Design and Evaluation of Adaptive Coordinated Ramp Control Strategies on Deerfoot Trail Using Paramics Microsimulation

Final Report

Submitted by

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Executive Summary

In this report, a new proactive coordinated ramp metering approach is developed based on speed data obtained from vehicle probe technology (or in future from IntelliDrive). The objective function formulated in this approach minimizes the total vehicular travel time and delay experienced by vehicles on the freeway and on-ramps. A rolling horizon framework is formulated to obtain the optimum ramp metering rates for the next time interval. In addition, the developed approach employs a dynamic weighting scheme that gives different weights in the objective function to different freeway sections and the on-ramps. The developed approach is tested using Quadstone PARAMICS’ microsimulation software package. This probe-based adaptive ramp metering approach has been compared with a detector-based algorithm and pre-timed ramp metering algorithms. The comparative analysis of the three ramp metering approaches was conducted on an 8 km freeway section on Highway 2 in Calgary, Alberta, Canada with Quadstone PARAMICS’ microsimulation. The performances of the algorithms were examined and compared, in terms of freeway and system delays, densities and speeds. A sensitivity analysis has also been conducted to compare the performance of the developed probe-based approach for different percentages of market share of probe data (i.e. number of vehicles acting as probes). The results of the analysis indicate that the probe-based algorithm consistently outperformed the two other approaches in terms of all performance measures. The probe-based approach is shown to exceed the performance of the detector-based approach with a market share of vehicle probes as low as 3%. The results of the analysis are promising and show the effectiveness of developing ramp metering control algorithms taking as main input parameters speed data from vehicle probes on the freeway.
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Chapter 1. INTRODUCTION

1.1 BACKGROUND

The rapid increase in travel demand has led to severe congestion in metropolitan areas. The congestion is especially concentrated on urban freeways that carry high volumes of traffic, resulting in long queues, increased emissions, degraded infrastructure utilization and reduced safety. Ramp meters have proven to be one of the most effective techniques for improving traffic flow on freeways. These meters maintain smooth freeway mainline flow by limiting vehicle entrance at on-ramps, thereby reducing freeway congestion while providing increased safety in merging and reducing rear-end collisions on the ramps themselves. Another important benefit of ramp metering is that some short freeway trips may divert to adjacent under-utilized arterial streets to avoid queues at the meters. In case of the existence of excess capacity on surface streets, it may be worthwhile to divert traffic from congested freeways to surface streets (Papageorgiou, 2003). Previous studies have demonstrated that efficient ramp metering strategies can reduce notably total travel time on freeways (Kotsialos et al., 1999).

1.2 RESEARCH CHALLENGES

The greatest challenge of designing a ramp metering strategy is its capability of preventing freeway congestion without creating large on-ramp queue overflows. In oversaturated traffic conditions on the network, giving priority to the freeway to maintain a high level of service on the mainline may result in long queues on on-ramps, which might result upstream signal blocking and increase vehicle emissions on the on-ramps.

In addition, one of the main challenges related to the implementation of advanced ramp metering strategies is the high cost associated with the need for intensive coverage of infrastructure based vehicle detection systems. Real-time and estimated future traffic conditions on the highway, such as traffic volume, travel time and speed, are critical inputs in the development of these freeway control strategies. Thus, most advanced ramp metering algorithms rely on traffic flow, density or occupancy information from point detectors (mainly inductive loop detectors) located upstream or downstream of the ramp (or both, in some cases). Since traffic flow information is not a reliable indicator of congestion, occupancy or density readings from these point detectors are often adopted as the main input parameters in designing advanced ramp metering algorithms. Density, which, in theory, is a measurement obtained over a stretch of a freeway, is estimated from occupancy, which is measured by point detectors over a certain time period and input in the ramp metering algorithms. Qui et al. (2010) pointed out the inadequacy of estimating the density of a freeway section using point detectors, particularly in the presence of significant lane changing behaviour close to sections containing on-ramps and off-ramps. Thus, the use of these local density estimates, which are not representative enough of the traffic state of the entire freeway, may lead to less than optimal results when implementing ramp metering (Qui et al. 2010).

On the other hand, in order to have an effective coordinated ramp meters, high coverage of the point detector may be required (e.g. Advanced Real Time Ramp Metering System (Liu et al., 1993),ARMS, algorithm needs three detectors, upstream, midstream and downstream of each on and off ramp). This corresponds to high costs associated with the installation, maintenance and communication equipments needed for these detectors, resulting in many municipalities
being reluctant to install ramp meters. Furthermore, probe vehicles can give reliable network-wide travel time information. Probe vehicle technology is often used in Intelligent Transportation System (ITS) applications for real time traffic data collection. The term ‘probe vehicle’ in this report is defined as a vehicle disseminating accurate information on its location and speed in real time. Common probe vehicle systems include (Qui, 2007):

- Automatic Vehicle Location (AVL) in which probe vehicles communicate with transmitters mounted on existing signpost structure;
- Automatic Vehicle Identification (AVI) which consists of a vehicle equipped with electronic tags communicating with roadside transceivers for collecting travel time;
- Global Positioning System (GPS) probes that both receive and transmits signals from and to control center; and finally
- Cellular Probes that collect travel time data by discreetly tracking cell phones within cellular network, and traffic related information can be determined from these collected data.

### 1.3 PROPOSED METHODOLOGY

With recent rapid technological developments and the increasing use of Global Positioning System (GPS) enabled cell phones, there is considerable scope to address these challenges at reasonable cost. Real-time travel time and speed data from probe vehicles are already available on major roadways from new mobile phones that are location-enabled via built-in GPS receivers (Sacco, 2007). Google has recently expanded its online traffic layer based on GPS-enabled phone technologies to cover major U.S. highways and arterials, as well as major Canadian highways (Weitz, 2009). In the future, this data will be made even more available from IntelliDrive (IntelliDrive 2010).

Probe vehicles are able to provide direct estimates of space mean speed (SMS), which is a reliable indicator of congestion. Thus, this research develops a proactive coordinated ramp metering approach that uses the SMS data directly provided by probe vehicles as the main input parameters. This probe-based SMS data is then used to determine reliable density estimates using Van Aerde’s (1995) traffic flow model. This transition is due to using the Cell Transmission Model (Daganzo 1993) for short traffic prediction. The developed approach also attempts to reduce congestion within the whole corridor system.

The approach used focuses on: (1) the formulation of the ramp metering rates to simultaneously address the two often conflicting objectives of reduced freeway congestion and decreased delays on ramps; (2) the development of ramp metering algorithms based on speed data from vehicle probes to decrease the cost of deployment of ramp metering strategies and (3) integrating system wide control on multiple ramp meters along with the whole freeway segment in the vicinity of the on-ramps. The developed approach is shown to be capable of reduce and smooth densities on the entire freeway thus suppressing shockwave formation. This approach is evaluated in comparison with the performance of 1) no ramp metering control 2) a pre-timed ramp metering control and 3) a detector-based ramp metering approach.
1.4 MOTIVATION, GOALS AND CONTRIBUTIONS

The greatest challenge of designing a ramp metering strategy is its capability of preventing freeway congestion without creating high on-ramp delays. Additionally, most advanced ramp control algorithms rely on data provided from traffic detectors. These detectors are expensive to deploy and maintain, and they are not economically sustainable. They are also of limited utility as they provide only local information, such as flow or occupancy. Probe vehicle can give reliable network-wide travel time information at relatively low cost (Cayford et al., 2008).

The main objectives of this research are: 1) to assess the effectiveness of using speed data from probe vehicles as the main input parameters to develop ramp metering algorithm and 2) to formulate the problem from a system wide perspective to minimize total system travel time (i.e. concurrently freeway travel times and delays on ramps).

In this report, a proactive coordinated ramp metering strategy is developed based on speed data obtained from vehicle probe technology (or in future from IntelliDrive). The objective function formulated in this approach minimizes the total vehicular travel time and delay experienced by vehicles on the freeway and on-ramps. A rolling horizon framework is formulated to obtain the optimum ramp metering rates for the next time interval. In addition, the developed approach employs a dynamic weighting scheme that gives different weights in the objective function to different freeway sections and the on-ramps. The developed approach is tested using Quadstone PARAMICS’ microsimulation software package.

This report made the following contributions to the literature:

i. **Using vehicle probes instead of traditional detection based technologies as the main input parameter to ramp metering algorithms.** This report developed an innovative ramp metering approach that relies on probe base speed information as main input in the ramp metering problem formulation. The use of probe information data to formulate advanced control algorithms is a pioneering one in the field of transportation engineering.

ii. **Adopting a Dynamic Weighting Scheme for different freeway sections and on-ramps**

This report better addresses the equity issues as related to ramp metering strategies by introducing a dynamic weighting scheme in the ramp metering problem formulation. This weighting scheme has the advantage of drawing dynamically the attention of the algorithm on the portion of the system experiencing critical congestion.

iii. **Using a system approach in the formulation of the ramp metering algorithms**

The approach used focuses on the formulation of the ramp metering rates to simultaneously address the two often conflicting objectives of reducing freeway travel time and decreasing the delays on ramps. Travel times on the freeway are estimated directly from section space mean speeds rather than indirectly from point detectors placed in the vicinity of the on-ramps.

1.5 ORGANIZATION OF REPORT

The rest of the report is organized as follows. In the second chapter, previous ramp metering algorithms are first reviewed; followed by an overview of vehicle probe technology. In the third chapter, a description of the new probe based ramp metering algorithm is presented followed by the simulation test and comparison of the results in chapter four. The fifth chapter then compares the simulation results with a pre-timed and a detector based ramp metering to
further evaluate the performance of the algorithm. In chapters four and five, sensitivity analysis is conducted to examine the performance of the developed algorithm for various congestion levels, estimation steps, and percentages of vehicle probe market share. Concluding comments and recommendations for future work are presented in the final chapter.
Chapter 2. LITERATURE REVIEW

This chapter presents a background of ramp metering algorithms and vehicle detection technology. This chapter is divided into sections. Section 2.1 reviews the various ramp metering strategies, with special attention to coordinated ramp metering strategies. Second 2.2 presents the different vehicle detection technologies including loop detectors and probe vehicle technology.

2.1 RAMP METERING STRATEGIES

Ramp meters have proven to be one of the most cost-effective techniques for improving traffic flow on freeways. These meters maintain smooth freeway flow by controlling the entrance of vehicles from the on-ramps, thereby increasing freeway throughput while providing increased safety by reducing sideswipe and rear-end crashes (Piotrowicz and Robinson, 1995). Previous studies have demonstrated that efficient ramp metering (RM) strategies can reduce significantly total travel time on freeways (Papageorgiou, 2003 and O’Brien, 2000).

Recurrent congestion reduces available freeway capacity at rush hours, when this capacity is mostly needed, causing excessive delays and emissions and reduced safety (Papageorgiou and Kotsialos, 2002). When congestion forms on freeways, the discharge rate from the bottleneck is reduced (i.e. 5% to 10% less than freeway capacity (Hegyi et al., 2005)). In addition, off-ramps and interchanges covered by the congestion are often blocked, which decreases the chance to exit vehicles from the freeway. Similar effects are observed in the cases of nonrecurring congestion caused by incidents, road works, etc.

Congestion on freeways forms because too many vehicles attempt to use them in an uncontrolled fashion. However, treatment of highways as controllable facilities with the use of properly designed ramp metering has been shown to significantly reduce total travel time on freeways (Kotsialos and Papageorgiou, 2002). Furthermore, by preventing freeway congestion, ramp metering policies are able to service a much larger number of vehicles on the freeway than when no metering policies are used (Horowitz et al., 2002).

The positive impact of ramp metering on both freeway and adjacent road network traffic conditions was confirmed in a specially designed field evaluation on the Boulevard Peripherique in Paris, France (Papageorgiou and Kotsialos 2002). In addition, before and after evaluations of ramp management strategies in Minneapolis/St. Paul, Minnesota, offer strong evidence that operations on ramps, freeways and even adjacent arterials are improved, once these strategies are appropriately implemented and operated (Tinklenberg, 2001).

