A Proactive Travel Time Based Ramp Metering Algorithm for an Isolated Ramp

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ABSTRACT

This paper focuses on the design of a proactive ramp metering control on an isolated ramp. The developed approach exploits the use of vehicle probe travel time data as the main input parameters to the ramp metering control algorithm. The problem is formulated with the objective of minimizing total system vehicular travel time and includes: 1) travel time on the freeway, upstream and downstream of the ramp; and, 2) the wait time on the ramp. 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. The developed approach is tested using Quadstone Paramics’ microsimulation model on an isolated ramp on Highway 2 in Calgary, Canada. The developed algorithm is analyzed under various traffic conditions on the freeway and ramp. In addition, a sensitivity analysis is conducted to examine the performance of the developed algorithm for various values as the ramp input parameters: percentages of penetration of probe data and estimation step intervals. The results of the analysis are promising, showing the effectiveness of developing ramp metering control algorithms based on travel time data from vehicle probes.

Keywords: Adaptive Ramp Metering, Proactive Ramp Metering, Cellular Probe, CTM, Travel Time, Freeway Control

INTRODUCTION

Recently, 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 increasing freeway speeds while providing increased safety in merging and reducing rear-end collisions on the ramps themselves. Another important benefit of ramp metering is that short freeway trips may divert to adjacent under-utilized arterial streets to avoid queues at the meters. Thus, if there is excess capacity on surface streets, it may be worthwhile to divert traffic from congested freeways to surface
traffic.
Previous studies have demonstrated that efficient ramp metering strategies can drastically reduce total travel time on freeways (Kotsialos et al., 1999).

This paper 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; and, (2) the development of ramp metering algorithms based on travel time data from vehicle probes to drastically decrease the cost of deployment of ramp metering strategies.

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 excessively long queues for on-ramps, which result in high emissions and upstream signal blocking. This research develops ramp metering strategies that take into account traffic conditions on both freeways and 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 advanced ramp metering strategies.

In an era of rapid technological change, there is considerable scope to address this issue at a reasonable cost. Real-time data from vehicle probes are already available on major roadways from cell phone probe technologies. 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 particular, new mobile phones are location-enabled via built-in GPS receivers (Sacco, 2007). It is also envisioned that this travel time data will be even more easily available in the future from IntelliDrive. Travel time is the inverse of speed, which is a reliable indicator of congestion. This data can be potentially exploited and used as one of the main input parameters in advanced traffic control algorithms.

This paper is organized as follows: Previous ramp metering algorithms are first reviewed. A brief overview of the vehicle probe detection is presented, which is followed by a description of the ramp metering approach developed in this research. The developed strategy is then tested on a simulated network in Quadstone Paramics microsimulation software to assess its potential for reducing travel times and improving speed compared to the case of no ramp metering. Then, a sensitivity analysis is conducted to examine the performance of the developed algorithm for various congestion levels, estimation steps, and percentages of vehicle probe penetration. Concluding comments and recommendations for future work are presented in the final section.
REVIEW OF RAMP METERING STRATEGIES

Recurrent congestion reduces substantially available freeway capacity at rush hours, when this capacity is mostly needed, causing excessive delays and emissions and reduced safety. When congestion forms on freeways, the discharge rate from the bottleneck is reduced (lower by some 5% to 10% than freeway capacity); and, the off-ramps and interchanges covered by the congestion are often blocked, which decreases the chance to exit vehicles from the freeway (Papageorgiou and Kotsialos, 2002). Similar effects are observed in the frequent 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 way. 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 offer strong evidence that operations on ramps, freeways and even adjacent arterials are improved, once these strategies are appropriately implemented and operated (Minnesota Department of Transportation, 2001).

Ramp metering rates may be fixed for certain periods, based on historical data, or may be variable minute-by-minute (i.e. adaptive), based on real-time traffic parameters. In addition, ramp metering may operate either in isolation or in a coordinated fashion. Coordinated ramp metering control strategies establish metering rates for various ramps on the basis of total freeway conditions.

