will occur on section *h* with the inflow of a single vehicle through entrance ramp *i* and is estimated by surveying the trip path distribution of vehicles from each entrance ramp.

Figure 3.1 –Meaning of the Parameters

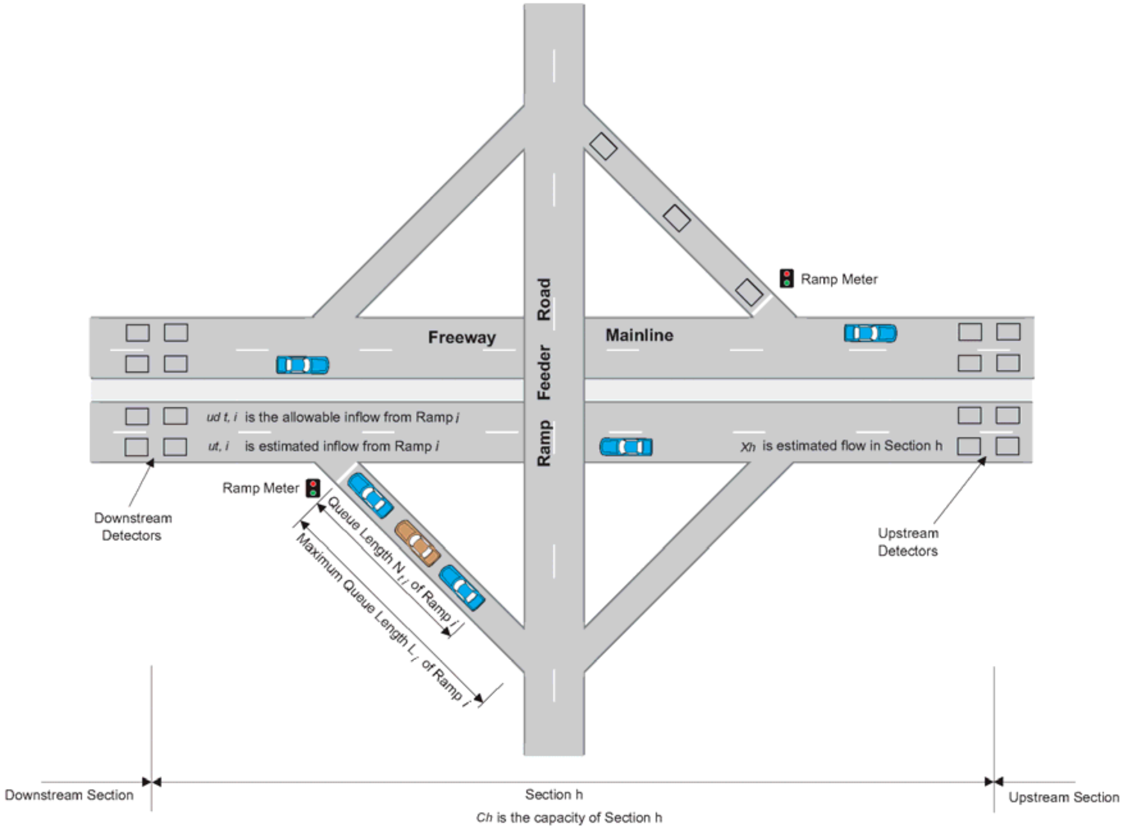

Figure 3.1 shows the meaning of the parameters used in the Linear Programming algorithm.

The bottleneck strength within section *h* is used to determine the capacity C_h of section ***h***. Setting $\boldsymbol{a}_i$ to 1 gives a maximum of inflow volume between *t* and *t* + *dt*. Setting $\boldsymbol{a}_i$ to the mean trip length of vehicles entering the freeway through entrance ramp *i* gives the maximum vehicle-kilometres ***d***. Due to the constraints in the equations when demand entering from a ramp exceed a certain value the LP problem may not have a feasible solution, in which case another control strategy is adopted.

Should fluctuations exceed the thresholds the second sub phase – sequential control is employed. When LP Control is no longer effective and congestion is expected in one or more sections or when one or more sections are already congested sequential control is employed. The system tries to dissolve congestion quickly to avoid capacity reductions and flow breakdown. Upstream on-ramps are closed successively in accordance with the severity of the congestion. Off-line analyses and simulations are used to determine when and where sequential control should be used, including which ramps should be restricted or closed. As an additional measure vehicles may be forced to exit the freeway upstream of the congested section via off-ramps. Such measures are directed to freeway traffic via Variable Message Signs (VMS).

3.2 ACCEZZ Fuzzy Logic Controller

Further to 2.5.1.2 ACCEZZ is described here in more detail. ACCEZZ uses pattern recognition (neural networks) to assess the traffic situation and expert rule systems to determine ramp metering rates. Genetic algorithms are then used to optimize the ramp metering rates. Should the expert rules not cover the situation then fuzzy-neural networks are used to find a metering solution.

Figure 3.2 –Fuzzy Logic Operation

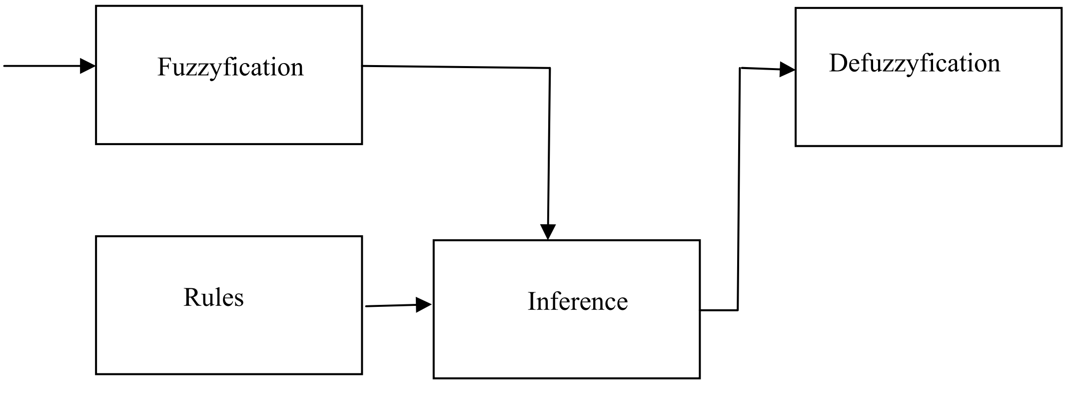

Figure 3.2 shows the fuzzy logic process.

The fuzzy logic component of the algorithm uses seven measured (crisp) inputs taken every fifteen seconds (as shown in table 3.1) and classifies them into five fuzzy (textual) classes depending on their value – very small, small, medium, big and very big – and assigns a degree of membership within that class. These fuzzified inputs are then run through a IF-THEN rule base to infer a control action. The control action will produce a set of crisp or defuzzified values that can be given to the ramp meters to produce a control regime.

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Table 3.1 - ACCEZZ Fuzzy Sets

		Number and Terms of Fuzzy Sets		**Shape of Fuzzy Sets**
Local Speed	Small	Medium	High	Gauss
Local Flow	Small	Medium	High	Gauss
Local Occupancy	Small	Medium	High	Gauss
Downstream V/C Ratio	Very High			Triangular
Downstream Speed	Very Small			Triangular
Check-in Occupancy	Very High			Triangular
Queue Occupancy	Very High			Triangular
Metering Rate	Low	Medium	High	Triangular

Table 3.1 shows the fuzzy sets of the inputs and the outputs of ACCEZZ [4].

Table 3.1 shows the fuzzy sets used for the inputs and outputs of ACCEZZ. The inputs and outputs are: local speed – the speed on the freeway near the ramp meter, local flow – the flow in vph on the freeway near the ramp meter, local occupancy – the density of vehicles on the freeway near the ramp meter, downstream V/C ratio – the volume/capacity ratio(ie. actual volume versus maximum capacity), downstream speed – the speed on the freeway downstream from the ramp meter, check-in occupancy – the density of vehicles entering the ramp queue, queue occupancy – the density of vehicles in the ramp, and the metering rate – which is the only output, and is the rate that vehicles are allowed to enter the freeway through the ramp meter.

The activation describes when the classes become active, for instance, if the queue occupancy is very high then the class is fully activated.

Table 3.2 - ACCEZZ Fuzzy Rules

Rule	Default Rule Weight	Premise	Metering Rate Outcome
1	1.5	OC_S	B
2	1.5	OC_M	M
3	2	OC_B	S
4	2	SP_S, F_B	S
5	1	SP_M, OC_B	M
6		SP_M, OC_S	B
7	1	SP_B, F_S	B
8	3	DS_VS, V_VB	S
9	3	C_VB, QQ_VB	B

Where F=flow, C=checkin occupancy, V=Volume/Capacity ratio, OC=freeway occupancy, DS=downstream freeway speed, SP=freeway speed on the freeway at the meter, QQ=queue occupancy, VS=very small, S =small, M=medium, B=big, VB=very big

Table 3.2 shows the rules used by ACCEZZ [4].