2.2 TYPES OF RAMP METERING STRATEGIES

Several attempts have been made in the past toward the development of efficient ramp control strategies. Different methods have been proposed to calculate the optimum metering rate that controls the number of vehicles allowed to enter the freeway from the on-ramps. Ramp metering may operate either in pre-timed or adaptive:

1) Pre-timed Ramp Metering: As the name indicates, pre-timed control ramp metering strategies have fixed cycle time and phase length. The ramp metering rate is mainly determined as function of historical traffic information. A metering plan is established and then its operations changes depending on time of day, day of the week and/or the presence of special events. Clearly, this algorithm does not react to any sudden fluctuation of traffic condition resulting from either incidents or increased demand. The low capital costs associated with these fixed time control
metering makes them attractive as a backup to other metering approaches or for situations when a primary responsive or adaptive approach fails (Nevada Department of Transportation, 2010). However, these approaches do still have the advantage of reducing incidents at the entrance ramps.

2) Adaptive Ramp Metering: Adaptive ramp metering control varies their rates minute-by-minute or second by second based on real-time traffic parameters. Jin and Zhang (2001) have categorized adaptive ramp metering algorithms into four types:

1. Isolated ramp metering such as demand capacity (Masher et al., 1975) and ALINEA (Papageorgiou, 1991), in which the metering rates are obtained only based on the local traffic condition. A local ramp controller operates independently of the other controllers on the freeway. It only manages the traffic condition of a local section of the freeway. In case of multiple congestion spots in different parts of the network, this type of control will not be able to identify them and as a result may not be as effective.

2. Cooperative ramp metering, in which the metering rates are first computed with local traffic information, then adjusted according to the conditions of the entire system such as the helper algorithm (Lipp et al., 1991).

3. Competitive ramp metering, in which one ramp metering rate is based on the local traffic condition and another ramp metering rate is based on system conditions. These rates are computed and compared, and the most restrictive one is chosen such as the Seattle bottleneck algorithm (Jacobsen et al., 1989) and the SWARM algorithm (Paesani, 1997).

4. Integral ramp metering, in which local traffic conditions and system-wide traffic conditions are both used to determine metering rates such as METALINE (Papageorgiou et al., 1990), ARMS (Liu, 1993) and the Dynamic Metering Control Algorithm (Chen et al., 1997).

2.1 DETAILED DESCRIPTION OF VARIOUS RAMP METERING STRATEGIES

Table 2.1 below groups various known ramp metering strategies by: categories, type of input data required and location of the measurement. Detailed description of these ramp metering strategies is presented in this section.

<table>
<thead>
<tr>
<th>Ramp Metering Name</th>
<th>Type of Strategy</th>
<th>Type of Measurement</th>
<th>Measurement Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>Demand Capacity Strategy</td>
<td>local</td>
<td>occupancy measurement</td>
<td>upstream</td>
</tr>
<tr>
<td>ALINEA</td>
<td>local</td>
<td>occupancy measurement</td>
<td>downstream</td>
</tr>
<tr>
<td>AD-ALINEA</td>
<td>local</td>
<td>occupancy measurement</td>
<td>downstream</td>
</tr>
<tr>
<td>FL-ALINEA</td>
<td>local</td>
<td>flow measurement</td>
<td>downstream</td>
</tr>
<tr>
<td>UP-ALINEA</td>
<td>local</td>
<td>occupancy measurement</td>
<td>upstream</td>
</tr>
<tr>
<td>METALINE</td>
<td>coordinated</td>
<td>occupancy measurement</td>
<td>downstream</td>
</tr>
<tr>
<td>SWARM</td>
<td>coordinated</td>
<td>distance headway</td>
<td>upstream</td>
</tr>
<tr>
<td>Bottleneck Algorithm</td>
<td>coordinated</td>
<td>occupancy measurement</td>
<td>upstream</td>
</tr>
<tr>
<td>Zone Algorithm</td>
<td>coordinated</td>
<td>flow measurement</td>
<td>upstream</td>
</tr>
<tr>
<td>Helper Algorithm</td>
<td>coordinated</td>
<td>occupancy measurement</td>
<td>upstream</td>
</tr>
<tr>
<td>Advanced Real Time Metering System(ARMS)</td>
<td>coordinated</td>
<td>flow measurement</td>
<td>upstream, midstream and downstream(3 per section)</td>
</tr>
</tbody>
</table>
2.1.1 Demand Capacity Strategy

This strategy is widely implemented in the United States (Masher et al. 1975). It is based on comparing the demand volume ($q_{in}$) upstream of the ramp with the capacity of the bottleneck downstream of the ramp. Since flow measurement is not a reliable indicator of freeway congestion, occupancy measurements downstream of the ramps are often used. If this value is above a preset threshold, the freeway is considered congested and minimum metering rate $r_{min}$ is used:

$$r(k) = \begin{cases} 
Cap - q_{in}(k) & \text{if } O_{out} \leq O_{cr} \\
r_{min} & \text{otherwise}
\end{cases}$$

2.1.2 ALINEA

ALINEA (Asservissement Lineaired'Entree Autoroutiere), developed by Papageorgiou et al. (1991), adjusts the ramp metering rate in real time to keep the occupancy downstream of the ramp at a specific value (i.e. critical occupancy). This algorithm had multiple successful field applications such as Paris, Amsterdam, Glasgow, and Munich (Papageorgiou et al., 1997). In this strategy, the control parameter is based on downstream measurement since the main goal is to maintain capacity flow downstream of the ramp and is based on a feedback strategy:

$$r(k) = r(k - 1) + K_R[\hat{o} - o_{out}(k - 1)]$$

Where $r(k) =$ meter rate (volume) in time interval $k$

$K_R =$ tuneable parameter (weighting factor) greater than zero

$o_{out} =$ local occupancy at ramp (measured by one mainline detector)

$\hat{o} =$ Pre-defined occupancy value at capacity (or a desired occupancy maximum value) for the location

In many ramp metering strategies, the controller reacts in crude way to excessive occupancies after a threshold value ($O_{cr}$) is exceeded. However, ALINEA reacts smoothly even to slight differences $\hat{O} - O_{out}(k)$, which is shown to be effective in preventing congestion. Papageorgiou et al. (1991) have shown that extreme high values of $K_R$ may lead to oscillatory unstable behaviour. In other words, the higher the value of $K_R$ the stronger the regulator reacts.

Although ALINEA is able to maintain free flow conditions on the freeway, it creates long queues at the ramps close to bottleneck locations. However, there are several extensions to ALINEA strategy that addressed these concerns and also increase the efficiency of the algorithm. Some of these extensions are listed below:
2.1.3 AD-ALINEA

Smaragdis et al. (2004) have developed ALINEA strategy allowing automatic tracking of critical occupancy that might change in real time due to weather condition, or traffic composition.

Compared with the bottleneck capacity $q_{\text{cap}}$, the critical occupancy $O_{\text{cr}}$ was found to be less sensitive yet, $O_{\text{cr}}$ may not stay the same value due to different environmental conditions (darkness, rain, etc.) or traffic composition (e.g. percentage of trucks). In these cases it would be desirable to track the set values of $O_{\text{cr}}$ in real time by changing the values of $O_{\text{cr}}$.

AD-ALINEA designs an estimation algorithm that utilizes real-time measurements and attempts to produce estimates $O_{\text{cr}}(k)$ of the currently prevailing critical occupancy, for which the freeway flow $q_{\text{out}}$ is maximized. The $O_{\text{cr}}(k)$ estimated are then used as set values by the ordinary ALINEA strategy. The estimation algorithm for the real time critical occupancy first finds the derivative $D=dq_{\text{out}}/dO_{\text{out}}$ at $O_{\text{cr}}(k-1)$. If $D$ is sufficiently positive, the new estimate $O_{\text{cr}}(k)$ will be $O_{\text{cr}}(k-1)$ plus an increment $\Delta$ (e.g. $\Delta=1\%$) of the current critical occupancy estimate. In contrast, if $D$ is a negative, the increment will be subtracted from the current estimate.

2.1.4 FL-ALINEA

FL-ALINEA is another extension to ALINEA algorithm developed by Smaragdis and Papageorgiou (2003) based on downstream flow measurement instead of occupancy. Its formula is identical to the formula used for ALINEA, except that it measures flow, and tries to reach a set point flow rather than set point occupancy. When the occupancy is over the critical occupancy indicating that the freeway is already over capacity the metering rate is set to the minimum rate.

2.1.5 UP-ALINEA

When only upstream occupancy measurements are available, UP-ALINEA (Smaragdis and Papageorgiou, 2003) instead of ALINEA uses the occupancy upstream instead of downstream. The on-ramp flow entering the freeway is also required. This algorithm uses the following equation to estimate the downstream occupancy $O_{\text{out}}$ using the upstream occupancy, and incorporating the effects of the ramp traffic:

$$O_{\text{out}}(k)=O_{\text{in}}(k)[1+q_{\text{r}}(k)/q_{\text{in}}(k)]*\lambda_{\text{in}}/\lambda_{\text{out}}$$

$q_{\text{r}}$: measured ramp flow
$q_{\text{in}}$: upstream measured freeway flow
$\lambda_{\text{in}}, \lambda_{\text{out}}$: number of mainstream lanes upstream and downstream respectively.

Note that for the estimation of the downstream occupancy (or flow) based on upstream measurements: $q_{\text{out}}$ is assumed to be determined as: $q_{\text{out}} = q_{\text{in}} + q_{\text{ramp}}$.

The algorithm becomes identical to the traditional ALINEA.

2.1.6 X-ALINEA/Q Ramp Queue Control

X-ALINEA/Q is also developed by Smargdis and Papageorgiou (2003). In this algorithm, the formation of large queues on the metered ramps problem is addressed. The extension can be combined with other ALINA-based ramp metering strategies. Demand flow entering and ramp queue length measurements are also essential in this strategy. This algorithm first calculates the ramp metering rate in an identical fashion to the traditional ALINEA, and then minimum rate which keeps the ramp queue at or below the maximum allowable queue length is calculated and the maximum of these two rates are chosen as the ramp metering rate. By this adjustment the ramp metering rate will be acting more smoothly and can potentially control on-ramp queues.
formation rather than reactively taking action even with the presence of long on-ramp queues. One of the differences between traditional ALINEA and X-ALINEA/Q is that ALINEA uses a binary queue control algorithm, where once the queue rises above a certain threshold, ramp metering is completely suspended. X-ALINEA/Q, however, only increases the metering rate enough to maintain the maximum allowable queue length, in order to improve the mainline traffic flow as much as possible, without completely backing up the ramp traffic. (Scariza, 2003)

2.1.7 METALINE
METALINE (Papageorgiou et al. 1990) is an extension of ALINEA to a coordinated strategy where:

\[ r(k) = r(k - 1) - K_1 [O(k) - O(k - 1)] + K_2 [\hat{O} - O(k)] \]

- \( r = [r_1 \ldots r_m]^T \) vector of m controllable on-ramp volumes
- \( o = [o_1 \ldots o_n]^T \) vector of n measured occupancies on the freeway
- \( O = [O_1 \ldots O_m]^T \) a subset of \( o \) that includes m occupancy locations for which pre-specified set values \( \hat{O} = [\hat{O}_1 \ldots \hat{O}_m]^T \)
- \( K_1 \) and \( K_2 \): tuneable weighting factors for each ramp location

The main challenge in METALINE is to properly choose pre-specified values of \( K_1 \) and \( K_2 \) and the target occupancy vector. This information is vital for the successful operation of METALINE. (Zhang et al., 2001)

Papageorgiou et al. (1997) has compared the efficiency of ALINEA and METALINE and found METALINE has no advantages over ALINEA under recurrent congestion but performs better under non-recurrent congestion. However, METALINE is by far more difficult to set up and calibrate.

2.1.8 SWARM
SWARM (System Wide Adaptive Ramp Metering System) (Paesani et al., 1997) is a coordinated traffic responsive ramp metering strategy which was deployed on a number of freeways in Los Angeles. This strategy consists of two levels:
- SWARM 1 as a coordinated ramp metering that includes a traffic forecasting step
- SWARM 2 as local traffic responsive ramp metering.

Traffic conditions are forecasted in SWARM1 to determine the coordinated metering rates based on anticipated traffic density. Linear regression and Kalman Filter processes are used to determine the predicted density trend at each detector.