In the last two decades, remarkable local ramp metering algorithms have been developed, including:

- ALINEA (Asservissement Lineaire d'Entree Autoroutiere), the well-known feedback regulator local traffic responsive ramp metering algorithm introduced by Papageorgiou et al. (1991).
- The demand capacity algorithm by Masher et al. (1975) and Koble et al. (1980).
- System wide adaptive ramp metering (SWARM), a combination of coordinated and local traffic responsive ramp metering algorithms developed by NET Corporation. (NET, 1996 and Paesani et al., 1997).
- The zone ramp metering algorithm employed by the Minnesota Department of Transportation (DOT) for many years (Stephanedes, 1994).
In the ALINEA strategy, the ramp metering rate is adjusted in real time to keep the occupancy downstream of the ramp at a specific value (i.e. critical occupancy). There are several extensions to the ALINEA algorithm (FL-ALINEA, UP-ALINEA, UF-ALINEA and X-ALINEA/Q) to improve its performance (Smaragdis and Papageorgiou, 2003). The demand capacity algorithm, one of the earliest traffic responsive ramp metering controls, is a feed forward algorithm, since upstream flow (or occupancy) is measured and the difference with the desired downstream capacity is the basis of the ramp metering rate.

SWARM uses two functions: First, it attempts to maintain headway at detectors upstream of the ramp by optimizing density, in order to maintain maximum flow. Second, it computes ramp metering rates by calculating the number of vehicles in each zone, in order to maintain demand such that each zone is kept at Level of Service LOS D (Chu and Liu, 2003). The algorithm developed by Zhang and Ritchie (1997) combines artificial neural networks and automatic control theory, which can be tuned on-line and the control can consequently be adapted in case of changes to the environment.

The zone ramp metering algorithm implemented in Minnesota smoothes freeway congestion, while limiting meter wait times by releasing vehicles onto the freeway based on ramp demand. The target wait time is to be less than 4 minutes, so that ramp wait times are not excessive. The Seattle bottleneck algorithm computes the ramp metering rate at the local ramp level based on the difference between estimated capacity and measured upstream volume.

Thus, in most of the reviewed literature, the ramp metering algorithms are often formulated as mathematical optimization problems that attempt to reduce the travel time on the freeway or increase the freeway throughput. Despite the great reduction in freeway travel time resulting from the application of these research efforts, still more attention needs to be given to the delay experienced on the ramp not only as a constraint that limits the on-ramp queue, but also as part of the overall system travel time or delay.

The algorithm developed in this paper minimizes the total delay experienced by all vehicles based on the ramp metering rate on the on-ramp. The state of the traffic in the next time step is predicted based on the Cell Transmission Model (CTM) proposed by Daganzo (1993). In addition, this paper examines the potential of using travel time data from vehicle probes as the main input parameters to the formulated ramp metering algorithms.

A brief overview of the use of probe technologies detection is presented next and is followed by a detailed overview of the developed ramp metering approach.

**OVERVIEW OF VEHICLE PROBE DETECTION**

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. 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). 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, 2007) and are expected to be the primary navigation device for personal use by 2012 (Kim, 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.

Mobile phone technologies have become reliable enough to provide services that will have a huge impact on transportation related subjects. Monitoring location-related and time-related data from cell phone subscribers on a wireless network for estimating traffic conditions would provide a relatively low-cost data collection method for traffic engineers. Hsiao and Chang (2005) also concluded that a sufficient sample size, longer data collection interval, shorter location update interval, and larger mobile penetration rate are crucial factors to generating accurate traffic information.

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 than the more localized coverage offered by loop detectors.

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). 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).