Table 3.2 shows the expert rules used by ACCEZZ. Without considering their specific weighting's (as listed in table 3.2) these rules are:

1. IF <local mainline occupancy = small>
   THEN <metering rate = high>
2. IF <local mainline occupancy = medium>
   THEN <metering rate = medium>
3. IF <local mainline occupancy = high>
   THEN <metering rate = small>
4. IF <local mainline speed = small> AND <local mainline flow = high>
   THEN <metering rate = small>
5. IF <local mainline speed = medium> AND <local mainline occupancy = high>
   THEN <metering rate = medium>
6. IF <local mainline speed = medium> AND <local mainline occupancy = small>
   THEN <metering rate = big>
7. IF <local mainline speed = high> AND <local mainline flow = small>
   THEN <metering rate = high>
8. IF <downstream mainline speed = very small> AND <local mainline density = very high>
   THEN <metering rate = small>
9. IF <ramp check in occupancy = very high> AND <ramp queue occupancy = very high>
   THEN <metering rate = high>

Table 3.3 - Activation Ranges Of The Fuzzy Classes

Fuzzy Classes	Downstream Speed	Downstream Occupancy	Queue Occupancy
VS	88.5kmh - 64.4kmh	N/A	N/A
S	N/A	N/A	N/A
M	N/A	N/A	N/A
B	N/A	N/A	N/A
VB	N/A	11 – 25%	12 - 30%

Table 3.3 shows the activation ranges of some of ACCEZZ's fuzzy classes [4].

Table 3.3 shows the activation ranges of some of ACCEZZ’s fuzzy classes. If the mainline speed at the downstream detector is between 64.4 km/h and 88.5 km/h then the very small (VS) fuzzy class is activated. If mainline occupancy at the downstream detector is in the range of 11 to 25% of maximum occupancy and the ramp queue occupancy is between 12 and 30% of maximum occupancy then the very big (VB) class is activated.

The traffic (nonlinear plant) data as measured by detectors and controlled by ramp meters produces a noise or disturbance vector, produced from the incoming and outgoing traffic flow on the mainline in accordance with figure 3.2.

Figure 3.3 - Genetic Fuzzy Control System

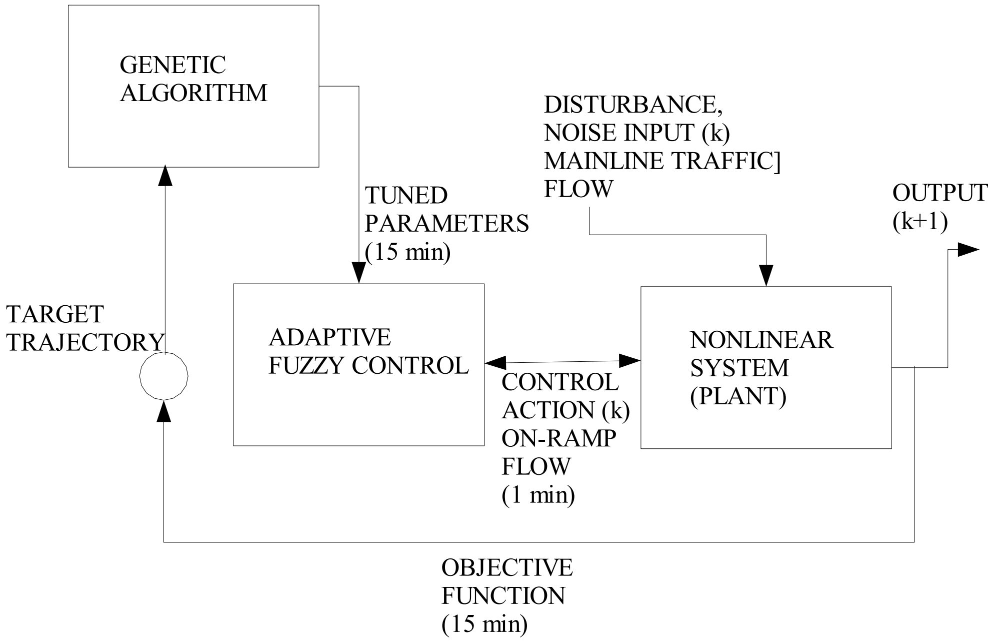

Figure 3.3 shows the genetic fuzzy control system used by ACCEZZ [4].

Figure 3.3 flow charts the control system used by ACCEZZ.

The traffic responsive, coordinated metering rate is determined by the fuzzy logic algorithm every minute and the parameters of the fuzzy system are updated periodically every 15 minutes by a genetic tuning process.

Figure 3.4- Genetic Tuning of the Parameters

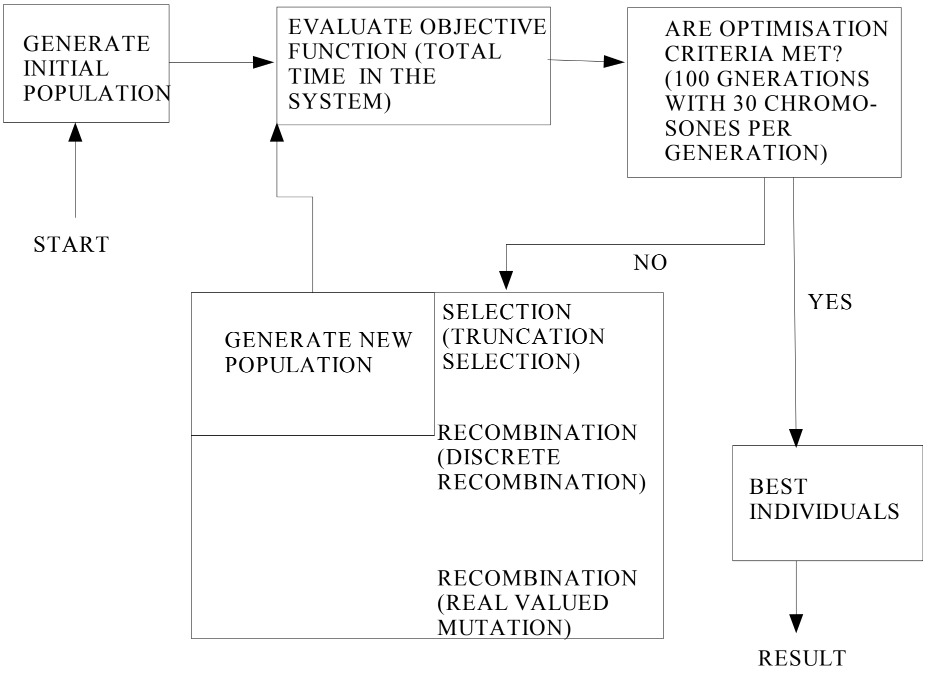

Figure 3.4 shows the genetic tuning of ACCEZZ's parameters [4].

The evolutionary algorithm uses chromosomes to represent input parameters. A set of chromosomes forms a population which is evaluated and graded by a fitness evaluation function. Depending on the grading given to the chromosomes the successful ones are used to develop a next generation of candidate solutions.

The evolution from one generation to the next involves the following main steps:

1. fitness evaluation of chromosomes,
2. selection of suitable parents for the next generation,
3. reproduction of a next generation by recombination and mutation.

Table 3.4 - Comparison of ACCEZZ to other Traffic Performance Measures

	No-Control	**Linear Programming**	**ACCEZZ**
Total Freeway Travel Time (veh-hr's)	7581	7410	7112
Average Speed (kmh)	88.4	91	91
Total Fuel Consumption (gallons)	19067	19428	19200

Table 3.4 shows the results of the comparison of ACCEZZ to the no-control and linear programming control measures using a computer simulation [4].

Table 3.4 shows that in their simulation study Bogenberger and Keller [4] found ACCEZZ outperformed a linear programming algorithm. This indicates that the linear programming approach on its own is not effective enough in dealing with ramp meter optimization and needs further enhancement.

3.3 A New Algorithm

Taking Yoshino et al’s [105, 115] algorithm as a reference a new mathematical model based on the linear programming and fuzzy logic approach is developed which follows on from Yoshino et al [105, 115] and includes some fuzzy variables.

The key idea of this new algorithm is to treat the estimated demand $u^d_{t,i}$ and ramp weighting a_i as fuzzy variables as these two parameters change depending on the traffic conditions. While Yoshino et al [105, 115] treat estimated demand and ramp weighting as constants which need to be arbitrarily set by the user the new algorithm will use fuzzy membership functions to determine the values of these variables.

3.3.1 Mathematical Model of the Control Inflow Process

Following on from Yoshino et al [105, 115] the Control Inflow Process is formulated as a linear programming problem. The following notation is used:

d_t is the control cycle, 5 minutes for the control system of the Hanshin Expressway;
$u_{t,i}$ is the inflow between t and $t + dt$ in the i-th ramp (vph);
$N_{t,i}$ is the queue length between t and $t + dt$ in the i-th ramp;
$u^d_{t,i}$ is the estimated demand of inflow through ramp i ($i = 1, 2, ..., k$) between time t and $t + dt$ (vph);
L_i is the maximum queue length in i-th ramp (capacity of i-th ramp);
X_h is the volume estimated to flow at section h of the freeway, $h = 1, 2, ...m$ (vph);
C_h is the maximum number of vehicles in h-th section (capacity of h-th section);
a_i is the weight of the i-th ramp;
$Q_{i,h}$ is a constant, the influence factor of entrance ramp i on section h;
k is the total number ramps;
m is the total number of sections.

Table 3.5 Algorithm Inputs

Input	Typical Detector Locations	No. of Samples
Upstream Volume (vph)	Next upstream mainline detector	3
Downstream Volume (vph)	Multiple downstream detectors	3
Occupancy	Downstream detector	3
Downstream Speed (kmh)	Downstream detector	3
Queue Length	Queue detectors of the ramp	6
Inflow (vph)	Ramp detector	3

Table 3.5 lists the inputs that the algorithm takes.

The linear programming problem is solved once every five minutes, so the sampling rate as shown in the right column is for this period of time. For instance, every five minutes the algorithm takes three samples of upstream volume from the next upstream mainline detector.

The algorithm takes the inputs as listed in table 3.5. The number of samples it takes is listed in the right column. The algorithm solves the linear programming problem once every five minutes. The algorithm depends on close spacing of loop detectors and accurate O-D data in order to operate effectively.