The target density for each metering cycle is calculated by:

\[ \text{Target Density} = \text{Current Density} - \frac{1}{T_{\text{crit}}} \times \text{Excess Density} \]

Where \( T_{\text{crit}} \) is used as a tuneable parameter for future time intervals. Excess density is identified if anticipated density is above saturation density. The volume reduction is calculated as:

\[ \text{Volume Reduction} = (\text{Local Density} - \text{Target Density}) \times \text{Number of Lanes} \times \text{Distance to next detector station} \]

The volume reduction value is then distributed to upstream ramps based one ramp demand, ramps queues, etc.

SWARM2 uses two functions, assigns metering rates based on distance headway measurements (converted to density) at the detector site just upstream from each metered ramp.
SWARM uses predicted volumes, rather than measured traffic conditions for locating the bottlenecks. Accordingly, the performance of SWARM is very sensitive to the accuracy of the predictions. (Zhang et al, 2001)

2.1.9 Bottleneck Algorithm

Bottleneck Algorithm (Jacobson et al., 1989) is a coordinated control strategy that was developed by Washington State Department of Transportation. Similar to SWARM, it has a two level structure: a local and a coordinated level. The local level compares freeway demand upstream and freeway capacity downstream in real time and accordingly sets local metering rates so that demand does not exceed downstream capacity. The coordinated level identifies the bottleneck and decides on the volume reduction and then distributes that reduction value to onramp meters upstream of the bottleneck. Bottleneck recognition has two conditions. First, the measured occupancy should exceed critical occupancy, second vehicle storage shortage should be satisfied which is:

\[ Q_{\text{red}} = Q_u + Q_{\text{on}} + Q_{\text{off}} - Q_{\text{down}} \geq 0 \]

Where \( Q_{\text{red}} \) = number of vehicles stored in the bottleneck section in past minute

\( Q_u \) = number of vehicles entering the section at upstream detector

\( Q_{\text{on}} \) = number of vehicles entering the section from onramp

\( Q_{\text{off}} \) = number of vehicles exiting the section from the off-ramp

\( Q_{\text{down}} \) = number of vehicles exiting the section at downstream detector

If \( Q_{\text{red}} \geq 0 \), number of vehicles stored in the bottleneck should be reduced.

The algorithm determines the amount of volume reduction from each upstream onramp based on weight factors. These weight factors are obtained based on: 1) the distance of each onramp from the bottleneck location and 2) demand pattern at the onramps. This algorithm is similar to SWARM but does not have prediction function. (Jacobson et al., 1989)

2.1.10 Zone Algorithm

Zone algorithm (Lau, 1997) divides the freeway into zones containing several metered and non-metered ramps. Zones can have variable length where the upstream end of each is a free-flow area and the downstream end is usually a critical bottleneck. The main objective of the algorithm is to balance the volume of traffic leaving the zone. The maximum volume that can enter the system within the zone is:

\[ M + F = (X + B) - (A + U) \]

Where

\( A \) = Upstream mainline volume (measured)

\( U \) = Sum of unmetered entrance ramp volumes (measured)

\( M \) = Sum of metered ramp volumes (controlled)
F = Sum of metered freeway to freeway ramp volumes (controlled)
X = Sum of exit ramp volumes (measured)
B = Downstream bottleneck capacity (constant – usually 2220 vehicles per hour per lane)

Based on the above equation and the historical peak-hour loop counts, the ramp metering rate - which is a lookup of six distinct rates from no metering to a cycle length of 24 seconds- is selected. (Lau, 1997)

2.1.11 Helper Algorithm

Helper algorithm (Lipp et al., 1991) has also two levels. At the local level, each meter selects one of six pre specified possible ramp metering rate, based on upstream mainline occupancy. If the ramp queue detector is activated, the ramp metering rate increases one level per time interval to clear the excessive ramp queues. At the coordinated level, the ramps are classified as not critical if they are not operating at the most restrictive rate and if the ramp queue detector is not activated. When ramp metering become and remain restrictive for three consecutive time interval, the ramp metering rate at the next upstream ramp reduces for one level. This process moves upstream until the problem is solved or all upstream ramps are overridden.

2.1.12 Linear Programming Algorithm

Implemented on the Hanshin Expressway near Kobe, Japan (Yoshino et al., 1995), this algorithm needs a very comprehensive data collection system with closely spaced detectors on mainline and multi point detectors on all entrance and exit ramps.

The algorithm uses real time data and pre-defined variables as well as some tuneable variables such as influence factor of historical O-D information for each unique combination of ramp inflow and downstream segment; and weight factors for each ramp as part of the objective function to allow for weighting ramp inflows. In the algorithms, the roadway is divided into h segments between i ramps. Detection of speed \( Y_h \) is used to calculate the real time capacity each section i. Queue length \( N_i \) is found from the ramp detectors; and historical or measured data is used as the demand \( D_i \). \( L_i \) is defined as maximum allowable queue length on the ramp based on the storage capacity of each ramp. \( Q_{hi} \) is being defined as a weight factor determined based on the traffic discharge from ramp i to section h. This weight is based on historical data. A is defined as weight factors for each ramp. This weight factor gives preference or discourages the use of a specific ramp. \( U_i \) is the flow at ramp i. The objective function is:

\[
Z = (A_1 * U_i) + (A_2 * U_2) + \ldots + (A_i * U_i)
\]

\[
ST: (Q_{main} * U_i) + (Q_{1h} * U_1) + (Q_{2h} * U_2) + \ldots + (Q_{ih} * U_i) \leq C_h \text{ for all segments } h
\]

\[
0 \leq U_i \leq N_i + D_i N_i + D_i - U_i \leq L_i
\]

\[
U_{min} \leq U_i \leq U_{max}
\]

This LP equation, is solved simultaneously for all ramp meters in the influence areas to maximize the metering rate for all meters. There is no direct communication between ramps; the only coordinated characteristic of the model is through this interaction of variables described above (Bogenberger and May, 1999).

2.1.13 Adaptive Fuzzy Algorithm

Fuzzy logic control is particularly very useful when an accurate system model is unavailable. Speed or traffic flow could be classified according to the "Level of service (LOS)"
concept as defined in the Highway Capacity Manual (HCM, 2000). Similarly, occupancy can also be classified in terms of LOS. These LOS classifications could be used as input data in the fuzzy model. The membership function for a particular function is a symmetrical triangle with the same width and with an overlap of 50%. The membership function for the output variable (as metering rate) could also be a triangular form with three different values: High, medium and low. In this method, the measured variables such as speed or flow is the inputs of the fuzzy controller. The value is then fuzzified, inferred and defuzzified to get a crisp output value which is the ramp metering rate.

Two fuzzy logic based ramp metering algorithms have been implemented, a coordinated approach in Seattle and a local responsive one in Zoetermeer in Netherlands. Both have been successful. The local responsive ramp metering showed to outperform other local ramp metering algorithms such as the well-known local responsive approaches ALINEA and Demand Capacity. (Bogenberger and May, 1999) Since fuzzy logic can handle the nonlinearity of the freeway system and the ability to control an unknown system, it has a great advantage to other traditional ramp metering controllers.

2.1.14 Dynamic Ramp Metering Model

The dynamic ramp metering model (Chen et al., 1997) has a local control and an area-wide control logic. Local control attempts to maintain traffic conditions close to the target traffic conditions that are provided by area-wide control (i.e. based on critical occupancy). The area-wide control adopts a rolling horizon based predictive control algorithm that minimizes total system travel time (i.e. travel time on freeway and delay on ramps). A state estimation and an origin destination prediction model have also been developed for estimating future travel demand.

2.1.15 Advanced Real Time Metering System (ARMS)

ARMS (Liu et al., 1993) is a proactive algorithm that incorporates a congestion risk factor into its formulation. The probabilistic congestion risk function describes the possibility of downstream congestion near future with respect to the entrance ramp. It predicts traffic conditions to detect potential bottlenecks formations. In the case of a bottleneck formation, the algorithm works to resolve congestion once it develops. The algorithm is based on mainline flow rate information.

2.2 DETECTION TECHNOLOGIES FOR TRAFFIC CONDITIONS

From the above literature, it is clear that most ramp metering algorithms optimize the traffic based on occupancy, approximate density or flow information measured in the vicinity of the ramp. However, traffic conditions in the proximity of ramps are not representative of the whole freeway section. Density or traffic flow readings from point detectors placed upstream or downstream of the ramps are not able to detect shockwave formation that can occur due to lane changing behaviour or to the presence of a slow moving vehicle. This may lead to a sub-optimal solution when using local information to design ramp metering strategies. If density is estimated over the whole freeway section, ramp metering formulation is able to optimize the traffic on the system from a network-wide perspective.

Data constantly provided by probe vehicles can estimate traffic conditions by continuously providing SMS information over all freeway sections. In addition, data from probes can reflect
the occurrence of shockwaves on a freeway section (i.e. due to lane changing behaviour). Cellular phone tracking is one of the available promising vehicle probe methods for the production of reliable network-wide travel time and speed information (Cayford, 2008). Today, more than four billion people carry mobile phones, and the number is continuing to rise (PA News, 2009). By 2012, the number of new mobile phones that will be location-enabled via built-in GPS receivers will have doubled (Sacco, 2010); and, these GPS-enabled cell phones are expected to be the primary navigation device for personal use by 2012 (Kim, 2010). Qui and Cheng (2007) underlined the promising role that mobile phone detection technology can play for the next generation of traffic data collection. However, there is still a great deal of controversial debate about the privacy issues surrounding extracting information from these probes.

Most of the research on probe vehicles is still focused on traffic state estimation and prediction. This research takes a further step and exploits the use of data derived from vehicle probes (and, in the future, from IntelliDrive) to develop ramp metering algorithms using data from probe vehicles to design advanced traffic control logic. Assuming that the privacy issues around extracting information from probes are resolved, this research assumes that the average speed of vehicles equipped with the GPS-enabled cell phones can be obtained during each time step interval and on each segment of the freeway separately. In what follows, the various traffic detection methods are reviewed and compared to the vehicle probe detection method.

2.2.1 Point Detection Technology

Point detection technology is currently the most widely used sensor in traffic detection systems. These sensors are mostly capable of measuring flow and occupancy, and are able to estimate speeds. They are also used to detect queues and vehicle presence for actuated traffic signals, as well as incident and congestion detections. Loop detectors are unable to measure directly the space mean speed (SMS) of vehicles. If SMS readings are required, then a two-loop speed trap should be employed (Sreedevi, 2007). Such estimates of SMS takes computes segment travel time from spot mean speed readings at the two point detectors rather than by tracking the accurate travel time of vehicles on the segment. On the other hand, point detectors have high life-cycle cost as associated with the installation, maintenance and communication costs.

Loop detectors, microwave radar and infrared are example of point detection technology. Loop detectors are flexible in design and can provide basic traffic parameters (e.g. volume, presence, occupancy, speed, headway and gap). These sensors have frequent failure. Sources of loop malfunction such as stuck sensors can produce incorrect data and may lead to inaccurate detection. Installation and maintenance of such systems necessitates lane closure and requires cut of pavement surface which decreases the pavement life. Microwave radars are generally insensitive to inclement weather and have the ability of provide direct speed measurements. However, in this technology it cannot detect the stopped vehicles since they require a vehicle to be moving or otherwise changing its signature characteristics with respect to time. The infrared technology transmits multiple beams for accurate measurement of vehicle position, speed and class but the operation of this sensor may be affected by blowing snow or fog when visibility is low (Mimbela and Klein, 2000).