Assuming that the privacy issues are resolved, this paper considers travel time provided from vehicle probes (cellular or GPS-enabled) as the main input in the developed ramp metering algorithms. It is assumed that the average speed of vehicles equipped with the GPS-enabled cell phones can be obtained during each time step interval on each segment of the freeway separately. Average vehicle speeds for each time step and segment are used as the main input variables for the proposed ramp metering algorithm. This approach is expected to drastically reduce the cost of deployment of ramp metering strategies.
PROPOSED FRAMEWORK AND PROBLEM FORMULATION

The proactive ramp metering strategy developed in this research is formulated as an objective function that minimizes the delay experienced by all vehicles in the system, including both the freeway and the on-ramp. Speed data are first used to estimate the traffic conditions (e.g. densities and speeds) on every section for the next time step. The ramp metering rate allows vehicles to enter the system from a minimum of 240 vehicles per hour to a maximum of 900 vehicles per hour.

The number of vehicles discharged to the freeway from the on-ramps and the predicted traffic condition on each section of the freeway are examined to detect the possible occurrence of a back propagating shockwave. Such shockwaves are due to a sudden increase of flow and density on the freeway caused by traffic discharged from the on-ramp. Thus, the predicted delay that may be experienced for the next time step on this network is estimated, and the ramp metering rate with the minimum delay is chosen for the next time step of the ramp meter. This iterative process runs continuously for every time step. Two different time steps are examined in this research: 1-minute intervals and 30-second intervals.

Prediction of the traffic state is based on CTM, developed by Daganzo (1993), where speed is calculated from the updated flow and density rather than being directly updated. 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. Gomes et al. (2008) used CTM to prove that proper ramp metering always increases flow and freeway speed and reduces total travel time, because of a larger discharge flow from delaying the traffic breakdown conditions on the highway. In addition, shockwave analysis, proposed by Lighthill and Whitham (1955), is incorporated in this predictive model to estimate the traffic conditions if any back propagating shockwave is created on the freeway, due to increased flow from on ramps.

Figure 1 shows a simple freeway network divided into four sections of equal length. Each section has an average speed obtained for each time step. Initially, at the beginning of each time step, each section is assumed to have homogenous traffic conditions.

![Schematic view of a freeway close to an on-ramp](image)

Figure 1 – Schematic view of a freeway close to an on-ramp

The number of vehicles that can flow from section i to section i+1 for the next time step \(y_{i+1}(t)\) is estimated based on CTM. The number of vehicles transferring from one section to the next consecutive segment is the minimum of (1) the number of vehicles that exist from the
upstream section; (2) the capacity of the next section; or (3) and the amount of current empty space available at the downstream segment:

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

Where \( N_i(t) \) = Jam density at section i in time step t
\( C_i(t) \) = Capacity at section i in time step t
\( K_i(t) \) = Density at section i in time step t
\( Y_i(t) \) = Number of vehicles transferring from section i-1 to i in time step t
\( L_i(t) \) = Length of segment 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:

\[ K_i(t+1) = K_i(t) + Y_i(t) - Y_{i+1}(t) \]

The speed data upstream of section i is assumed to be equal to \( V_i(t) \), which is assumed to be readily available from vehicle probe sensing technology, as explained previously. The traffic flow leaving section i+3 is assumed to be the maximum, which is equal to capacity.

Figure 2 shows the overall framework ramp metering algorithm.
1) Obtain segment speed data $V_i(t)$

2) Estimate the traffic condition on the next time step based on different alternative flow rates entering from on-ramp

3) If any back propagating shock-wave between sections exist, modify the anticipated traffic condition for next time step based on the different alternative ramp metering rates.

4) Estimate the delay/travel time of all vehicles on the freeway for next time step based on different alternative ramp metering rates.

5) Calculate the delay being experienced by vehicles on the on-ramp based on different ramp metering rates in addition to previous cumulative delay variable

6) Minimize the objective function of total travel time to obtain the optimal ramp metering rate for next time step:

$$\text{Min Total Travel Time}(R) = \sum \text{Travel time at freeway sections} + \text{Delay at the on-ramp}$$

7) If there is any queue left on the on-ramp, store the remaining queue length and cumulative delay of vehicles on the on-ramp to be used for next time step iteration.