It is assumed that the maximization of inflow is equivalent to the minimization of time delay. It is also assumed that each section may have only one ramp. This means that $k = m$ in this case. Therefore the mathematical model of the Control Inflow Process is simpler than that of Yoshino et al [105, 115]. Thus the LP model of Control Inflow in this case is as follows:

Maximize the objective function for ramp flow at each ramp $u_{t,1}$

$$Z = a_1 u_{t,1} + a_2 u_{t,2} + \dots a_k u_{t,k}$$

Subject to the constraints:

Ramp demand at the 1st ramp must be less than or equal to the maximum capacity for the 1st section C_1,

$$X_1 = Q_{1,1} u_{t,1} \le C_1$$

Ramp demand for the 2nd ramp combined with the demand from the next upstream ramp must be less than or equal to the maximum capacity for the second section C_2,

$$X_2 = Q_{1,2} u_{t,1} + Q_{2,2} u_{t,2} \le C_2$$

Ramp demand for the kth ramp combined with the demand from the upstream ramps must be less than or equal to the maximum capacity for the mth section C_m,

$$X_m = Q_{1,m} u_{t,1} + Q_{2,m} u_{t,2} + \dots Q_{k,m} u_{t,k} \le C_m$$

And:

Ramp demand plus ramp queue must be less than or equal to the ramp flow rate,

$$0 \le u_{t,i} \le N_{t,i} + u^d_{t,i} \qquad i = 1,2,\dots k$$

Ramp queue plus ramp demand minus ramp flow must be less than or equal to the maximum queue length,

$$N_{t,i} + u^d_{t,i} - u_{t,i} \le L_i \qquad i = 1,2,\dots k$$

This is a linear programming problem and it can be solved by the simplex method. However in the real situation the Control Inflow Process is not a deterministic one. For example, the weights of ramps can vary depending on the time of day and traffic conditions. The same comments can be made on parameters $\boldsymbol{u^d}_{\boldsymbol{t,i}}$**.** They are fuzzy variables.

In order to maximize inflow on the mainline coefficients $\boldsymbol{a_i}$ of the ramps can be changed. It is necesary to also minimize the queue length of each ramp which is somehow equivalent to the maximization of inflow on the freeway. This means that ramps with long queues relative to their capacity will have large coefficients whereas others may have smaller coefficients. Thus it is concluded that in the above Linear Programming model there are two different fuzzy variables: $\boldsymbol{a_i}$ and $\boldsymbol{u^d_{t,i}}$.

It is assumed that membership functions of both fuzzy variables are determined by triangles – see figures 3.5, 3.6.

Figure 3.5 illustrates the control inflow process. The algorithm sits in the LP Control Sub-phase and utilizes off-line analyses and fuzzy variables in determining the metering rate.

Figure 3.5 Control Process for the New Algorithm

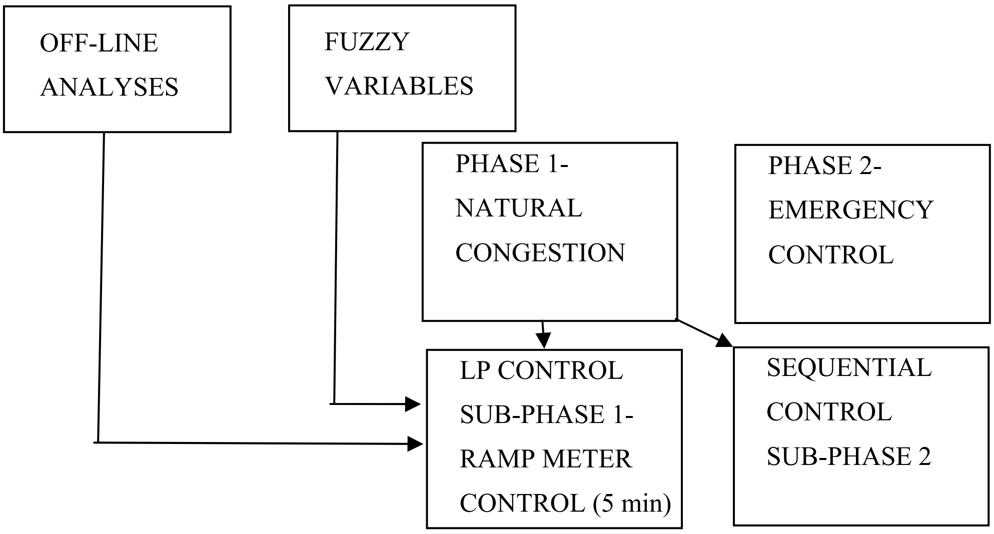

Figure 3.5 illustrates the control process for the new algorithm.

Figure 3.6 Fuzzy Classes for Ramp Weighting a_i

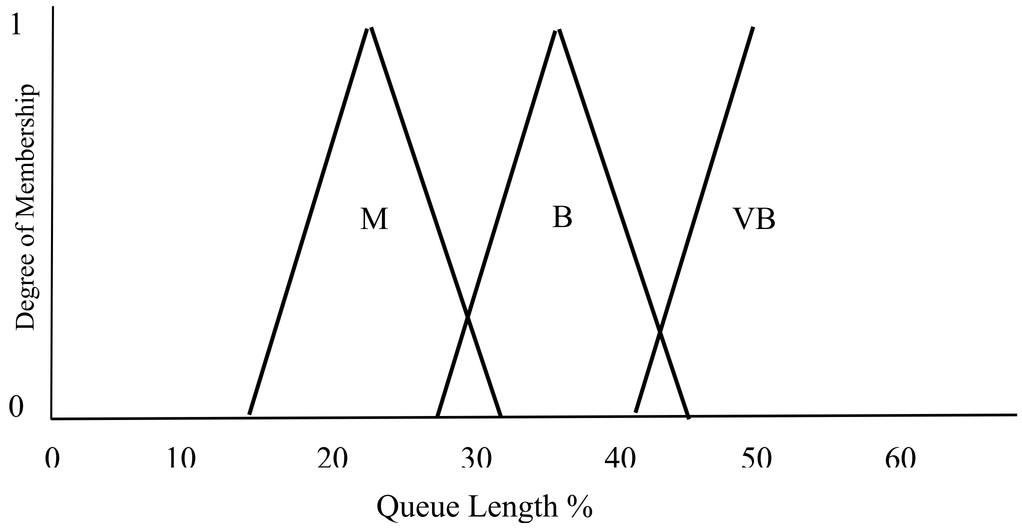

Figure 3.6 shows the fuzzy classes for ramp weighting a_i.

Queue length is defined as a % of the total storage available in the ramp. Its membership is represented by triangles – see figure 3.9. This corresponds with estimated demand $\boldsymbol{u^d}_{t,i}$ as shown in figure 3.7.

Figure 3.7 Fuzzy Classes for Estimated Demand $u^d{}_{t,i}$

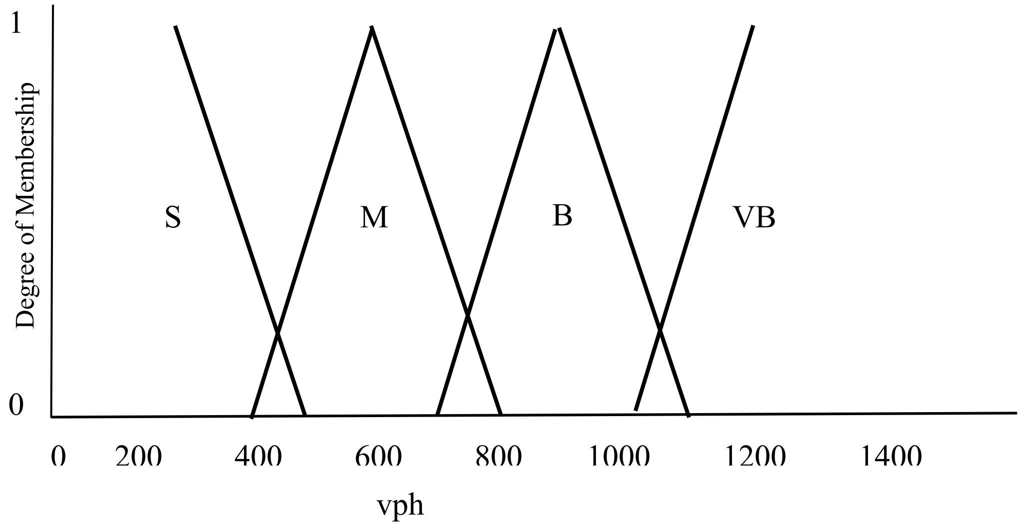

Figure 3.7 shows the fuzzy classes for estimated demand $u_{d\,t,i}$ in vehicles per hour (vph).

Estimated demand has been allocated four classes, with their activation ranges as shown in figure 3.7. The VB class is activated over 1000 vph. The final membership function for ramp weighting $\boldsymbol{a_i}$ is max(M,B,VB). The final membership function for estimated demand $\boldsymbol{u}^{d}_{t,i}$ is max(S, M, B, VB). The use of maximum membership functions avoids difficulties with overlapping membership functions. Taylor et al used overlapping membership functions in their ramp meter fuzzy logic algorithm. This overlapping can cause problems in the decision making process [78, 81, 83].

Due to the large variations that occur in estimated demand and the need for detailed inputs in order to make the linear programming algorithm operate effectively a four class not a three class triangular approach was decided upon.