Video image processors which are mainly used for surveillance can also be used to measure traffic. Video cameras monitor multiple lanes and zones and can provide wire-area detection when information gathered at one location can be linked to another. Video detection should be installed at 50 to 60 ft g height for optimum presence detection and speed
measurement. However, its performance is affected by inclement weather conditions and day to night transition. (Mimbela and Klein, 2000)

2.2.1 Probe Vehicle Detection Technology

The probe vehicle technology is used in Intelligent Transportation System (ITS) applications for real time traffic data collection. The term ‘probe vehicle’ in this report refers to a vehicle travelling on the network with its location and speed information collected in real time by the control center. Common probe vehicle systems include (Qui, 2007):
- Automatic Vehicle Location(AVL) in which probe vehicles communicate with transmitters mounted on existing signpost structure;
- Automatic Vehicle Identification(AVI) which consists of a vehicle equipped with electronic tags communicating with roadside transceivers for collecting travel time;
- Global Positioning System(GPS) probes that both receive and transmits signals from and to control center; and finally
- Cellular Probes that collect travel time data by discreetly tracking cell phones within cellular network, and traffic related information can be determined from these collected data

Today, more than four billion people carry mobile phones and the number is continuing to rise (PA News, 2009). The ubiquitous and location-enabled nature of mobile phones signifies that the mobile phone has moved from a pure communication tool to a networked mobile personal measurement device that makes it attractive for building large-scale network sensing systems using the phones as mobile sensor nodes. Qui and Cheng (2007) indicated the promising role that mobile phone detection technology can play for the next generation of traffic data collection.

Compared with other traffic data collection technologies, cellular phone technology has several advantages, especially for travel time or speed information, as highlighted by Qui (2007):

1) No in-vehicle equipment needs to be installed.
2) No volunteers or recruited drivers are required.
3) It has a potentially large sample size.
4) It has low deployment cost, since wireless carriers already have the monitoring system.

In addition, cellular technology has wider network coverage compared to the more localized coverage offered by loop detectors.

Sample size is an important parameter to be determined when using probe vehicles to collect real-time traffic information. Studies by Ferman et al. (2003) show that link travel speed and travel time distribution can be affected by many factors and the variance of probed vehicles within one time interval may be very large especially for arterial roadway use. May (1990) has suggested the following equation to calculate the required sample size based on macroscopic traffic flow theory:

\[ n = \left( \frac{t * S}{\varepsilon} \right)^2 \]

Where 
- \( n \) = required sample size 
- \( T \) = \( t \) distribution value of selected confidence level 
- \( S \) = standard deviation of travel speed values 
- \( \varepsilon \) = allowable error

It is, however, very important to note that the expressed equation assumes a perfect location accuracy. In other words, sample size should be larger than the calculated value from
above equation in practice since the location accuracy may not be perfect. A simulation study by Hsiao and Chang (2005) also shows that enough sample size, including larger vehicle generation rate, longer data collection interval, shorter location update interval, and larger mobile penetration rate are crucial factors to generate traffic information.

Many concerns have been raised around the privacy issues in collecting and using mobile phone based traffic information. To address these privacy issues, both cell tower and GPS-enabled cell phone methods replace identifiable information from the data with a randomly chosen identification (ID) through a process known as pseudo-anonymization. However, there are still some concerns about privacy, since apparently it is still possible to re-identify individuals from trajectory data (Herrera et al. 2009). However, others claim that the privacy issue is already resolved, since data is immediately disassociated from the phone and is combined with the general stream of traffic data (Gruteser and Grunwald, 2003).

2.3 DISCUSSION AND MOTIVATION

Most of the common traffic data collection methods and advanced control algorithms rely on roadside inductive loop detectors. These techniques are expensive to deploy and maintain, and they are not economically sustainable. These applications are also of limited utility as they provide only local information, such as flow or occupancy. As it was discussed, Cellular phone tracking is one of the most promising vehicle probe methods for the production of reliable network-wide travel time information (Cayford et al., 2008).

Data constantly provided by probe vehicles can estimate traffic conditions by continuously providing SMS information over all the freeway sections. Assuming that the privacy issues around extracting information from probes are resolved, this research exploits the use of the average speed of vehicles equipped with the GPS-enabled cell phones assuming that this speed data can be obtained during each time step interval on each segment of the freeway separately. This SMS data derived from vehicle probes is used as the main input parameters to formulate advanced ramp metering algorithms. This SMS probe-based data is then converted to density estimates using Van Aerde (1995) traffic flow model. This transition is due to using the Cell Transmission Model (CTM) proposed by Daganzo (1993). CTM is uses these density estimates for a short term state prediction model for the next time steps. The formulated ramp metering algorithms minimizes the total delay experienced by all vehicles in the system based on the ramp metering rate on the on-ramps.
Chapter 3. FRAMEWORK FOR THE PROBE-BASED PROACTIVE RAMP METERING APPROACH

This chapter describes the developed probe-based proactive ramp metering framework. Although this framework is mainly formulated as coordinated ramp metering, it can be configured to be also applicable to local ramp metering strategy. The developed approach exploits information on speed data over the whole freeway network as the main input parameters to the ramp metering control algorithm. This speed data is continuously provided by vehicle probes that are assumed to disseminate at a specified time interval their Space Mean Speed (SMS) information. Density estimates are then obtained over the entire freeway by using a traffic flow model. Shockwave formations and locations are also identified and included in the algorithm. The Cell Transmission Model (CTM) and shockwave analysis are used to predict the travel time on the freeway. Delays on the ramp are obtained based on deterministic queuing theory. Thus, the developed algorithm computes the optimal ramp metering rates based on minimizing the total system travel time that includes: 1) the travel time on the freeway upstream and downstream of the ramp and 2) the wait time on the ramps over an extended horizon. Therefore, a rolling horizon framework was formulated to estimate the optimal ramp metering rates for the next time intervals. Thus, only the ramp metering rates corresponding to the earlier time step are considered final and implemented.

3.1 DEVELOPED FRAMEWORK AND PROBLEM FORMULATION

Figure 3.1 shows a simple freeway network divided into various sections. As the figure shows, traffic detectors are only installed on the on-ramps and no detectors are installed on the main freeway. The traffic condition on the freeway is thus only monitored by vehicle probes that disseminate continuously their speed information. The average speed of probe vehicles over the entire time step, , on each section, , of the freeway are obtained as an estimate of space mean speed (SMS). In this research, a time step of the order of 30 seconds or 60 seconds is adopted.

Initially, at the beginning of each time step, each section (i) of the freeway is assumed to have homogenous traffic conditions. Current and future traffic conditions at each section are estimated for the next five time intervals, , ..., , after getting an update of probe vehicles speed data on the freeway at current time step, .

Figure 3.1 Schematic view of a freeway segment with the ramp metering control algorithm

A rolling horizon based traffic prediction model was developed to model the flow propagation on the downstream sections of the freeway for the next estimation time interval.
Thus, optimal ramp metering rates that minimize the predicted network travel times and delays over the next times steps \((t, t+1, \ldots \text{ and } t+5)\) on each on-ramp, \(r\), are obtained based on the forecasted traffic condition on the freeway. In other words, the predicted delays that are likely to be experienced over the next five steps of the future time horizon are estimated first and used to determine the optimal ramp metering algorithms over the next time steps. However, only ramp metering rates corresponding to the earlier time step, \(t+1\), are considered final and implemented. The remaining steps are re-estimated in the succeeding estimation steps in a rolling horizon fashion as illustrated in Figure 3.2.

![Figure 3.2 Rolling horizon estimation](image)

Traffic conditions for the future time steps are predicted based on the Cellular Transmission Model (CTM) developed by Daganzo (1993). CTM can be used to predict traffic’s evolution over time and space, including transient phenomena, such as the building, propagation and dissipation of queues. In addition, the ramp metering algorithm checks for the occurrence of a possible back propagating shockwave which results from a sudden increase of flow and density on the freeway because of traffic discharged from the on-ramps (Lighthill and Whitham 1955).

As described next, optimal ramp metering rates, allow vehicles to enter the freeway at a rate ranging between 3 to 15 vehicles per minute as the minimum and maximum ramp metering rates, respectively.

In summary, the developed framework consists of nine major steps as depicted in Figure 3.3.
In the first step, the SMS data are extracted from probe vehicles (or in future from IntelliDrive) on each freeway segment and for each time interval. Accordingly, densities and flows at each section of the freeway are estimated based on these SMS data using Van Aerde’s (1995) traffic flow model as follows:

$$k = \frac{1}{C_1 + \frac{C_2}{U_f - U} + C_3 \cdot U}$$

$$q = \frac{U}{C_1 + \frac{C_2}{U_f - U} + C_3 \cdot U}$$

Where  $C_1 =$ fixed distance headway constant
$C_2 = \text{first variable distance constant}$

$C_3 = \text{second variable distance headway constant}$

$U_f = \text{free flow speed}$

$U = \text{average SMS speed as obtained from vehicle probes}$

The second step estimates the traffic condition based on the CTM developed by Daganzo:

$Y_i(t) = \min\{K_{i-1}(t) \cdot L_{i-1}, C_i(t), (N_i(t) - K_i(t)) \cdot L_i\}$

where $N_i(t) = \text{jam density at section i in time step t}$

$C_i(t) = \text{capacity at section i in time step t}$

$K_i(t) = \text{density at section i in time step t}$

$Y_i(t) = \text{number of vehicles transferring from section i-1 to i in time step t}$

$L_i(t) = \text{length of section i}$

The above CTM equation states that the number of vehicles ($y_i(t)$) that can travel from section i to section i+1 (Figure 1) for the next time step are the minimum of either:

1. The number of vehicles that exited the upstream section, $K_{i-1}(t) \cdot L_{i-1}$;

2. The capacity of the next section, $C_i(t)$; or

3. The amount of current empty space (i.e. number of vehicles) available at the downstream segment, $(N_i(t) - K_i(t)) \cdot L_i$.

The density for the next time step ($K_i(t+1)$) is equal to the density during the current time step plus the inflow of traffic minus the outflow of traffic:

$K_i(t+1) = K_i(t) + Y_i(t) - Y_{i+1}(t)$

For sections where an on-ramp joins the freeway, the number of vehicles discharged from the on-ramp to the freeway is also added to the density for that section. Similarly, for sections where an off-ramp is connected to the freeway, a split fraction of the density is subtracted based on the off-ramp demand.

In the third step, any potential back propagating shockwaves on the freeway sections are constantly checked. In case of no occurrence of back propagating shockwaves, the delay on the whole freeway is computed based on the predicted flow and density segments obtained in previous steps and are estimated as:

$\text{Freeway Travel Time}_{section i}(t+1) = \frac{L_i}{V_i(t+1)}$

Where $L_i = \text{length of section i}$

$V_i(t+1) = \text{predicted speed}$

However, in the case of presence of shockwaves, the speed of the shockwave between two consecutive sections (i and i+1) is calculated as:

$WS_{ij} = \frac{Q_j - Q_i}{K_j - K_i}$

Where $WS_{ij}$ is the speed of the shockwave between sections i+1 and i

$Q_i$ is the flow rate on section i
and $K_i$ is the density on section $i$.

The location of the shockwave is then estimated; and, the delay on the freeway is calculated based on the length of the new segments with uniform traffic patterns as identified by shockwave formation, rather than the fixed segment locations initially presented by CTM. These delays estimated by shockwaves are taken into consideration in the problem formulation that computes the optimum ramp metering rates in step 6.

The fourth step assigns a different weight, $W_i$, to every freeway section, as based on prevailing traffic conditions of that particular freeway section. These weight factors represent the number of vehicles on each freeway segment. The purpose of these weights is to draw more attention to the sections of the freeway experiencing critical congestion. These weights are also considered in step 6 as part of the problem formulation. These weights are dynamic and are computed for each section of the freeway and for every time step separately as:

$$W_i(t) = K_i(t) \times L_i$$

Where $W_i$ = weight factor for section $i$
$L_i$ = Length of section $i$

Figure 3 shows an example of a possible back propagating shockwave changing the traffic condition of the freeway network in a given time step. Each colour is associated with a different traffic condition. Thus, the travel time estimation is based on the new traffic condition, if any back propagating shockwave is being anticipated.

![Figure 3.4 Example of back propagating shockwave of i due to an increase in flow and density from on-ramp](image)

An example of the formulation for the shockwave effect on section $i+1$ is illustrated in the following equations. The formulation is set up in a way that checks the shockwave effects from the most downstream section toward the most upstream. In the case of an occurrence of a back propagating shockwave, the new locations of segments with uniform traffic patterns are calculated based on the shockwave speed. The travel time and weight factors for the segments are obtained based on the updated freeway segment traffic information.