Figure 2 – Proposed proactive travel time based ramp metering framework
As the figure indicates, the framework consists of following seven major steps:

**Data Collection**

**Step 1:** The average speed data, $V_i(t)$, on each section is assumed to be available from vehicle probe technology. Densities and flows at each section are estimated based on conventional traffic flow models, namely Greenshield’s model. A jam density of 125 vehicles per kilometre per lane is assumed. The free flow speed is assumed to be the speed limit on each section of the freeway (which ranges from 100 to 110 km/h).

**Traffic Estimation**

**Step 2:** Based on the current data, the traffic condition for next time step is estimated using CTM. For section $i+2$, the number of vehicles entering the freeway from the on-ramp are also added to the density for section $i+2$:

$$K_{i+2}(t+1) = K_{i+2}(t) + Y_{i+1}(t) - Y_{i+2}(t) + R(t+1)$$

**Step 3:** Any potential back propagating shockwave between freeway sections are checked. The speed of the shockwave between two consecutive sections $i$ and $j$ is calculated as:

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

where $w_{ij}$ is the speed of the shockwave between sections $j$ and $i$.

**Step 4:** The travel time of vehicles on the freeway, based on different possible ramp metering rates, are anticipated. This is explained in the Estimation of Travel Time on the freeway section.

**Step 5:** The delay experienced by vehicles on the ramp is calculated. This is explained in the Estimation of Delay for the On-Ramp Queue section.

**Optimization Step**

**Step 6:** The optimal metering rate is computed. As mentioned previously, the approach proposed in this paper is aimed at simultaneously addressing two often conflicting objectives: reduced freeway congestion and decreased delays on ramps.

Optimal ramp metering rates at time step, $t$, are obtained by optimizing a bi-objective function, $Z$, consisting of 2 criteria:

- $Z_1$, which minimizes the total travel time on the freeway system:
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\[ Z_1 = \sum_{j=1}^{i+3} (W_j \times Travel\ Time_j) \]

- \( Z_2 \), which minimizes the delay for the vehicles waiting to be served on the on-ramp:

\[ Z_2 = Delay_{on-ramp} + Cumulative\ Delay \]

where \( W_j \) = Weight factor for section \( j \)

Travel Time\(_j\) = Average travel time on freeway section \( j \)

Details on the estimation of freeway travel time and delay on the ramps in the objective function are provided in the next section.

**Queue Accumulation Check**

**Step 7**: If there is any queue left on the ramp, the queue length and the cumulative delay of the vehicles will be stored for computation of the next time step optimization.

**Formulation of the Objective Function**

The problem is formulated as an objective function that consists of the following delays:

1) Estimated delay for all four freeway segments (Figure 1) based on the ramp metering rate, \( R \),
2) The delay at the ramp as a function of \( R \), and
3) The cumulative delay on the on-ramp from previous time steps, if a queue of vehicle remains before the beginning of the next time step.

Thus, the objective function used for obtaining the optimal ramp metering rate for next time step can be written as:

\[ \text{Min } Total\ Delay\ at\ the\ network}(R) = \sum_{j=1}^{i+3} W_j \times Freeway\ Travel\ Time_{section_j}\ (t + 1) + Delay_{on-ramp}(t + 1) + Cumulative\ Delay(t) \]

The algorithm examines different possible ramp metering rates for each time step; and, the ramp metering rate that generates the minimum total travel time is chosen as the optimal ramp metering rate for the next time step. Details on estimating the travel time on freeway and delay on the ramp are explained in the next two sections.