Figure 3.8 M Fuzzy Class for Ramp Weighting $\boldsymbol{a_i}$

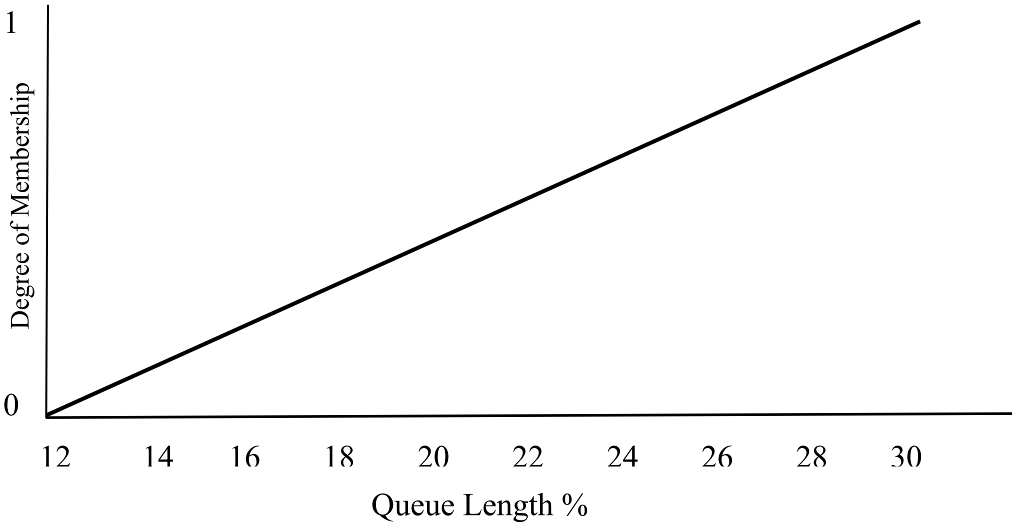

Figure 3.8 shows the M fuzzy class for ramp weighting ai. Queue length is defined as a % of the total storage available in the ramp.

Figure 3.8 shows the M fuzzy class for ramp weighting $\boldsymbol{a_i}$. The class is activated when the queue length reaches 12% of the available queue storage and fully activated at 30%. Full activation occurs at 30% due to the time lag that occurs between when an aggressive metering strategy is adopted and when it starts to affect and alter the current traffic conditions. These ranges are in accordance with those used for the Washington State DOT fuzzy logic algorithm and ACCEZZ. Criticisms of the inadequacy of the

Washington State DOT fuzzy logic algorithm’s ability to deal with large ramp queues resulted in some extra fuzzy classes being used – see 2.5.1.7.

Instead of only using a VB class with the activation ranges prescribed above, the VB class has now become the medium (M) class, and two other classes, the big (B) and very big (VB) classes have been added. The activation ranges of these classes are shown in figure 3.6. The B class overlaps the M class by 4% and is activated at 26% and reaches full activation at 44%. The VB class is activated at 40%. By adding these extra classes peak ramp queues can be better dealt with, and ramp delay and ramp spillback reduced, improving travel times. As the metering strategy is not open to a large range three classes and not more were decided upon. Due to their minimal impact on mainline flows queue lengths under 12% are not subject to metering. Queue lengths over 40% require a maximum metering rate due to their propensity to quickly develop into much longer queues as evidenced by empirical studies from the literature review.

Table 3.6 Activation Ranges of the Ramp Weighting a_i Fuzzy Classes

Fuzzy Classes	**Queue Length**
M	12 – 30%
B	26 – 44%
VB	40 – 100%

Table 3.6 shows the activation ranges for the ramp weighting ai fuzzy classes. Queue length is defined as a % of the total storage available in the ramp.

Table 3.6 lists the ramp weighting a_i fuzzy classes; for ramp weighting, the fuzzy classes used are medium (M), big (B), and very big (VB). Each of the three classes, denoted by the subscript e is defined by a centroid c_e , a base width b_e and are described by a function $f_e(x)$, where f_M, f_B, f_{VB} are the function names for each class.

Figure 3.9 Triangle Representing the Ramp Weighting a_i Fuzzy Classes

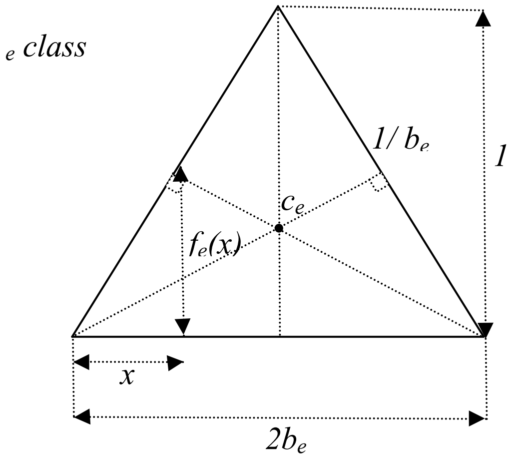

Figure 3.9 shows the triangle representing the ramp weighting a_i fuzzy classes.

The M and B classes are defined by an iscosceles triangle with a base of 2 b_e and a height of 1. The triangle is centred at c_e and has slopes of $\pm 1/b_e$. From [78] the degrees of membership are calculated from the crisp input x according to:

$$f_e(x) = \begin{cases} \frac{1}{b_e}(x - c_e + b_e) \text{ for } c_e - b_e < x < c_e \\ -\frac{1}{b_e}(x - c_e - b_e) \text{ for } c_e < x < c_e + b_e \end{cases}$$

$f_e(x) = 0$ for all classes unless noted otherwise – meaning that there is no activation of the class. The VS and VB classes are defined by a right angled triangle. The VS class is only used for estimated demand.

For the VB class the peak is at 1, so c_e is 1 - $b_e/3$. The class is 1 if $x > 1$. For the VB class,

$$f_e(x) = \begin{cases} \frac{1}{b_e}(x - 1 + b_e) \text{ for } 1 - b_e < x < 1 \\ 1 \text{ for } x > 1 \end{cases}$$

For VS the peak is at 0 and the centroid c_e is at $b_e/3$. The class is 1 if $x < 0$. For the VS class,

$$f_e(x) = \{1 \text{ for } x < 0$$

$$-\frac{1}{b_e}(x - b_e) \text{ for } 0 < x < b_e$$

The degree of activation indicates how true that class is on a scale of 0 to 1. As can be seen from figure 3.6, as an example, if the queue length was 28%, the M class would be true to some degree, and the B class would also be true to some degree, while the remaining classes would be zero. These classes are derived through fuzzification from the numerical inputs. The maximum of all classes is F=max($f_{M,}f_{B,}f_{VB}$).

To simplify the code and allow all variables to use the same fuzzification equations two scaling parameters set the low limit (*LL*) and the high limit (*HL*) for the dynamic control range of each variable. From [78, 81, 83] the following equation fuzzifies the crisp (raw) variables from the (*LL, HL*) range to the (0, 1) range.

$$scaled\,crisp\,\mathrm{var}iable = \left(\frac{crisp\,\mathrm{var}iable}{HL - LL}\right) - \left(\frac{LL}{HL - LL}\right)$$

The ramp weighting is determined by the following fuzzy logic rules.

Table 3.7 – Fuzzy Logic Algorithm Rules for Ramp Weighting a_i

Rule	Premise	Rule Weight
1	QL_M	1.0
2	QL_B	2.0
3	QL_VB	3.0

Where VS=very small, S =small, M=medium, B=big, VB=very big, and QL =queue length.

Table 3.7 lists the rules included in the algorithm, if queue length is medium (M) the rule weighting is 1.0, big (B) 2.0 and very big (VB) 3.0.

These rules are:

1. IF <ramp meter queue length = medium>
   THEN <crisp ramp queue length = 12 to 30%>
2. IF <ramp meter queue length = big>
   THEN <metering rate = 26 to 44%>
3. IF <ramp meter queue length = very big>
   THEN <metering rate = 40 to 100%>

By breaking the queue weightings into three classes these rules should deal more effectively with ramp meter queues. The weighting on the class reflects their criticallity, with the maximum rule weight applied to queue lengths that are VB.

The steps taken in the new algorithm are thus:

Algorithm 1. An algorithm for the control of inflow process:

Step 1. Initialization: Input data:
time period;
$\boldsymbol{N}_{t,\,i}$ is queue length between t and t + dt in the i-th ramp (the number of cars),
$\boldsymbol{L}_i$ is maximum queue length in i-th ramp (capacity of i-th ramp),
$\boldsymbol{C}_h$ is the maximum number of vehicles in h-th section (capacity of h-th section),
$\boldsymbol{k}$ is the total number ramps,
$\boldsymbol{m}$ is the total number of sections.

Step 2. Calculation of membership functions: Calculate the values of membership functions of a weight $\boldsymbol{a}_i$ of i-th ramp and the estimated demand $\boldsymbol{u}^d{}_{t,i}$ for a given time period in i-th ramp as per figures 3.6 and 3.7.

Step 3. Calculation of weights and demands: Calculate the values of weights a_i and the estimated demands $\boldsymbol{u}^d{}_{t,i}$ in i-th ramp following fuzzification procedure descibed previously.

Step 4. Calculation of inflows: Calculate inflows by solving linear programming problem for given values of weights $\boldsymbol{a}_i$ and the estimated demands $\boldsymbol{u}^d{}_{t,i}$.

The membership functions for $\boldsymbol{a}_i$ and $\boldsymbol{u}^{d}_{t,i}$ are determined according to figures 3.6 and 3.7. Triangles define fuzzy membership of each fuzzy class S, M, B and VB as both demand and ramp weighting are not deterministic or discrete, but operate on a sliding scale. Estimated demand builds up, peaks and breaks down. Ramp weighting should respond accordingly; as estimated demand increases, typically so should ramp weighting.

3.4 Discussion

A new traffic-responsive coordinated control algorithm using the linear programming/fuzzy logic approach was developed to optimize freeway travel times. As demonstrated in appendix 3 this algorithm was implemented in C++.