If (a back propagating shockwave exists on section $i$) then

\[
\begin{align*}
S_{i+1} &= \frac{q_{i+1} - q_i}{k_{i+1} - k_i} \times \text{Time step} \\
L_{i+1} &= S_{i+1} + L_{i+1}
\end{align*}
\]

Travel Time \text{section } i+1(t + 1) = \frac{L_{i+1}}{V_{i+1}(t + 1)}

$W_{i+1}(t) = K_{i+1}(t) \times L_{i+1}$

Where $S_i$ is the location of section $i$ and $L_i$ is the length of section $i$.

In the fifth step, the vehicular delay on each on-ramp is estimated based on:
Predicted delay for the next time interval with a ramp metering rate of \( r \), and
2. Cumulative delay previously experienced by the vehicles.

The current vehicle demand on the on-ramps is obtained from the detectors placed on each ramp (Figure 3.1). The difference between the number of vehicles allowed to enter the freeway during the next time step and the demand arriving at the on-ramp, plus a possible residual queue on the ramp from previous time steps (if not yet served), would be used to predict the delay on the ramp. If this figure is less than zero with the associated ramp metering rate, the delay at ramp will also be set to zero.

\( D \) is number of vehicle entering the on-ramp during the last time step. This value is obtained by the detectors placed at the on-ramps. The current demand is the summation of the vehicle arrival during the past time step plus any vehicle queue left from the previous time steps. The current demand minus the ramp metering rate \( R \) for next time step will form the queue length (i.e. number of vehicles in the queue). The queue length is saved and used for the calculation of the ramp metering rate (i.e. to calculate the wait times in the queue with alternative ramp metering \( R \)). When the optimal ramp metering rate for the next time step is chosen, the remaining queue of vehicles and the queue length created with the chosen ramp metering rate, will be kept for delay estimation and queue length for the next time step iterations. If the queue length at the on-ramp on a time step reaches zero, the remaining delay will also be set to zero for next time step.

The equation below shows the detailed estimation of delay on the ramp used in the formulation of the ramp metering strategy. The discrepancy between the number of vehicles allowed to enter the freeway during the next time step with the demand arriving at the on-ramp, plus a possible cumulative queue on the ramp from previous time steps (if not yet served), would determine the predicted delay on the ramp. If the discrepancy is less than zero with the associated ramp metering rate, the delay at ramp will also be set to zero.

\[
If (\text{Ramp Metering Rate} \times \text{Time Step} \leq D + \text{Cumulative Queue on Ramp}) \quad \text{then} \\
\{\text{Delay on Ramp} = (D + \text{Cumulative Queue on Ramp} - \text{Ramp Metering Rate} \times \text{Time Step}) \times \text{Cumulative Delay on Ramp}\} \\
\text{else} \\
\{\text{Delay on Ramp} = 0\}
\]

\( D = \text{Number of vehicles arrive to the ramp during the last interval} \)

In the sixth step, the integral coordinated ramp metering strategy is obtained by optimizing a weighted bi-objective function, \( Z \), which consists of minimizing two criteria \( Z_1 \) and \( Z_2 \) as:

- \( Z_1 \) minimizes the total travel time on the freeway system and is expressed as:

\[
Z_1 = \sum_{i=1}^{\text{Number of Freeway segments}} W_i(t) \times \text{Travel Time}_i (t + 1)
\]

- \( Z_2 \) minimizes the delay for the vehicles waiting to be served on the on-ramps as follows:
The objective function is also subject to an additional constraint that restricts queues on the on-ramps in reaching the surface street network. If the queue detector identifies that the queue on the ramp is at an upstream intersection, the ramp metering rate will change to its maximum rate (i.e. 15 vehicles per minute).

The algorithm estimates the total anticipated delay for a certain time horizon using brute force. In other words, all possible combinations of ramp metering rates in the system model are examined. Due to the high computational efficiency of recent computer processors, this process takes less than 3 seconds to complete. A more advanced optimization search method can be used in the future, if the number of combinations is increased.

It is to be noted that the described framework is applicable to both local and coordinated ramp metering strategies. A local ramp metering algorithm can be implemented by following the same steps described in Figure 3 with the exception of the rolling horizon step.

3.2 CONCLUSION AND SUMMARY

This chapter presented a novel integral coordinated ramp metering strategy taking as main input speeds data from vehicle probes. The algorithm computes the optimal ramp metering rates based on minimizing the system travel time, including both the travel time on the freeway and the wait time on the ramps over an extended horizon. Thus, a rolling horizon framework is formulated to estimate the optimum ramp metering rates for the next time intervals however, only the ramp metering rates corresponding to the earlier time step are considered final and implemented. The developed model also adopts a dynamic weighting scheme that gives different weights in the objective function to different freeway sections. These weighting schemes are updated dynamically at every estimation step, based on the prevailing densities of the freeway sections. The developed algorithm uses the Cell Transmission Model and shockwave analysis to predict the travel time on the mainline. It also uses queuing analysis to estimate the delay for the on-ramp. The prevailing traffic condition on the freeway mainline is estimated directly from vehicle probes. In Chapter 4, the developed probe-based ramp metering approach is rigorously tested and various experiments are conducted to examine the performance of the approach with various congestion levels. In addition, sensitivity to various probe-based ramp metering input parameters is examined.
Chapter 4.  CASE STUDIES, RESULTS AND SENSITIVITY ANALYSIS

In this chapter, the developed algorithm is analyzed on a simulated network in Quadstone PARAMICS microsimulation software to assess its potential for reducing travel times and improving speed as compared with the case of no ramp metering. PARAMICS Analyser is used to calculate all the performance measures (e.g. travel time, delay, densities and etc). The developed coordinated proactive ramp metering algorithm is tested on a simulated real network. These measurements from PARAMICS Analyser is based on trajectory of all the vehicles during the simulation on the study area and is not from detectors or probe vehicles used in simulation. A sensitivity analysis is also conducted to examine the performance of the developed algorithm for various congestion levels, estimation steps, and percentages of vehicle probe penetration rate.
4.1 COORDINATED RAMP METERING

4.1.1 Description of the Network

The developed algorithm was tested using Quadstone PARAMICS microsimulation software package. The experiments were conducted on 8 km southbound section of Deerfoot Trail (Highway 2) in Calgary, Canada. As shown in figure 4.1, the study area extends from McKnight Boulevard to Memorial Drive and includes four on-ramps.

![PARAMICS simulation model of the study](image)

The PARAMICS simulation model was coded based on the data provided by the City of Calgary as related to detailed geometry, speed limits, curves, number of lanes, etc. Using PARMICS Estimator module, an outdated 2001 Origin/Destination trip tables was then updated based on recent traffic counts available from Alberta Transportation (2009) for A.M. peak hour traffic.
An application programming interface (API) was developed in PARAMICS software to extend the functionality of the package in extracting the data and in implementing and testing the developed algorithm. The southbound freeway was divided into eight sections for south bound traffic. The developed API takes all speed information from probe vehicles that were tracked on those sections. As in the local ramp metering case, by using the vehicle types to define these probe vehicles the percentage of probe vehicles can be easily changed through the PARAMICS interface. The speeds for individual probe vehicles were taken at every simulated second, and the average speed of each section was computed at the end of time step. These inputs were converted to section densities using Van Aerde model and were then fed to the optimum ramp metering algorithm. The developed API is also able to dynamically change the light cycle on the ramp in PARAMICS to match that optimal rate.

4.1.2 Simulation Results

The performance of the probe-based ramp Algorithm is tested for AM traffic over 80 minutes. The first 20 minutes simulation was considered as warm-up period and was thus discarded from the analysis. The performance of the developed ramp metering algorithm is measured by comparing the following Measure of Effectiveness of the ramp metering case with the no-ramp metering case:

1. Mainline Delay which is the time difference between the free flow and current travel time on the freeway sections (sec).
2. Mainline Density: which computes the density on the freeway (veh/km)
3. Mainline Speed: which computes the average speed on the freeway (km/hr)

Each scenario corresponds to the average of 10 PARAMICS runs with different random seeds. In addition, all the analysis compares the results of 2 scenarios: a probe-based ramp metering scenario with a no-ramp metering scenario.

The results of the runs showed a significant improvement in the traffic condition under the coordinated ramp metering control. In general, a 25% decrease in travel time, 7% decrease in density and 8% increase in average speed were observed on the freeway as a result of implementing the developed ramp strategies. Figures 4.2 and 4.3 compare the densities on the freeway next to the 4 ramps for the no-ramp scenarios and the coordinated ramp scenarios respectively. As the figure illustrates, the implementation of the proposed ramp metering algorithm was effective in smoothing the densities on the freeway and less fluctuations in the values of densities are obtained.
Figure 4.2 lane density of the freeway during time under no ramp metering control

Figure 4.3 Average lane density of the freeway during time under probe based ramp metering control

Figure 4.4 illustrates the percentage difference in delays for the two examined scenarios (i.e. without and with ramp metering control scenarios). The results show again the robustness of the
developed proactive ramp metering strategy in decreasing the delays on the Freeway. This is especially noticeable on the freeway sections around McKnight Blvd and 16th Avenue Ramps where high traffic congestions are present in the no ramp metering scenario. However, Figure 4.4 shows mixed results for the changes in % delays on the freeway around Memorial Dr Ramp. Increased delays are even shown around simulation time of 50 min. This rather increased delay might be explained by the effect of coordinating the 4 on-ramp meters in the study area. Due to the heavy congestion on the freeway downstream of McKnight Blvd Ramp, the ramp metering rates on these merges are more restrictive. However, for both with and without ramp metering scenarios, the congestion level on the freeway around Memorial Dr. Ramp is comparatively lower than the other parts of the freeway network. Thus, more traffic seems to be diverted from McKnight Blvd. to the parallel roads, i.e. Barlow Tr. and Edmonton Tr., shown on Figure 4.4 to avoid the long time wait on McKnight Ramps. This diverted traffic would enter the freeway, at later points, including Memorial Dr. Ramp which has less restrictive ramp metering rate. There has to be increased diversion from McKnight ramp to 32 Ave and 16 Ave ramps as well. However, as these ramps are still congested it is expected that some traffic will be taking McKnight ramp. This is likely resulting in an increase average delay on this specific part of the freeway for some simulation interval. However, overall over the whole length of the simulation interval the percent difference in delays is still being reduced on the freeway around this ramp.

![Figure 4.4 Delay percentage difference under ramp metering and no control](image)

**4.1.3 Sensitivity Analysis to Various Algorithm Parameters**

In this section, as in the isolated ramp metering case, a sensitivity analysis is conducted to examine the performance of the developed algorithm for: 1) four different percentages of market share for the vehicle probes and 2) two different estimation time steps. The results of the tests are reported next.
4.1.3.1 Impact of Market Share

In these runs, seven different penetration rates were examined: Table 4.1 summarizes the results of the simulation for the different penetration rates. Although the results show that the strategy’s effectiveness does not significantly change with the larger market share of probe vehicles; however, the difference in the improvements are significant at the low percentages of market share. Even at a market share of vehicle probes as low as 1%, the algorithm seemed to outperform no control scenario in terms of delay and travel time although their performance measure values are very close.