**Estimation of Travel Time on the Freeway**

In estimating delays on the freeway, a weighted formulation is adopted, which gives a weight, \( W_j \), to the various freeway sections. The weight factors in the travel time / delay objective function are computed for each section of the freeway for every time step. These weights are dynamic parameters that are updated for each time step, based on prevailing freeway conditions (i.e. densities on each freeway section). The weights are obtained at each time steps from:

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\[ W_i(t) = K_i(t) \cdot L_i \]

where \( W_i \) = Weight factor for section i
\( L_i \) = Length of section i

In cases of no occurrence of back propagating shockwaves, the delay for the whole freeway is computed based on the predicted flow and density segments obtained in previous steps and are estimated as:

\[
Freeway\ Travel\ Time_{section\ i}(t + 1) = \frac{L_i}{V_i(t + 1)}
\]

If any back propagating shockwave exists, the delay for the whole freeway is computed based on shockwave theory. 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 block 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 – Example of back propagating shockwave of i+2 due to an increase in flow and density from on-ramp](image)

An example of the formulation for the shockwave effect on section i+3 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+3)
then
\[
\{ \begin{array}{l} \quad X_4 = \frac{Q_{i+4} - Q_{i+3}}{R_{i+4} - R_{i+3}} \ast Time\ step \\ \quad L'_4 = X_4 + L_4 \\ \quad Travel\ Time_{section\ i+4}(t + 1) = \frac{L'_4}{V_{i+4}(t + 1)} \\ \quad W_{i+4}(t) = K_{i+4}(t) \cdot L'_4 \end{array} \}
\]

Else
\[
\{ \begin{array}{l} \quad Travel\ Time_{section\ i+4}(t + 1) = \frac{L_{i+4}}{V_{i+4}(t+1)} \\ \quad W_{i+4}(t) = K_{i+4}(t) \cdot L_{i+4} \end{array} \} \]
Estimation of Delay for the On-Ramp Queue

The delay estimation for the on-ramp queue is calculated based on (1) the cumulative delay previously experienced by the vehicles, and (2) the predictive delay for the next time interval with a ramp metering rate of \( R \). Since vehicles on the ramps are more likely entering in platoons (i.e. pulsed system) from a nearby signalized intersection, the arrival of vehicles into the ramp are assumed to have a frequency of and an arrival rate of \( X \), where \( \bar{C} \) is the average cycle length of vehicle arrival to the ramp and \( X \) is number of vehicle entering the on-ramp during each arrival cycle. The queue length (i.e. number of vehicles in the queue) is saved and used for the calculation of the ramp metering rate. The remaining queue of vehicles will also be kept for delay estimation for the next time step. 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 queue demand in the current framework is based on a deterministic arrival rate per time step. This simplistic assumption should be addressed in the future to reflect the more realistic fluctuation of the demand on the ramp. The equation below shows the detailed the 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.

\[
\text{If } (Ramp \text{ Metering Rate} \times \text{Time Step}) \leq \left( \frac{\text{Time Step}}{\text{Ramp arrival cycle}} \right) \times X + \text{Cumulative Queue on Ramp} \\
\text{Then}
\]

\[
\{ \\
\text{Delay on Ramp} = \left( \left( \frac{\text{Time Step}}{\text{Ramp arrival cycle}} \right) \times X + \text{Cumulative Queue on Ramp} - \text{Ramp Metering Rate} \times \text{Time Step} \right) \times \text{Time Step} + \text{Cumulative Delay on Ramp} \\
\}
\]

\{\text{Delay on Ramp} = 0\}

where \( X \) = Number of vehicles entering the ramp per arrival cycle.

EXPERIMENTAL ANALYSIS AND RESULTS

The developed algorithm was tested using Quadstone Paramics microsimulation software package. To test the performance of the proposed model on solution quality, a sensitivity analysis of various parameters of the developed algorithm was conducted. The results of the experiments are presented next.

The experiments were conducted with a real test network, which represented an on-ramp at the Memorial Drive and Deerfoot Trail (Highway 2) interchange in Calgary, Canada. The
A simulation network included a 5-km corridor on Deerfoot Trail with an equal distance of 2.5 km before and after the on-ramp as shown in Figure 4. The ramp had a length of 500 meters.