The Hanshin Expressway model uses a constant for ramp weighting that is determined by the user. Ramp weighting needs to change depending on queue occupancy. Queue occupancy changes over a typical day and is not always predictable. For this reason it was decided to make it a fuzzy variable whose membership is determined by a triangle. The same can be said for estimated demand. To estimate demand the Hanshin Expressway model relies on accurate O-D data, which is not always available. A problem with the ramp weightings used in some fuzzy logic algorithms is their inability to deal effectively with large ramp queues and anticipate ramp queue overflows. For this reason two extra classes were used for ramp queues. Typically only the VB class is used, but in the new algorithm an M class replaced the VB class, and B and VB classes were added. Membership of these classes is determined by the length of the ramp queue as a percentage of the available ramp queue storage, making ramp weighting more responsive to the unique characteristics of each ramp. A dual lane ramp meter with a large number of vehicles in its queue would have a lower weighting than a short single lane ramp meter with a long queue. The new algorithm will be more responsive to dynamic changes in the traffic conditions and provide a more appropriate metering response.

Chapter 4. A Case Study for the Monash Freeway in Melbourne.

A virtual trial site is used as a basic underlying reference for developing this particular model. To test the performance of the new algorithm an experiment is proposed to optimize outbound travel times on the Monash freeway along the section bounded by Warrigal Road and Ferntree Gully Road. This experiment can be undertaken at Vicroads virtually using the Vissim traffic simulator. The ramp meter control algorithm is to be used to regulate virtual ramp meters at the Warrigal Road, Huntingdale Road, Stephensons Road and Blackburn Road on-ramps. As this work needs to be undertaken at Vicroads it is outside the scope of this thesis and recommended as future work.

4.1 The Virtual Trial Site

Figure 4.1 Ramp Metering Virtual Trial Site on the Monash Freeway.

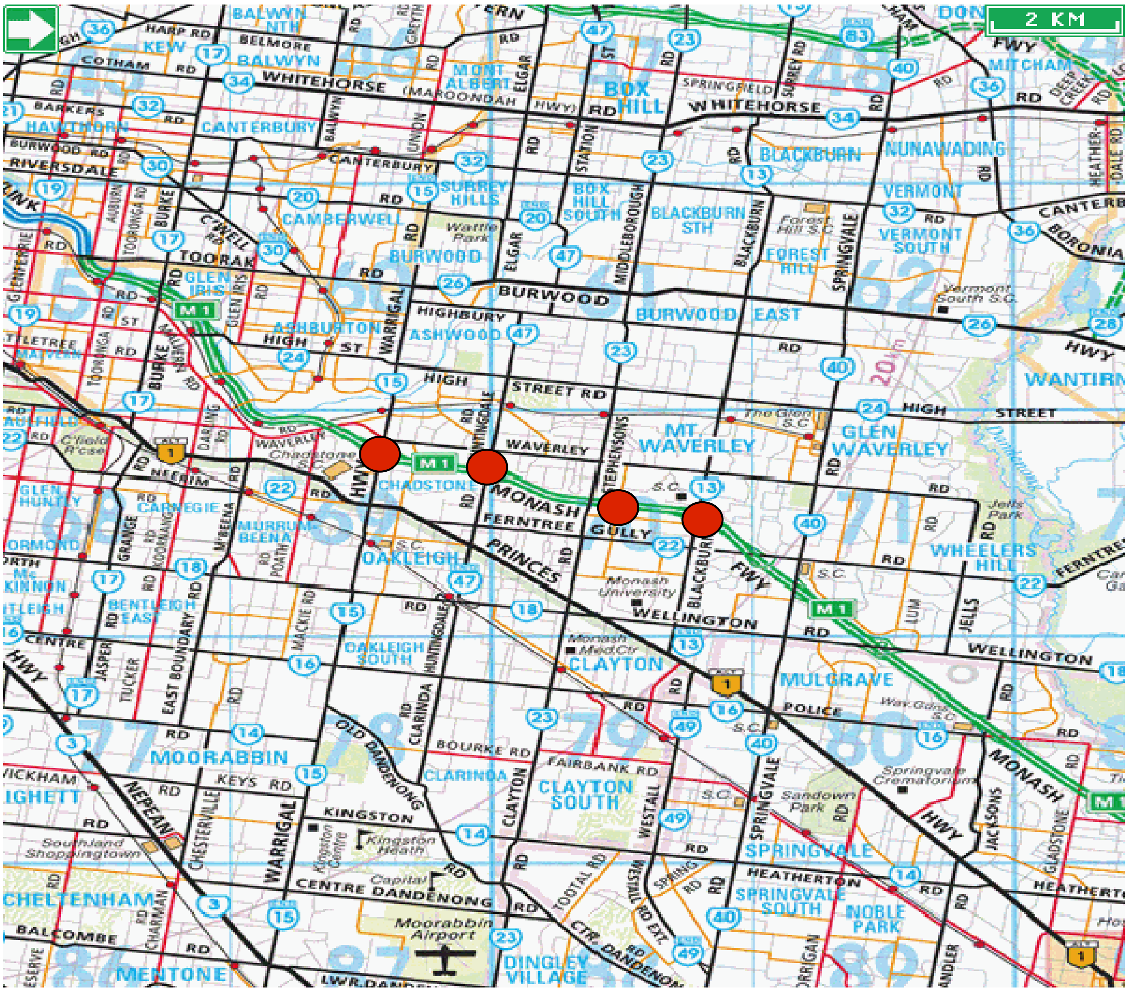

Figure 4.1 shows the ramp metering virtual trial site on the Monash freeway. The virtual ramp meters will be situated at the outbound on-ramps of Warrigal Road, Huntingdale Road, Stephensons Road and Blackburn Road at the points shown.

This section of the Monash freeway carries significant traffic volumes during peak periods. Appendix 2 contains the actual traffic data. The on-ramps along this section have to deal to a large volume of traffic, and due to their proximity to each other all need to be metered to prevent traffic avoiding existing metered ramps from overloading them. Because of equity issues associated with inbound traffic only the outbound ramps were considered in this study – see section 2.4 for more on this issue.

4.2 Vicroads Ramp Meter Control Algorithm

Figure 4.2 Vicroads Existing Algorithm.

```
Program
Identifier;

If P1 = 0 then
      Start(P1);
End;
If P1 = 24 then
      Interstage(1,2)
End;
If P1 = 38 then
      Interstage(2,3)
End;

If P1 = 107 then
      If Occup_rate(407) < 0.9 then
            Interstage(3,4)
      End;
End;

If P1 = 127 then
      If Stage_active(3) then
            Interstage(3,5)
      Else
            Interstage(4,5)
      End;
End;



If P1 = 140 then
      Interstage(5,1);
      Reset(P1)
End;
```

```
if Occup_rate(401) > 0.9 then
      If T_red(499) > 8 then
            Set_sg(499,green);
      end;
end;

if Occup_rate(403) > 0.9 then
      If T_red(499) > 7 then
            Set_sg(499,green);
      end;
end;

if Occup_rate(405) > 0.9 then
      If T_red(499) > 6 then
            Set_sg(499,green);
      end;
end;

if Occup_rate(407) > 0.9 then
      If T_red(499) > 5 then
            Set_sg(499,green);
      end;
end;



If T_green(499) >= 1 then
            Set_sg(499,red);
end;

if not init then /*initilization*/ init:=1 end
```

Figure 4.2 shows the Vehicle Actuated Programming (VAP) code for the existing Warrigal Road ramp meter controller.

The existing ramp meter control algorithm used by Vicroads to control the Warrigal Road ramp meter is listed in figure 4.3 above. The code is written in VAP code which is used by the Vissim traffic simulator to run traffic control devices. VAP uses the following notation:

P1 is the run time in seconds.
Set_sg(499, green) means set traffic signal group (in this case, the ramp meter) identifier number 499 to green.
Occup_rate(405) is the occupancy rate at loop detector 405.
T_red(499) means the condition where signal group (ramp meter) 499 is on the red stage.
Stage_active(3) means if the current signal stage (i.e. red or green) has been active 3 seconds.
Interstage(3,4) sets the interstage time in between when the signal group (ramp meter) is red or green.

As can be seen from the code the existing algorithm used by Vicroads is a very simple time and occupancy based algorithm. Vicroads uses another algorithm for the morning peak and this algorithm for the afternoon peak. In between these times the ramp meters are switched off. There is no contingency for incidents other than manual operator override. Frequently the operator overrides the algorithm and has to tweak the system to make it perform better – refer to the traffic survey in section 4.7 for results of my traffic survey during one of these problem times.

4.3 The Simulation

Vissim was used to build a reduced model of the Monash freeway between Warrigal Road and Ferntree Gully Road complete with existing ramp meters from a larger model that resides at Vicroads. The model also includes virtual ramp meters at the sites of proposed meters. Vissim uses .fma files for the O-D matrices. Vehicle actuated programming (.vap) files are used to control the ramp meters. These files are typically fairly simple in nature and not ideally suited to the complexity of linear programming. For this reason, a .dll may be used for the control algorithm. Vissim also uses .pua files to control the interstage (the interstage is the period between traffic control stages). Due to the simple binary nature of ramp meters the interstage .pua files should not be used. Vissim provides evaluation reports for each link at each detector location, which Vicroads has located in its Vissim model to mimic the real locations of loop detectors on the freeway and on-ramps. The following reports can be generated, travel times (.rsz files), ramp queues (.stz files) and delays (.vlz files).