<table>
<thead>
<tr>
<th>No Ramp Metering Control</th>
<th>Network wide Delay (sec per vehicle)</th>
<th>Network Wide Travel Time (sec per vehicle)</th>
<th>Mainline Average Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Probes Based Ramp Metering</td>
<td>480</td>
<td>1106</td>
<td>79</td>
</tr>
<tr>
<td>40% penetration</td>
<td>408</td>
<td>1030</td>
<td>82</td>
</tr>
<tr>
<td>30% penetration</td>
<td>415</td>
<td>1037</td>
<td>80</td>
</tr>
<tr>
<td>20% penetration</td>
<td>419</td>
<td>1042</td>
<td>81</td>
</tr>
<tr>
<td>10% penetration</td>
<td>416</td>
<td>1038</td>
<td>81</td>
</tr>
<tr>
<td>6% penetration</td>
<td>406</td>
<td>1032</td>
<td>80</td>
</tr>
<tr>
<td>3% penetration</td>
<td>425</td>
<td>1050</td>
<td>80</td>
</tr>
<tr>
<td>1% penetration</td>
<td>477</td>
<td>1102</td>
<td>78</td>
</tr>
</tbody>
</table>

Table 4-1 Comparison of no control with different probe penetration rate under probe based ramp metering

4.1.3.2 Impact of Time Step Intervals

The developed ramp metering algorithm was also examined under two different time step intervals as the estimation steps: 30 and 60 seconds. The results are reported in Table 4.2 and show that overall the algorithm was more effective with a 30-second time step interval. The results show that the traffic condition and its optimal ramp metering rate are quite sensitive to the time step interval and would show improvement when the ramp metering algorithm runs at a more frequent time update. One possible explanation for the higher performance of the 30-second update, compared to the 60-second update, may be attributed to the fact that a more frequent update of the ramp metering rate plays an important role in smoothing traffic on the freeway because of a more frequent estimation and prediction of the traffic state condition.
4.1.4 Impact of Congestion level

The goal of this experiment is to investigate the impact of congestion level on the performance of the probe-based ramp metering algorithm. In these experiments, the network was loaded at five different congestion levels that represent: moderate congestion (i.e. 85% of current demand), congested network (which represents recurrent congestion i.e. calibrated demand) and three higher congestion levels (i.e. 110%, 120% and 130% of recurrent congestion). These latter high congestion levels would represent possible occurrence of different levels of non-recurrent congestion.

Table 4.3 summarizes the results of the five scenarios. These results summarize the averages of the 5 simulation runs corresponding to different seed values.

As shown in Table 4.3, for both moderate congestion and recurrent congestion scenarios, the probe-based ramp metering algorithm is shown to be effective in improving the freeway conditions by increasing the average speed on the freeway by 5% and by reducing the average delay on the freeway (by 28% and 23% for moderate and congested scenarios respectively). The comparatively low standard deviation values for the simulation runs, as shown in Table 4.8, indicates the reliability of the algorithm and its ability to increase the reliability of travel times on the freeway.

For the three higher congestion scenarios that represent various non-recurrent congestion levels, the results also show that the ramp metering strategies are capable of successfully managing the freeway amid the high congestion. The results show that, depending on the congestion level, the resulting improvements in speed on the freeway range from 7% to 10% as compared to the no-ramp metering case. In addition, the resulting reductions in delay on the freeway range between 14% to 26% also depending on the congestion level examined.

These results show the robustness on the ramp probe-based ramp metering algorithms in responding effectively to both recurrent and non-recurrent congestion. That is mainly attributed to two characteristics of the algorithm: it continuously checks for the location of shockwaves and then draws the attention of the algorithm to these sections of the freeway experiencing critical congestion (i.e. higher density than the neighbouring section). In addition, the probe-based ramp metering algorithm identify future bottleneck locations based on its traffic prediction algorithm.
which allow proactive actions be taken to prevent traffic congestion rather than cope with it after it has already occurred.

<table>
<thead>
<tr>
<th>Congestion Levels</th>
<th>No Ramp Metering Case</th>
<th>Ramp Metering Case</th>
<th>% Improvements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Description</td>
<td>% demand as</td>
<td>Average Speeds</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td>compared to</td>
<td>(km/hr)</td>
<td>densities</td>
</tr>
<tr>
<td></td>
<td>Base scenario</td>
<td>(veh/km/ln)</td>
<td>(veh/km/ln)</td>
</tr>
<tr>
<td>Moderate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>congestion</td>
<td>80%</td>
<td>88</td>
<td>47</td>
</tr>
<tr>
<td>Scenario:</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Base Scenario:</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>current</td>
<td></td>
<td></td>
</tr>
<tr>
<td>congestion</td>
<td>100%</td>
<td>74</td>
<td>129</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Various Levels of</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>High</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Congestion</td>
<td>110%</td>
<td>67</td>
</tr>
<tr>
<td></td>
<td>Scenarios</td>
<td>120%</td>
<td>64</td>
</tr>
<tr>
<td></td>
<td>130%</td>
<td>63</td>
<td>225</td>
</tr>
</tbody>
</table>

Table 4-3: Ramp Metering performance under different congestion levels

4.1.5 Impact of adverse weather condition: case study of heavy snow conditions

The goal of this experiment is to examine the flexibility and expandability of the algorithm to account for more complex situations encountered on the freeway system. Adverse weather conditions have been shown to have a substantial impact on traffic flow operations and on road capacity. Given the climate of the City of Calgary, the capacity of the road network is often deteriorated due to heavy snow precipitation.

Drop in links’ characteristics of free-flow speed, speed limits, or capacity due to snowy road condition can be incorporated in PARAMICS by activating the adverse weather condition option. That option needs details on the precipitation height and visibility reduction. The parameters adopted in these tests are

Literature indicated that snowy and slushy road conditions have a significant impact on capacity and speed reduction. The Highway capacity Manual (2000) suggests that for a freeway operating at 120 km/hr as free flow speed, drop in capacity can reach up to 30% and reduction in free flow speed by 50 km/hr can be due to heavy snow conditions under heavy snow condition. Thus, in this experiment, to reflect that special adverse road condition, the probe-based ramp metering algorithm was modified by dropping the free flow speed, jam density and capacity of the freeway by 20%.

Table 4.4 summarizes the results of the 5 runs for both the no-ramp metering and ramp-metering cases. The results show that the ramp metering has little impact in improving the speeds on the freeway (only 1% improvement). These minor improvements are likely due the predominance of slow moving vehicles resulting from snowy road conditions. However, the resulting 3% reduction in density indicate that the ramp metering is still capable of effectively smoothing traffic over the entire freeway section with a lower average density amount. The uniform distribution of densities on the freeway is likely resulting from the ability of the ramp meters to suppress the shockwave formation resulting from the presence of slow moving vehicles. That is also expected to reduce the occurrence of incidence under such adverse road weather condition.
On the other hand, Table 4.4 shows a significant improvement in delays (an overall average of 30% reduction). That decrease in the freeway delays shows that despite the little improvements in speed encountered by vehicles, the overall mainline conditions improve significantly enough to counter these delays reductions and improve the overall freeway travel time.

Thus in summary, this experiment show the limitations of the probe-based ramp metering in improving the speed on the freeway when the freeway is experiencing a significant drop in capacity. Nevertheless, the results indicate that the algorithm is still capable to reduce delays and densities. That shows the flexibility and the expandability of the algorithm to account for such complex situations resulting in significant drop in road capacity.

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>No Ramp Metering</th>
<th>Ramp Metering</th>
<th>% Improvements under Snowy Road Conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Speed</td>
<td>Average Value</td>
<td>34.8</td>
<td>35.2</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>1.31</td>
<td>1.28</td>
</tr>
<tr>
<td>Delay</td>
<td>Average Value</td>
<td>168</td>
<td>118</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>17.59</td>
<td>30.98</td>
</tr>
<tr>
<td>Average Density</td>
<td>Average Value</td>
<td>36</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td>Standard Deviation</td>
<td>1.87</td>
<td>1.78</td>
</tr>
</tbody>
</table>

Table 4-4: Ramp metering performance under adverse roadway conditions (heavy snow)

4.1.6 Impact on Parallel roads

As shown in Figure 4.1, the simulation model includes two main roads parallel to Highway 2: Barlow trail and Edmonton trail. Implementation of Ramp metering can potentially impact the traffic condition on these roads due to the diversion. Although it is difficult to accurately predict the travel behaviour of the network users by such an implementation, micro simulation can show a possible results of these changes by updating the cost tables based on the travel times of different routes. Within PARAMICS driver’s choice of route through the network is governed by the information held in Cost Tables. Cost Tables are used to effect the route-choice decisions of each vehicle within the network at key times during the simulation (Paramics Modeller, 2010).

The simulation results shows that ramp metering implementation does not significantly affect the traffic condition on these roads. Table 4.5 and 4.6 summarize the results by comparing the no control and probe based ramp metering control for both Barlow Trail and Edmonton Trail respectively.

<table>
<thead>
<tr>
<th></th>
<th>Delay (sec)</th>
<th>Density (veh/km/ln)</th>
<th>Speed (km/h)</th>
<th>Travel Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ramp metering</td>
<td>196</td>
<td>36</td>
<td>35</td>
<td>270</td>
</tr>
<tr>
<td>Probe based metering</td>
<td>193</td>
<td>36</td>
<td>35</td>
<td>268</td>
</tr>
<tr>
<td>Percent difference</td>
<td>-1.1</td>
<td>0.2</td>
<td>0.4</td>
<td>-0.8</td>
</tr>
</tbody>
</table>

Table 4-5 MOE comparison of ramp metering and no control on Barlow Trail
<table>
<thead>
<tr>
<th></th>
<th>Delay(sec)</th>
<th>Density(veh/km/ln)</th>
<th>Speed(km/h)</th>
<th>Travel Time(sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>No ramp metering</td>
<td>194</td>
<td>36</td>
<td>35</td>
<td>268</td>
</tr>
<tr>
<td>Probe based metering</td>
<td>189</td>
<td>36</td>
<td>35</td>
<td>263</td>
</tr>
<tr>
<td>Percent difference</td>
<td>-2.6</td>
<td>0.2</td>
<td>0.1</td>
<td>-1.9</td>
</tr>
</tbody>
</table>

Table 4-6 MOE comparison of ramp metering and no control on Edmonton Trail

These results show that ramp metering implementation, does not result in significant changes in the traffic condition on these parallel roads.

4.2 CONCLUSION

This chapter presented the simulation results of novel integral proactive ramp metering strategy for both local and coordinated fashion taking as main input speeds data from vehicle probes.

The ramp metering algorithm showed overall improvement in traffic condition (i.e. average travel time, flow and speed) on the freeway and network-wide for arbitrary demands when implemented locally. The results of the analysis indicated a superior performance of the algorithm under high and medium traffic conditions on both the ramp and on the freeway and for high demand of the freeway and moderate demand on the ramp. As expected, no improvement was shown for the case of high demand on the ramp and moderate demand on the freeway. The sensitivity analysis for various penetration rates of the vehicle probes showed that the developed algorithm becomes more effective with increased penetration percentages. Finally, the simulation results showed that the developed algorithm performs better when the data is updated in 30-second time steps, compared to 1-minute intervals.

The developed coordinated ramp metering algorithm was tested using Quadstone PARAMICS microsimulation software on 4 on-ramps on Highway 2 in Calgary, Canada. Sensitivity analysis was also conducted to examine the impact of different estimation step intervals. The results showed an overall improvement in traffic condition on the freeway during AM peak congestion. Finally, the simulation results showed that this new ramp metering algorithm performs better with more frequent algorithm update.

Chapter 5 compares the results of the new probe-based ramp metering with 2 ramp metering strategies: a pre-timed and a detector-based strategy.
Chapter 5. COMPARATIVE ANALYSIS OF PROBE BASED WITH DETECTOR BASED AND PRE-TIMED RAMP METERING

In this chapter, the probe-based adaptive ramp metering described in chapter 3 has been compared with a detector-based algorithm and pre-timed ramp metering algorithms, using Quadstone PARAMICS microsimulation model. The comparative analysis of the three ramp metering approaches was again conducted on the same case study described in chapter 4 which consists of 8 km freeway section on Highway 2 in Calgary, Alberta, Canada. The performances of the algorithms were examined and compared, in terms of freeway and system delays, densities and speeds. A sensitivity analysis has also been conducted to compare the performance of the developed probe-based approach for different percentages of market share of probe data (i.e. number of vehicles acting as probes).

The performance of the developed ramp metering algorithm was measured by comparing the following measures of effectiveness:

1. Mainline delay, which is the time difference between the free flow and current travel time on the freeway sections (sec);
2. Mainline density, which computes the density on the freeway (veh/km/lane);
3. Mainline speed, which computes the average speed on the freeway (km/hr);

Three scenarios were developed and compared for the same morning traffic condition:

1. Pre-timed RM,
2. Detector-based RM,
3. Probe-based RM.

Each of the above-examined scenarios corresponds to the average of 5 PARAMICS runs with different random seeds. The same set of random seeds was used for the simulation of different scenarios. All scenarios are compared with a probe-based ramp metering scenario.