![Figure 4 – Paramics simulation model of the study area.](image)

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. By setting a starting link taken from Paramics, the links were then separated into four sections of equal length. The program then took all speed information of the vehicles that were tracked on those sections. Using the vehicle types to define these probe vehicles, the percentage of probe vehicles was changed through the Paramics interface. The speeds were taken at every simulated second, and the average speed of each section was computed at the end of every time step. These inputs were fed to the ramp metering algorithm, which computed the optimal ramp metering rate. The developed API was then able to dynamically change the light cycle on the ramp in Paramics to match that optimal rate.

The Paramics simulation model was coded based on the City of Calgary data related to detailed geometry, speed limits, curves, number of lanes, etc. Unfortunately, no real-time dependent Origin /Destination(O/D) flow tables were available with which to experiment. Hence, a synthesized O/D matrix was assumed to be the real one. This hypothetical demand was tested for congestion levels that were expressed in terms of different combinations of traffic demand levels for the on-ramp and mainline.

Table 1 summarizes the various traffic conditions considered in this paper. All scenarios were conducted for 2 cases: ramp metering and no ramp metering.

<table>
<thead>
<tr>
<th>Scenario Number</th>
<th>Scenario Description</th>
<th>Demand on Freeway</th>
<th>Demand on Ramp</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>High (10,000 veh/h)</td>
<td>High (1,300 veh/h)</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Medium (7,000 veh/h)</td>
<td>Medium (800 veh/h)</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>High (10,000 veh/h)</td>
<td>Medium (400 veh/h)</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Medium (7,000 veh/h)</td>
<td>High (1,000 veh/h)</td>
<td></td>
</tr>
</tbody>
</table>
The performance of the developed ramp metering algorithm was then examined by designing several experiments to test the impact of specific input factors on the performance of the ramp algorithm. The factors examined were:
- Percentage of penetration of vehicle probe data, and
- The effect of varying the estimation step.

The performance of the developed ramp metering algorithm was measured by comparing the following measures of effectiveness (MOEs) of the ramp metering case with the no-ramp metering case:
1) Mainline travel time: the freeway travel time (in seconds).
2) Network travel time: the overall network travel time, i.e. both the freeway and the ramp (in seconds).
3) Mainline flow: the throughput on the freeway (km/hr).
4) Network flow: the overall system throughput (i.e. both the freeway and the ramp) (km/hr).
5) Mainline speed: the average speed on the freeway (km/hr).
6) Network speed: the average speed on the whole system, i.e. both the freeway and the ramp (km/hr).

Performance of the Ramp Metering Algorithm under Various Congestion Levels

The performance of the developed algorithm was tested for various traffic conditions for the on-ramp and the freeway. A penetration rate of 40% for vehicle probes was assumed for all traffic scenarios. In other words, the system can track information on the average speed for only 40% of vehicles. A time step of 30 seconds and a freeway section length of 800 meters were used as the algorithm parameters. Each scenario was tested with 5 Paramics simulation runs with different seed values.

The first scenario is tested under high demand for both the freeway and the on-ramp. Table 2 reports the simulation results. These results summarize the averages of the 5 simulation runs corresponding to different seed values. As shown in Table 2, compared with the no-ramp metering case, the ramp metering scenario resulted in a reduction of the travel time on the mainline by 11%. An overall 5% reduction in travel time for the whole network (i.e. including all the vehicles on both the mainline and the ramp) was also observed. In addition, the average flow rate and average speed experienced an increase of 10% and 12.5%, respectively, on the mainline. The increase of the average flow rate and speed on the total network both reach 8%, compared to the case of no ramp metering. The low standard deviation of measures shown in Table 2 illustrates the low variability of the results.