4.4 The Data

Traffic flow data from Vicroads O-D survey and not the Melbourne Integrated Traffic Model (MITM) should be used to set the control conditions for the experiment. The O-D data was derived over the 10 November 2004 and should still be current. The O-D data is broken down into vehicle classifications with the following classification numbers along the Warrigal to Springvale section – 103 for cars, 203 for rigid trucks, 303 for semi-trailers and 403 for B-doubles. Separate O-D matrices are provided for each vehicle classification. As MITM is a strategic model it is less reliable than the O-D survey data, focusing on the entire metropolitan area of Melbourne instead of just the Monash freeway - as is the case with the O-D survey. The MITM does not take into account flows over the entire day; it uses speed/flow curves in a link-based model that doesn't allow for queuing. Links are objects with their own parameters – in this case sections of road joined to form a continuous model. MITM flows for the first fifteen minutes have had a standard error derived 1.33 adjustment factor applied to them, with a 1.07 adjustment factor applied after that. The O-D data has been reduced to only that which covers the study area and the study period (2.30pm to 7.30pm). The O-D data has been broken down into 1.5 hour blocks for greater accuracy. Separate simulations should be run for each hour from 2.30 to 7.30pm. In simulations conducted by Vicroads it was found that increasing peak hour flows by 7% induced flow breakdown. To test this finding Vicroads compared the speed flow curves from the simulations to the speed flow curves obtained from real freeway data.

4.5 Procedure for Conducting the Experiment

In accordance with Vicroads practice the simulation should be run for one hour (3600 seconds) with an additional 30 minutes (1800 seconds) to allow for traffic generation. The data from the first 1800 seconds should be discarded. An extra 100 seconds should be added onto the end of the simulation to ensure the simulated vehicles have reached their destination. The data from this extra 100 seconds should also be discarded. This produces a total simulation duration of 5500 seconds. The experiment should be repeated for every hour from 2.30 to 7.30pm using the O-D matrices for each period. Vicroads uses the following signal groups to identify each of the four ramp meters, K499 for the existing meter at Warrigal Road which is a dual lane meter with a truck bypass, and for the proposed meters; K401 for Huntingdale Road which is a dual lane meter with no truck bypass, K601 for Forster Road which is dual lane meter with a truck bypass and K701 for Blackburn Road which is a dual lane meter with a truck bypass. Loop detectors are spaced at 60 metre intervals on the Warrigal and Huntingdale Road on-ramps and every 75 metres on the Forster Road on-ramp.

Figure 4.3 Traffic Loop Detectors on the Study Section of the Monash Freeway

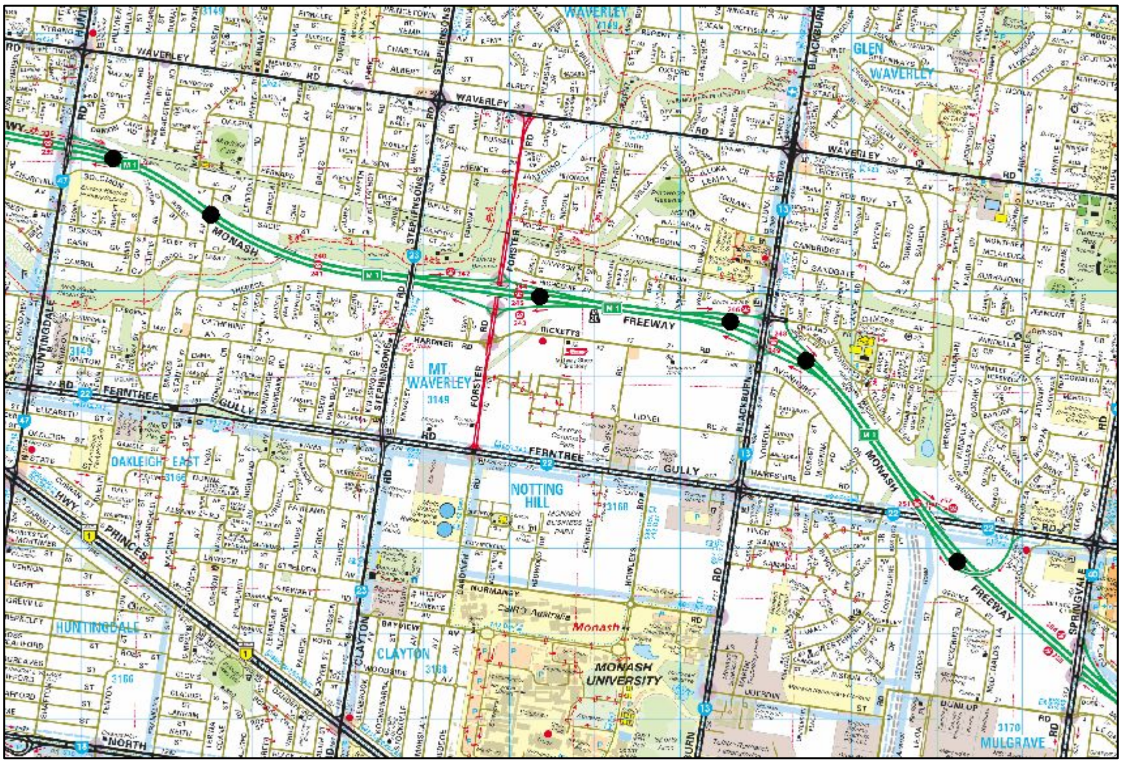

Figure 4.3 shows the traffic loop detectors on the study section of the Monash freeway where traffic data should be obtained for the control condition.

The control condition should be set to correspond with the traffic volumes at five separate times, the afternoon peak hour build-up from 2.30pm to 3.30pm, the afternoon peak hours from 3.30pm to 4.30pm, 4.30pm to 5.30pm, 5.30pm to 6.30pm and the afternoon peak hour builddown from 6.30pm to 7.30pm. Ramp inflows and upstream flows from the O-D survey provided by Vicroads should be used to set the control condition at these times in Vissim for the ramp inflows on Warrigal Road, Huntingdale Road, Stephenson’s Road and Blackburn Road and the upstream flow on the Monash freeway just before Warrigal Road. The travel time for vehicles traversing the Monash freeway between Warrigal Road and Ferntree Gully Road and the ramp meter delays (i.e.

travel times from entering the ramp to exiting the ramp) should be recorded for each of the nine study times. This data should form the unmetered control condition.

In the first test condition the Vicroads ramp meter controllers .vap files should be used to control the ramp meters. Currently each meter has its own .vap file, and the meters are not coordinated. This condition should test the effectiveness of the existing closed-loop algorithms over all four proposed and existing ramp meters. The same data as for the control condition should be collected for each of the nine times and averaged over three simulations.

In the second test condition the new algorithm should be used to control the meters. Using the Vissim SignalController and SignalGUI API’s a controller dynamic linked library (DLL) needs to be built. The experiment should be repeated in exactly the same way as for the control condition and the first test condition. This should allow a fair comparison of the effectiveness of the linear programming/fuzzy logic algorithm to Vicroads existing algorithm and to the unmetered condition.

4.6 Control of Errors

The robustness of Vissim combined with the experiment's control of all other established variables should eliminate extraneous or nuisance variables. A statistical level of significance of $p=0.05$, 1-tail with the appropriate degree of freedom should be applied to the results.

4.7 Limitations

As already discussed in section 4.3 the MITM data is not completely reliable being a strategic link-based model, but these shortcomings are reasonably overcome by the use of the O-D survey data. This data however may not fully simulate the dynamic effects of the upstream and downstream flow conditions outside of the study area.

In the Twin Cities, Minneapolis and St.Paul study quoted in Wu's [102] study about 70% of traffic would use alternative routes to avoid ramp meters, 75% would leave earlier to avoid delays and 75% would use another ramp to avoid ramp meters. Due to the difficulty in determining if these percentages would apply equally to Melbourne and the Monash freeway rerouting should not be included.

4.8 The Traffic Survey

A two hour traffic survey was conducted at the city-bound exit to Warrigal Road and the outbound on-ramp entrance, during the afternoon peak from 3.30pm to 5.30pm. A significant problem was observed at 4.30pm when traffic queued up along Warrigal Road, north of the Monash freeway, and started to spillback up to the Waverley Road intersection. This queue was caused by the ramp meter on the Warrigal Road on-ramp, which at this time of the day gives a high weighting to mainline traffic to accommodate the significant traffic volumes the Monash freeway carries – see Appendix 2. Delays for traffic entering the freeway were in excess of eight minutes. The existing closed-loop algorithm used by Vicroads for the Warrigal Road ramp meter was designed to favour mainline traffic at the expense of on-ramp travel times, particularly during peak hour. The new algorithm was designed to address this problem by working with all the ramp meters and mainline as one system, and then applying optimization to the whole system.

4.9 The Experiment

Vissim generated a report file for the PM Peak (4.30pm) control condition. This period experiences one of the highest amounts of congestion – see Appendix 2. The output data is listed here:

```
Table of Travel Times
No.  103 (Warrigal-Springvale ): from link   401 at  309.0 m to link   400 at  120.5 m,
Distance 7072.6 m, Travel Time 259 s.
```

The freeway model for the test area was produced by taking the required elements from the Monash freeway Vissim model and creating closed loops and parking areas to generate and store traffic for each link. O-D matrices were modified to only include the 14 zones of the study section and assigned to each parking area. They can be found in Appendix 1. The O-D matrices section numbers were matched to those on the model. The simulation was set to use the O-D matrices that are based on the data as presented in section 4.3. The simulation was run once to the time limits as discussed in section 4.4.

There were difficulties in running the new algorithm in the Vissim simulator. Converting the algorithm into a format that could be read by Vissim was the main problem. For future work the current Vicroads algorithms should be used to run the ramp meters and a test1_pm_peak.rsz report file generated for the times as discussed in section 3.4. The new algorithm should then be used to run the ramp meters and another test2_pm_peak.rsz report file generated, the data should then be evaluated in accordance with the procedure described in section 4.4.