For the probe based ramp metering scenarios, the freeway section of the study area was divided into eight sections. In the detector-based ramp metering scenario, eight point detectors were added in PARAMICS. A detector is placed at each section: one upstream and one downstream of each on-ramp. It should be noted that the detector-based strategy adopts the same objective formulation and same steps as its probe-based counterpart with the exception of skipping the derivation of density from the Van Aerde traffic flow model. Density readings are directly extracted from the links that have point detectors placed upstream and downstream of each on-ramp. These density readings are taken from PARAMICS by defining short links (around 10 meters) on the location of the detectors and obtaining the density information from the links during each time step.

In the probe-based algorithm, a given market share percentage of probe vehicles disseminating speed information was defined at the beginning of the simulation. For the probe-based ramp metering scenarios, a market penetration rate of 40% for vehicle probes was assumed. In other words, the system can track speed information from 40% of vehicles. The speeds for individual probe vehicles were taken at every simulated second, and the average speed of each section (i.e. space mean speed) was computed at the end of the time step (which was considered as 30 seconds in all runs). These inputs were converted to section densities and were then fed to the optimal ramp metering algorithm as described previously. The developed API is
also able to dynamically change the traffic light cycle on the ramp in PARAMICS to match that optimal rate.

5.1 COMPARISON WITH THE PRE-TIMED RAMP METERING SCENARIO

Figures 5.1 and 5.2 show the densities on the freeway next to the 4 ramps for the pre-timed ramp metering and probe-based ramp metering scenarios, respectively. It is noticeable that fewer fluctuations in the values of densities were obtained with the probed-based ramp metering approach. Thus, the use of the probe (or IntelliDrive) information in the ramp metering algorithm has been shown to effectively smooth and evenly distribute the densities over the entire freeway section with a lower average density amount. The uniform distribution of densities on the freeway is likely resulting from the ability of the ramp meters to suppress the shockwave formation that can be due to lane changing behaviour, traffic discharged from the on ramps or to the presence of a slow moving vehicle. This is achieved through two characteristics of the algorithm: it continuously checks for the location of shockwaves and then draws the attention of the algorithm to these sections of the freeway experiencing critical congestion (i.e. higher density than the neighbouring section).

Figure 5.3 illustrates the percentage difference in delays for the two examined scenarios (i.e. pre-timed ramp metering and probe-based RM). These simulation results correspond to network-wide delays that include delays on both the mainline and the on-ramps. The results again show the robustness of the developed probe-based ramp metering strategy in decreasing the delays on the freeway and the on-ramps. This is especially noticeable on the freeway sections around the McKnight Blvd and 16th Avenue on-ramps, where high traffic congestions are still present, even with the restrictive pre-timed ramp metering strategy. The reductions in total system delays were significant for the probe-based ramp metering scenario. On average, over the one-hour simulation run, there was a 14% reduction in total network delay, compared with the pre-timed ramp metering scenario.

![Figure 5.1 Density distribution under pre-timed RM](image)
The reduction of delay on the mainline was also shown to decrease under probe-based control. Table 5.1 summarizes the total delay on the mainline during 5 minutes intervals:

<table>
<thead>
<tr>
<th>Mainline Delay (Sec/veh)</th>
<th>Delay percent difference per interval</th>
</tr>
</thead>
</table>

Figure 5.2 Density distribution under probe-based RM

Figure 5.3 Delay percentage difference under pre-timed ramp metering and probe-based ramp metering (network-wide delays)
<table>
<thead>
<tr>
<th>Simulation Time</th>
<th>Probe Based</th>
<th>Pre-timed</th>
<th>Pre-timed</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:20:00</td>
<td>74</td>
<td>85</td>
<td>-12.9</td>
</tr>
<tr>
<td>0:25:00</td>
<td>89</td>
<td>114</td>
<td>-21.9</td>
</tr>
<tr>
<td>0:30:00</td>
<td>135</td>
<td>144</td>
<td>-6.3</td>
</tr>
<tr>
<td>0:35:00</td>
<td>148</td>
<td>155</td>
<td>-4.5</td>
</tr>
<tr>
<td>0:40:00</td>
<td>102</td>
<td>127</td>
<td>-19.7</td>
</tr>
<tr>
<td>0:45:00</td>
<td>94</td>
<td>149</td>
<td>-36.9</td>
</tr>
<tr>
<td>0:50:00</td>
<td>103</td>
<td>212</td>
<td>-51.4</td>
</tr>
<tr>
<td>0:55:00</td>
<td>144</td>
<td>247</td>
<td>-41.7</td>
</tr>
<tr>
<td>1:00:00</td>
<td>202</td>
<td>219</td>
<td>-7.8</td>
</tr>
<tr>
<td>1:05:00</td>
<td>201</td>
<td>234</td>
<td>-14.1</td>
</tr>
<tr>
<td>1:10:00</td>
<td>188</td>
<td>231</td>
<td>-18.6</td>
</tr>
<tr>
<td>1:15:00</td>
<td>209</td>
<td>254</td>
<td>-17.7</td>
</tr>
<tr>
<td><strong>Average of all intervals</strong></td>
<td><strong>21</strong></td>
<td><strong>-21</strong></td>
<td></td>
</tr>
</tbody>
</table>

Table 5-1  Mainline Delay under Probe based and Pre-timed control

5.2 COMPARISON WITH DETECTOR-BASED RAMP METERING SCENARIO

Figures 5.4 and 5.5 show the densities on the freeway next to the 4 ramps for the detector-based ramp metering and probe-based ramp metering cases, respectively. It should be noted that, in this particular simulation run, which corresponds to AM peak period, the freeway was very congested; thus, the detector-based ramp metering approach acted similarly to the pre-timed ramp metering method; and, the ramp metering rates were being maintained almost the same as in the pre-timed case. However, the probe-based ramp metering is shown to effectively smooth and better distribute the densities over the examined freeway sections.
Figure 5.4 Density distribution under detector-based RM

Figure 5.5 Density distribution under probe-based RM
Figure 5.6 illustrates the percentage difference in delays for the two examined scenarios (i.e. detector-based ramp metering and probe-based RM). Again, these simulation results correspond to network-wide delays, including mainline and on-ramp delays. The delays on the mainline were shown to be lower in the probe-based case during most intervals. Table 5.2 summarizes the delay on the mainline during 5 minutes intervals:

<table>
<thead>
<tr>
<th>Simulation Time</th>
<th>Mainline Delay (Sec/veh)</th>
<th>Delay percent difference per interval</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Probe Based</td>
<td>Detector Based</td>
</tr>
<tr>
<td>0:20:00</td>
<td>74</td>
<td>87</td>
</tr>
<tr>
<td>0:25:00</td>
<td>89</td>
<td>105</td>
</tr>
<tr>
<td>0:30:00</td>
<td>135</td>
<td>116</td>
</tr>
<tr>
<td>0:35:00</td>
<td>148</td>
<td>146</td>
</tr>
<tr>
<td>0:40:00</td>
<td>102</td>
<td>157</td>
</tr>
<tr>
<td>0:45:00</td>
<td>94</td>
<td>182</td>
</tr>
<tr>
<td>0:50:00</td>
<td>103</td>
<td>157</td>
</tr>
<tr>
<td>0:55:00</td>
<td>144</td>
<td>166</td>
</tr>
<tr>
<td>1:00:00</td>
<td>202</td>
<td>203</td>
</tr>
<tr>
<td>1:05:00</td>
<td>201</td>
<td>228</td>
</tr>
<tr>
<td>1:10:00</td>
<td>188</td>
<td>237</td>
</tr>
<tr>
<td>1:15:00</td>
<td>209</td>
<td>223</td>
</tr>
</tbody>
</table>
Table 5-2 Mainline Delay under Probe based and Detector based control

As the figure indicates, the probe-based methodology, in overall, outperformed its detector-based counterpart. The reductions in total system delays were significant and resulted in as much as a 12% reduction in total network delays compared with the detector-based ramp metering scenario over the whole simulation. These findings may be explained by the following:

1. First, it is possible that density readings, which are spatial parameters, are not accurately estimated by the point detectors.

2. Second, point detectors are only able to provide localized information on the traffic condition, just in the vicinity of the ramps, which is not representative of a relatively larger section of the freeway. This is especially true in the presence of weaving activity next to on- and off-ramps that results from significant lane changing behavior. These effects are further pronounced due to the high congestion levels on the highway.

3. Finally, point detectors are not able to accurately detect shockwave occurrence and the corresponding location resulting from lane changing behavior due to merging/diverting.

Consequently, the optimization function of the detector-based RM, which is optimized based on point detector readings, is possibly drawing the attention of the algorithm more to local traffic conditions in the proximity of the on-ramps. The opposite happens when using SMS data from vehicle probes to derive the density values from a traffic model. SMS data are accurately measured at different sections of the freeway covering the entire freeway. This probe-based SMS information is able to constantly monitor traffic state and detect shockwave occurrence over the entire freeway. These shockwaves are addressed in the algorithm, which attempts to smooth the density over the entire freeway while computing the optimal ramp metering. Vehicles are released from the on-ramps at the right time to meet that purpose and smooth the traffic over the whole freeway section.

5.3 SENSITIVITY ANALYSIS

A sensitivity analysis was conducted to examine the percentage of market share of probe vehicles (i.e. number of vehicles acting as probes) required for the probe-based ramp metering strategy to still outperform the detector-based ramp metering approach. Thus, seven different percentages of market shares for vehicle probes were examined.

In these runs, seven different penetration rates were examined: 1, 3, 6, 10, 20, 30 and 40%. The same set of seed values was used for the simulation of each scenario. Table 5.3 summarizes the results of the simulation for the seven examined market penetration rates.

Even at a market share of vehicle probes as low as 3%, the algorithm outperforms its detector-based counterpart and resulted in as much as a 7% decrease in network-wide delays and a 2% decrease in network-wide travel time and with a 1% increase in the mainline average speed. This can, again, be mainly attributed to the ability of the developed probe-based ramp metering algorithm to take into consideration SMS data and, therefore, density information on the entire freeway from probes in the computation of the optimal ramp metering, rather than just downstream and upstream of the ramps, as in the case of the detector-based algorithm. However, with 1% probe vehicles, the simulation results of the probe-based algorithm could not
outperform the detector based ramp metering concluding that with a very low percent penetration, the detector based ramp metering algorithm would perform better.

<table>
<thead>
<tr>
<th>Detector based Ramp Metering</th>
<th>Network wide Delay (sec per vehicle)</th>
<th>Network Wide Travel Time (sec per vehicle)</th>
<th>Mainline Average Speed (km/h)</th>
</tr>
</thead>
<tbody>
<tr>
<td>40% penetration</td>
<td>408</td>
<td>1030</td>
<td>82</td>
</tr>
<tr>
<td>30% penetration</td>
<td>415</td>
<td>1037</td>
<td>80</td>
</tr>
<tr>
<td>20% penetration</td>
<td>419</td>
<td>1042</td>
<td>81</td>
</tr>
<tr>
<td>10% penetration</td>
<td>416</td>
<td>1038</td>
<td>81</td>
</tr>
<tr>
<td>6% penetration</td>
<td>406</td>
<td>1032</td>
<td>80</td>
</tr>
<tr>
<td>3% penetration</td>
<td>425</td>
<td>1050</td>
<td>80</td>
</tr>
<tr>
<td>1% penetration</td>
<td>477</td>
<td>1102</td>
<td>78</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Probe Based Ramp Metering</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
</table>

Table 5-3 Comparison of detector based control with different probe penetration rate under probe based control

A one way ANOVA test was conducted to examine the significance in the variation of the algorithm performance under different penetration rates (i.e. 10%, 20%, 30% and 40%). The ANOVA test results are reported in Table 5.4. As the table indicates there is no significant difference in the resulting delays under different penetration rates ($F_{\text{statistics}} = 0.133 < F_{\text{critical}} = 3.24$). Thus, a 10% market share of probe vehicles is expected to be enough in providing the necessary input information for a reliable probe-based ramp metering algorithm. However, for lower market share the difference in the improvements are significant.