An experiment at Vicroads was undertaken for the control condition only. Vissim generated a report for this experiment. Future work at Vicroads should use the existing and the new algorithm in Vissim to run the ramp meters in the simulation model.

Chapter 5. Conclusions and Future Work

5.1 Conclusions

Ramp meters are traffic signals placed on freeway on-ramps to regulate the number of vehicles allowed to merge onto the freeway. By preventing platoons of merging vehicles disrupting freeway flows ramp meters significantly improve freeway travel times. Ramp meters are often controlled by an algorithm. Developing a ramp meter control algorithm to optimize freeway travel times is the aim of this thesis.

A literature review was carried out on the main existing ramp meter control algorithms and traffic simulators. There are three main classes of algorithm: open-loop occupancy control algorithms which match measured occupancy to a plot of historical traffic occupancy for each control period, closed-loop algorithms which adjust the metering rate to match desired occupancy to actual occupancy and advanced traffic-responsive coordinated control algorithms. Advanced traffic-responsive coordinated control algorithms are considered the most suitable as they control and coordinate a number of ramp meters creating a system-wide approach.

One type of this class was studied in detail - the model used on the Hanshin Expressway in Osaka. Following on from the Hanshin Expressway model a new mathematical model was developed. In the Hanshin Expressway model weightings for on-ramps and estimated demand are constants set by the user, making the algorithm inefficient when dealing with the daily fluctuations that occur in ramp queues and demand. In the new model ramp weightings and estimated demand are dealt with as fuzzy variables making them more responsive to real-time variations.

Membership for estimated demand and ramp weighting are determined from triangles, as demand is not deterministic or discrete but increases steadily during the build-up period then reduces steadily during the build-down period. Ramp weighting follows estimated demand, higher estimated demand equates to a higher ramp weighting. The ramp weighting M class starts to be activated when the ramp queue reaches 12% of capacity and is fully activated when the queue reaches 30% of capacity. The idea here is that any control action taken to prevent the ramp queue from overflowing and spilling back onto the feeder road needs some time to take effect, and waiting for the ramp queue to grow to an unmanageable level would result in such an overflow taking place.

In the new algorithm when determining ramp weights the measure of ramp queues is not the length, as is the case with the Hanshin Expressway algorithm, but the percentage of the total ramp storage that the queue occupies, making this measure a more accurate one when dealing with ramp meters with varying quantities of storage.

A criticism of popular fuzzy logic algorithms is their inability to deal with ramp queues. This is most likely partly due to their use of only one VB class to deal with ramp queues. For this reason two new classes have been added to deal with high ramp queues, the B and VB class. The new classes have overlapping activation ranges, with the B class being activated at 26% and reaching full activation at 44%, and the VB class being activated at 40%. This allows higher weightings to be assigned to a ramp should its competing ramps already have queues up to 30% of their storage capacity. The use of maximum membership functions avoids the problem of overlapping.

Estimated demand has been broken up into four fuzzy classes, with the VB class being activated at 1000 vph. This volume has been found to result in congestion on single lane ramp meters without platoon metering (2-3 vehicles per green). The activation ranges for these fuzzy classes allow them to deal with unexpected events too, such as an irregular surge of on-ramp traffic that may occur due to a major event.

The new algorithm was implemented in C++.

A traffic survey was undertaken at the Warrigal Road ramp meter to assess the performance of the existing closed-loop algorithm in maximizing on-ramp flow while minimizing delay. Significant spillback was found to occur at 4.30pm, where outbound traffic was queued on the on-ramp for long periods of time, spilling back to the Waverley Road intersection. The existing algorithm was found to be contributing to this problem by not placing enough weighting on ramp flows. The new algorithm has been designed to deal with this problem.

5.2 Future Work

The section of the Monash freeway in Melbourne from Warrigal Road to Ferntree Gully Road has been selected for a case study to test the effectiveness of this algorithm in optimizing travel times. This section of freeway operates four ramp meters controlled by closed-loop algorithms. These algorithms operate at a local level only and are not coordinated. The impact one ramp may have on the other is not considered by these algorithms nor is system-wide metering possible. Incidents need to be dealt with by operator intervention. The new algorithm offers the opportunity to coordinate these meters so feedback from other meters can be included in determining metering rates. This will produce a system-wide approach, allowing incidents and changes in the traffic dynamics to be responded to without the need for operator intervention.

A case study should be conducted for the test conditions with the new algorithm controlling the ramp meters in the Vissim Monash freeway model. The results should then be analysed to determine if the new algorithm is worthy of further investigation. Further experimentation would then be needed to optimize the fuzzification of the estimated demand and ramp weighting variables. As these experiments need to be done at Vicroads they are outside the scope of this project and recommended for future work.

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Appendices

Appendix 1 – Modified OD Matrices for the Trial Section

* O-D Matrix for Cars for the PM Peak

* These volumes are for 1 Hour 54 minutes, 0.00 to 1.54 !

3 4.5

* Scaling Factor

1.15

* Number of Zones

14

* Zones

1 2 3 4 5 6 7 8 9 10 11 12 13 14

* Number of trips between Zones

0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
92	0	4	4	4	0	0	0	0	0	0	0	0	0
359	18	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
228		18	4	22	0	0	0	4	0	0	0	0	0
574	18	0	22	0	0	0	9	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
994	57	35	26	4	0	0	26	9	0	0	66	0	0
1268	469	381	451	232	0	0	342	293	0	0	613	0	0

* O-D Matrix for Single Unit Trucks for the PM Peak

* These volumes are for 1 Hour 54 minutes, 0.00 to 1.54 !

3.0 4.5

* Scaling Factor

1.15

* Number of Zones

14

* Zones

1 2 3 4 5 6 7 8 9 10 11 12 13 14

* Number of trips between Zones

0	0	0	0	0	1	21	0	0	1	38	0	16	103
0	0	0	0	0	0	0	0	0	1	0	0	0	17
0	0	0	0	0	0	0	0	0	1	0	0	1	19
0	0	0	0	0	0	1	0	0	0	2	0	0	5
0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	2	0	0	2
0	0	0	0	0	0	0	0	0	0	0	0	0	3
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	19
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

* O-D Matrix for Semi Trailers for the PM Peak

* These volumes are for 1 Hour 54 minutes, 0.00 to 1.54 !

3 4.5

* Scaling Factor

1.15

* Number of Zones

14

* Zones

1 2 3 4 5 6 7 8 9 10 11 12 13 14

* Number of trips between Zones

0	0	0	0	0	1	6	0	0	0	30	0	40	36
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	1
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	

* O-D Matrix for B-Doubles for the PM Peak

* These volumes are for 1 Hour 54 minutes, 0.00 to 1.54 !

3 4.5

* Scaling Factor

1.15

* Number of Zones

14

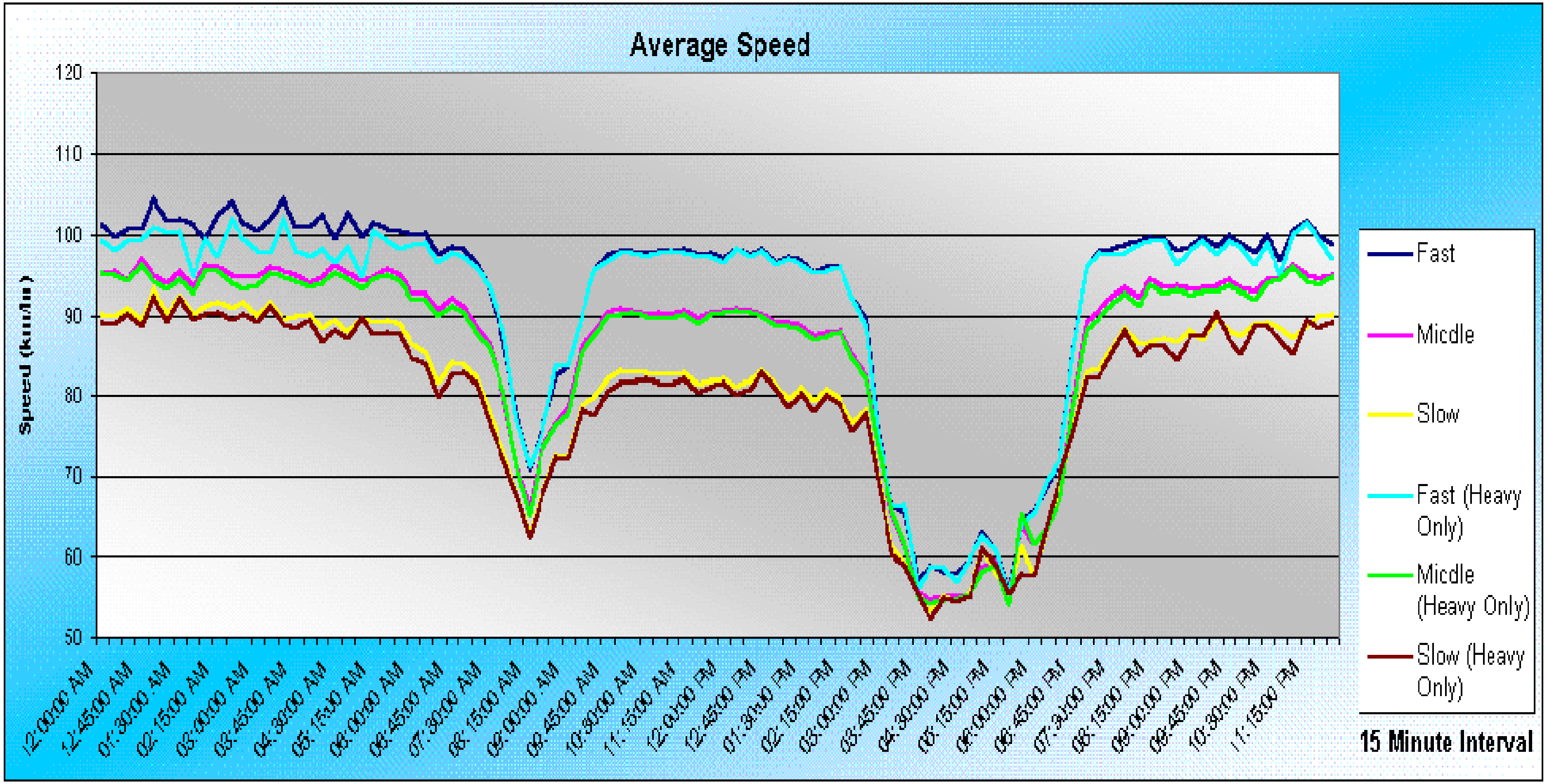
* Zones

1 2 3 4 5 6 7 8 9 10 11 12 13 14

* Number of trips between Zones

0	0	0	0	0	0	1	0	0	0	0	0	0	22
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0
0	0	0	0	0	0	0	0	0	0	0	0	0	0