<table>
<thead>
<tr>
<th>ANOVA</th>
<th>Source of Variation</th>
<th>SS</th>
<th>df</th>
<th>MS</th>
<th>F</th>
<th>P-value</th>
<th>F crit</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Between Groups</strong></td>
<td></td>
<td>325</td>
<td>3</td>
<td>108.3333</td>
<td>0.133163</td>
<td>0.93888</td>
<td>3.248872</td>
</tr>
<tr>
<td><strong>Within Groups</strong></td>
<td></td>
<td>13016.59</td>
<td>16</td>
<td>813.5368</td>
<td>0.93888</td>
<td>3.248872</td>
<td></td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td></td>
<td>13341.59</td>
<td>19</td>
<td>813.5368</td>
<td>0.93888</td>
<td>3.248872</td>
<td></td>
</tr>
</tbody>
</table>

Table 5-4 One-way ANOVA test result

5.4 SUMMARY

In this chapter, the performance of a probe-based ramp metering algorithm using the Quadstone PARAMICS microsimulation model has been compared with two other ramp metering algorithms: 1) pre-timed ramp metering algorithms and 2) a detector-based ramp metering algorithm. Both detector- and probe-based algorithms adopt the same problem formulation and compute the optimal ramp metering rates based on the minimization of the system travel time, including both the travel time on the freeway and the wait time on the ramps over an extended horizon.

The comparative analysis of the three ramp metering approaches was conducted on an 8 km freeway section on Highway 2 in Calgary, Alberta, Canada. The performance of the
algorithms were examined and compared, in terms of freeway delays, densities and speeds as well as system delays. A sensitivity analysis was also conducted to compare the performance of the probe-based approach for different market share percentages of probe data (i.e. percentage of vehicles acting as probes). The results of the analysis indicated that the probe-based algorithm consistently outperformed the two other algorithms in terms of all performance measures; at least once the market share exceeded a particular threshold. The sensitivity analysis showed strategy’s effectiveness does not significantly change with the larger market share of probe vehicles; however, the difference in the improvements is significant at the low percentages of market share.

The algorithm still outperformed the detector-based ramp metering approach, even with a market share of vehicle probes as low as 3%. The simulation result, however, showed that the detector based ramp metering algorithm would perform better than the probe based ramp metering with a very low penetration rate (i.e. 1%) of probe vehicles.

In summary, the above experiment shows that the probe-based ramp metering algorithm outperforms its pre-timed and detector-based ramp metering counterparts, in terms of decreasing overall system delays and freeway delays and smoothing the density distribution over the entire freeway segment. In addition to its superior performance, the probe-based ramp metering requires the installation of detectors only on the ramps. No detectors are needed on the freeway. The freeway state is directly monitored though probe vehicles providing SMS information. This is expected to decrease the cost associated with implementing ramp metering algorithms.

Chapter 6. SUMMARY AND DISCUSSIONS

This chapter presents the concluding comments of this report and suggests directions for future research. Overall conclusions and discussions are presented in section 6.1 which also summarizes the conclusions from the experiments conducted with the developed probe based ramp metering approach. Section 6.2 presents the author’s perspective on the contributions of the research to the adaptive and coordinated ramp metering problem. Finally, section 6.3 discusses more general and potential future research directions.

6.1 CONCLUSIONS

This report presented the development of a new proactive ramp metering strategy taking as main input parameters the space mean speed information as estimated by vehicle probes (or in future IntelliDrive). The new strategy computes the optimal ramp metering rate based on minimizing the total system travel time which includes: 1) the travel time on the freeway and 2) the wait time on the ramps over an extended horizon. A rolling horizon framework is incorporated to determine the optimum ramp metering rates for the next short term horizon (i.e. 2.5 to 5 minutes) rather than just reactively select the optimal ramp metering rates based on current conditions. However, only the ramp metering rates corresponding to the earlier time step are considered final and implemented. This approach is expected to act pro-actively in avoiding congestion occurrence. This algorithm uses the Cell Transmission Model and shockwave analysis to predict the travel time on the freeway. It also uses queuing analysis to estimate the
delay for the on-ramp. The prevailing traffic condition on the freeway mainline is estimated directly from vehicle probes with no data from point detectors. To address the equity issues surrounding the implementation of ramp metering, the ramp metering problem formulation assigns a dynamic weighting scheme that draws the attention of the algorithm to the sections of the highway or ramps experiencing critical traffic conditions. This weight factors are in fact the number of vehicles in each section. These weighting schemes are updated dynamically at every estimation step, based on the prevailing and/or forecasted densities of the freeway sections, as well as information on queue length for the on-ramp. To avoid long queues on the on-ramps that may affect the traffic on surface streets, queue spill back detectors are active and in case of the ramp queue reaching to the maximum specified value, the ramp metering rate will be changed to its maximum value (15 vehicles per minute).

The ramp metering problem formulation tests all different combinations of ramp metering rates for next 5 time step interval (each interval is 30 seconds or 1 minute) and the combination with minimum predicted total travel time will be chosen as the optimal ramp metering rate for next time step. However, only the ramp metering rates corresponding to the earlier time step are considered final are implemented.

Intensive experiments are conducted to test the developed approach. The algorithm was tested for: 1) local single ramp and 2) 4 co-ordinated ramps using Quadstone PARAMICS microsimulation software. The coordinated ramp metering algorithms was tested on a simulated network of Highway 2 (Deerfoot Trail) in Calgary, Canada. The developed algorithms have been rigorously examined for different traffic conditions and ramps input parameters.

### 6.1.1 Results for the Isolated Ramp Metering

The results of the isolated ramp metering analysis showed an overall improvement in traffic condition (i.e. average travel time, flow and speed) for both the freeway and network-wide. The results of the analysis indicated a superior performance of the algorithm under high and medium traffic conditions on both the ramp and on the freeway and for high demand of the freeway and moderate demand on the ramp. As expected, no improvement was shown for the case of high demand on the ramp and moderate demand on the freeway.

The sensitivity analysis examined the impact of different estimation step intervals. The results showed an overall improvement in traffic condition (i.e. delay, density and speed) on the freeway during AM peak congestion. Finally, the simulation results also showed that the developed algorithm performs better when the data is updated in 30-second time steps, compared to 1-minute intervals.

### 6.1.2 Results for the Coordinated Ramp Metering

The coordinated ramp metering algorithm was also tested based on calibrated real demand on Highway 2 in Calgary, Alberta, Canada. The implementation of the proposed ramp metering algorithm was shown to be effective in smoothing the densities on the freeway. The developed probe-based approach was also able to decrease drastically the delay (both total network delay and delay on freeway).

The sensitivity analysis examined the impact of different estimation step intervals. The results showed an overall improvement in traffic condition (i.e. delay, density and speed) on the freeway during AM peak congestion. Finally, the simulation results also showed that the developed algorithm performs better when the data is updated in 30-sec time steps, compared to 60-sec interval.
6.1.3 Comparative Analysis with other Ramp Metering Strategies

The performance of the probe-based ramp metering algorithm was also compared with two other ramp metering algorithms: 1) pre-timed ramp metering algorithms and 2) a detector-based ramp metering algorithm. Both the detector-based and probe-based algorithms adopt the same problem formulation to compute the optimal ramp metering rates. The only difference is that, the detector-based algorithm extracts density information from eight detectors and uses this measured density directly in the problem formulation. On the other side, the probe-based ramp metering approach computes the density of different sections of the freeway indirectly from the space mean speed (SMS) information as provided by probe vehicles without taking any information from the freeway detectors.

A comparative analysis of the three ramp metering approaches was conducted on the same simulated portion of Highway 2 in Calgary. The performance of the algorithms was examined and compared, in terms of freeway delays, densities and speeds as well as system delays. A sensitivity analysis was also conducted to compare the performance of the developed probe-based approach for different market share percentages of probe data (i.e. number of vehicles acting as probes). The results of the analysis indicated that the probe-based algorithm consistently outperformed the two other algorithms in terms of all performance measures. The sensitivity analysis showed that the developed algorithm’s effectiveness does not significantly change with larger than 10% market share of probe vehicles. However, the difference in the improvement is significant at the lower percentage of market share. Nevertheless, the algorithm was able to outperform the detector-based ramp metering approach, even with a market share of vehicle probes as low as 3%. On the other hand, the simulation result showed that the detector based ramp metering algorithm performed better than the probe based ramp metering with very low market share (i.e. 1%) of probe vehicles.

In addition to the above superior performance, the probe-based ramp metering requires the installation of detectors only on the ramps. No detectors are needed on the freeway. The freeway state is directly monitored through probe vehicles providing SMS information. These experiments shows the feasibility of developing ramp metering using as primary input SMS information from probes. This information can be easily provided from GPS-enabled cell phone and in the future from IntelliDrive. This is expected to significantly decrease the cost associated with implementing ramp metering algorithms.

6.2 RESEARCH DISCUSSION AND CONTRIBUTIONS

Previous ramp metering algorithms optimize the traffic based on occupancy, density or flow information measured in the vicinity of the ramp. However, traffic conditions in the proximity of ramps are not representative of the whole freeway section. Density or traffic flow readings from point detectors placed upstream or downstream of the ramps are not able to detect shockwave formation that can occur due to lane changing behaviour, traffic discharged from the on-ramps or to the presence of a slow moving vehicle specially around on and off ramps. This may lead to a sub-optimal solution when using local information to design ramp metering strategies. With density estimated over the whole freeway section, ramp metering formulation would be able to optimize the traffic on the system from a network-wide perspective. In addition, the algorithms continuously checks for the location of shockwaves and then draws the attention of the algorithm to these sections of the freeway experiencing critical congestion (i.e. higher density than the neighbouring section).
On the other hand, with the requirement of the presence of at least one point detector in the proximity of each on-ramp, intensive coverage of the point detector is needed to develop an effective coordinated ramp meters (e.g. ARMS algorithm (Lie et al., 1993) needs three detectors, upstream, midstream and downstream of each on and off ramp). This corresponds to high costs associated with the installation, maintenance and communication needed for the detectors.

This research develops a proactive coordinated ramp metering approach that uses the SMS data directly provided by probe vehicles as the main input parameters. Data constantly provided by probe vehicles can estimate traffic conditions by continuously disseminating their SMS information over all freeway sections. This probe-based approach is shown to outperform detector-based approaches, due to: 1) the higher accuracy of density estimates obtained from probes than from that from detectors and 2) the ability to take into account the traffic state on the entire freeway, rather than just in the vicinity of the ramps.

Thus, this report made the following contributions to the common practice in the field of transportation engineering:

1. **Using vehicle probes instead of traditional detection based technologies as the main input parameter to ramp metering algorithms**

The report developed an innovative ramp metering approach that relies on probe base speed information as main input in the ramp metering problem formulation. The use of probe information data to formulate advanced control algorithms is a pioneering one in the field of transportation engineering, breaking new ground for solving other Intelligent Transportation Systems (ITS) problem taking as main input data from probe vehicles. This approach is shown to have many advantages such as: 1) decreasing the costs associated with the installation and maintenance of detectors to implement ramp metering; 2) obtaining more reliable information as probe vehicles do not have problems of detector failure, and 3) using information on all freeway sections rather than just in the vicinity of on-ramps. This is especially true in the presence of significant lane changing behaviour close to sections containing on-ramps and off-ramps.

2. **Adopting a Dynamic Weighting Scheme for different freeway sections and on-ramps**

This report better addresses the equity issues as related to ramp metering strategies by introducing a dynamic weighting scheme in the ramp metering problem formulation. The weights are able to adjust dynamically based on prevailing and forecasted traffic conditions to give priority in each step to the sections of the freeways or/and onramps experiencing critical traffic conditions. The wait time factor on the objective function is also a dynamic parameter that is based on: 1) the prevailing demand, 2) length of residual queue on the on-ramp resulting from previous time steps and 3) the wait time perceived by vehicles on the queue from previous time steps.

3. **Using a system approach in the formulation of the ramp metering algorithms**

The developed approach takes a system wide approach in formulating the ramp metering problem. The approach used focuses on the formulation of the ramp metering rates to simultaneously address the two often conflicting objectives of reducing freeway travel time and decreasing the delays on ramps. Travel times on the freeway are estimated directly from section
space mean speeds rather than indirectly from point detectors placed in the vicinity of the on-
ramps.
REFERENCES