Appendix 2 – Vicroads Traffic Data for the control condition on the study area of the Monash Freeway – Average Speed per Time of Day



Appendix 3 - C++ Code of the New Algorithm

```
C     Last change:    10 Apr 2006    9:19 am*/
/*=============================================================*/
/*  Fuzzy linear programming approach to Control Inflow Process*/
/*=============================================================*/
/*     main programm*/

/*PARAMETERS*/
#define nramps1 100
#define nsection 10
#define nvar 1000

int main(void)
{
  double a1[nramps1],A[nvar][nvar],c[nvar];
  int u[nramps1],udemand[nramps1],l[nramps1],nqeue[nramps1],
Q[nramps1][nsection],c2[nsection];
  double time1,c1,d1,d2;
  int nramps,nsections,i,j,n,m,n1,n2,jmin,jmax;

  FILE* infile, *outfile;
  char infile1[] = "datainput1.txt";
  char outfi0[] = "results.txt";

  infile = fopen(infile1,"r");
  outfile = fopen(outfi0,"w");

  /* We can give l(i) and c(i) here, they are constants.*/
  /* m is the total number of sections which is always constant.*/
```

```
 time1=5.;

 nramps=10;
 for(i=0;i<nramps;i++)
 {
  l[i]=10;
 }

 nsections=2;
 for(i=0;i<nsections;i++)
 {
  c2[i]=100;
 }


/*==============================================================
==========*/
 /* Reading input files*/

/*==============================================================
==========*/
 for(i=0;i<nramps;i++)
 {
  fscanf(infile,"%d",&nqeue[i]);
 }
 for(i=0;i<nramps;i++)
 {
  for(j=0;j<nsections;j++)
  {
   Q[i][j]=0.;
```

```
    }
  }

/*==============================================================
====*/
  /*  Fuzzy logic part*/

/*==============================================================
====*/
  if( ((time1 >= 0) && (time1 < 6)) )
  {
    for(i=0;i<nramps;i++)
    {
      udemand[i]=2;
      a1[i]=1.0;
      for(j=0;j<nsections;j++)
      {
        Q[i][j]=1;
      }
    }
  }

  if( ((time1 >= 6) && (time1 < 12)) )
  {
    for(i=0;i<nramps;i++)
    {
      udemand[i]=10;
      a1[i]=2;
      for(j=0;j<nsections;j++)
      {
        Q[i][j]=1;
```

```
    }
  }
 }

 if( ((time1 >= 12) && (time1 < 18)) )
 {
   for(i=0;i<nramps;i++)
   {
     udemand[i]=20;
     a1[i]=2;
     for(j=0;j<nsections;j++)
     {
       Q[i][j]=1;
     }
   }
 }

 if( ((time1 >= 18) && (time1 < 24)) )
 {
   for(i=0;i<nramps;i++)
   {
     udemand[i]=10;
     a1[i]=1;
     for(j=0;j<nsections;j++)
     {
       Q[i][j]=1;
     }
   }
 }
```

```
/*===============================================================
====*/
 /*  Formulation of optimization problem*/

/*===============================================================
====*/
 n=3*nramps+nsections;
 m=2*nramps+nsections;
 for(i=0;i<m;i++)
 {
  for(j=0;j<n+1;j++)
  {
   A[i][j]=0.;
  }
 }
 for(i=0;i<nramps;i++)
 {
  c[i]=a1[i];
 }
 for(i=0;i<nsections;i++)
 {
  A[i][n+1]=c2[i];
 }
 n1=nsections;
 n2=nsections+nramps;
 for(i=n1;i<n2;i++)
 {
  A[i][n+1]=nqeue[i]+udemand[i];
 }
 n1=nsections+nramps;
 n2=nsections+2*nramps;
```

```
 for(i=n1;i<n2;i++)
 {
   A[i][n+1]=l[i]-nqeue[i]-udemand[i];
 }
 for(i=0;i<nramps;i++)
 {
   for(j=0;j<nsections;j++)
   {
     A[i][j]=Q[i][j];
   }
 }

/*=============================================================
====*/
  /*  Solving the linear programming problem.*/

/*=============================================================
====*/

  c1=100000.;
 for(i=0;i<n;i++)
 {
   if(c[i] < c1) c1=c[i];
 }
 while(c1 >= 0)
 {
   for(i=0;i<n;i++)
   {
     if(c1 == c[i]) jmin=i;
   }
   d1=100000.;
```

```
for(i=0;i<m;i++)
{
 if( (A[i][jmin] != 0.) )
 {

  d2=A[i][n+1]/A[i][jmin];
  if(d1 < d2) d2=d1;
  if(d1 == d2) jmax=i;
 }
}
for(i=0;i<n+1;i++)
{
 A[jmax][i]=A[jmax][i]/A[jmax][jmax];
}
for(j=0;j<m;j++)
{
 if( (j != jmax) )
 {

  for(i=0;i<n+1;i++)
  {
   A[j][i]=A[j][i]-A[jmin][i]*A[jmax][i];
  }
 }
}
for(i=0;i<n;i++)
{
 c[i]=c[i]-A[jmax][i]*c[jmin];
}
c1=100000.;
for(i=0;i<n;i++)
```

```
    {
      if(c[i] < c1) c1=c[i];
    }
  }

/*=============================================================
====*/
  fclose(infile);
  fclose(outfile);
}
```

Glossary

Area of influence sections of a freeway under the influence of a ramp metering system.

B-double is a heavy vehicle twin trailer combination that is 25 m in length.

Bottleneck strength a bottleneck is a traffic jam that happens in one location, not over the entire length of the freeway. Its strength is the severity of this jam, as measured by the flow in vph through the bottleneck.

Car following model is a computer model that bases simulated driver reaction only on reactions to the car in front. Such models are criticised as they don't allow for driver anticipation as drivers look past the car in front.

Gap is the difference in time between the tail of the leading vehicle crossing the upstream edge of the detector and the tail of the vehicle crossing the downstream edge of the detector.

Gap acceptance is the gap that drivers will accept before changing lanes and occupying it. Often used in traffic simulations.

Genetic fuzzy logic is a fuzzy system generated or adapted by genetic algorithms, where genetic algorithms develop or optimize the fuzzy rule base, instead of the rule base being set by the developer based on expert rules.

Global traffic demand is the demand on the study site of all traffic entering the roadway system, such as from access roads, the freeway etc.

Headway is the time between the head of the leading vehicle crossing the upstream edge of the detector and the head of the following vehicle crossing the upstream edge of the detector. Thus headway is identical to "gap".

HOV is a High Occupancy Vehicle, such as a bus.

Inbound used to describe traffic going towards the city

Interchange A collection of ramps, exits, and entrances between two highways

Interstage in traffic light sequencing this is the stage between the green and red phases.

Kalman Filter is a recursive filter that estimates the state of a dynamic system from a series of incomplete and noise measurements.

Lane changing

Local region around equilibrium, the local region is the area around a ramp meter that is directly under its influence. At equilibrium the traffic in this region is balanced, ie. the ramp queue is not extending past the end of the ramp and the freeway is flowing at its optimum capacity.

Local-level metering rate is the ramp metering rate that a particular ramp meter is using based solely on the area under its influence, without considering the effect it is having on traffic in other areas controlled by other ramp meters.

Loop detectors are magnetic loops placed under the road surface to detect vehicles crossing them, when used in pairs they can determine vehicle speeds, and lane occupancies from vehicle spacings.

Mean trip length is the average trip length of vehicles in a OD study.

Occupancy is the difference between the head of the vehicle crossing the upstream edge of the detector and the tail of the vehicle crossing the downstream edge of the detector.

OD Matrix places the results of an OD survey into a matrix, as shown in appendix 1. This matrix shows the number of a specific class of vehicle wanting to travel from specific origins to specific destinations. It can be used as an input into a traffic simulator to attempt to recreate real traffic dynamics.

OD means Origin-Destination. OD is a common term in traffic engineering determined from traffic surveys that counts the number of vehicles travelling from a specific origin to a specific destination. Often vehicle classes are separated in these surveys.

Off-line analysis

On-line analysis

Outbound used to describe traffic leaving the city

Variable Message Signs (VMS) are electronic signs used on roads to send messages to drivers, such as warnings of accidents or congestion ahead. They are variable as they can change the messages they send to drivers.

Weaving manoeuvres are traffic manoeuvres where vehicles cross each others paths, such as occurs at freeway exits.