The second scenario deals with medium demand (near capacity) on both the freeway and the on-ramp. The results are reported in Table 3, which show the excellent performance of the algorithm in improving the traffic flow, travel time and speed. The total network average flow rate and average speed increased by 14% and 9.5%, respectively. The total average travel time was reduced by 12%, compared to the case of no ramp metering. These results show the benefits of ramp metering, even for a moderately congested network. Again, as shown in Table 3, the results had low standard deviation, which indicates the high reliability of the algorithm.
Table 2 – Summary results for scenario 1: High demand conditions on both freeway and on-ramp

<table>
<thead>
<tr>
<th>Ramp Metering</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>No Ramp Metering</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>291</td>
<td>2.9</td>
<td>328</td>
<td>5.3</td>
<td>4.7</td>
<td>-11.2 %</td>
</tr>
<tr>
<td>Network Travel Time</td>
<td>282</td>
<td>2.6</td>
<td>297</td>
<td>4.7</td>
<td>1.1</td>
<td>-4.9 %</td>
</tr>
<tr>
<td>Mainline Flow</td>
<td>5505</td>
<td>193.0</td>
<td>4999</td>
<td>147.1</td>
<td>2.1</td>
<td>10.1 %</td>
</tr>
<tr>
<td>Network Flow</td>
<td>5338</td>
<td>183.7</td>
<td>4952</td>
<td>267.5</td>
<td>1.1</td>
<td>7.8 %</td>
</tr>
<tr>
<td>Mainline Speed</td>
<td>99</td>
<td>1.2</td>
<td>88</td>
<td>11.1</td>
<td>12.6 %</td>
<td>12.6 %</td>
</tr>
<tr>
<td>Network Speed</td>
<td>98</td>
<td>1.1</td>
<td>91</td>
<td>9.4</td>
<td>8.1 %</td>
<td>8.1 %</td>
</tr>
</tbody>
</table>

Table 3 – Summary results for scenario 2: Medium demand conditions on both freeway and on-ramp

<table>
<thead>
<tr>
<th>Ramp Metering</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>No Ramp Metering</th>
<th>Average</th>
<th>Standard Deviation</th>
<th>Percent Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>212</td>
<td>4.5</td>
<td>241</td>
<td>1.9</td>
<td>1.3</td>
<td>-11.9 %</td>
</tr>
<tr>
<td>Network Travel Time</td>
<td>207</td>
<td>4.2</td>
<td>224</td>
<td>1.3</td>
<td>0.6</td>
<td>-7.6 %</td>
</tr>
<tr>
<td>Mainline Flow</td>
<td>4638</td>
<td>332.1</td>
<td>4072</td>
<td>215.0</td>
<td>0.6</td>
<td>13.9 %</td>
</tr>
<tr>
<td>Network Flow</td>
<td>4546</td>
<td>249.7</td>
<td>3997</td>
<td>160.4</td>
<td>13.7 %</td>
<td>13.4 %</td>
</tr>
<tr>
<td>Mainline Speed</td>
<td>87</td>
<td>2.1</td>
<td>76</td>
<td>0.6</td>
<td>13.4 %</td>
<td>9.4 %</td>
</tr>
<tr>
<td>Network Speed</td>
<td>85</td>
<td>1.8</td>
<td>78</td>
<td>0.4</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The results of the above two scenarios are comparable to the field trial results reported by Hadj-Salem and Papageorgiou (1985) on Boulevard Peripherique in Paris, France. Although the performance of the ramp metering algorithm differs significantly depending on network characteristics, locations, geometric design, traffic demand, drivers' behavior, etc., a comparison is provided here to support the above simulation results. In addition, the results reported in our research are based on simulation and are only related to an isolated on-ramp; whereas, the field results described by Hadj-Salem and Papageorgiou are related to the whole corridor, consisting of several on-ramps and off-ramps. Hadj-Salem and Papariorgio reported the field trial results before and after implementing the ALINEA ramp metering strategy on part of Boulevard Peripherique in Paris (length of 12 km, comprised of 9 on-ramps and 11 off-ramps). The field test compared 14 days of ramp metering control with 14 days without control. The improvement in the total time spent (a similar performance measure to total network travel time) and mean speed under ramp metering for the mainline and the associated on-ramps were 8.1% and 7.8%, respectively.

The third scenario tested corresponds to a high demand on the freeway and a medium demand on the on-ramp. Table 4 shows the average reduction for the 5 runs. The results showed a 4.5% increase in the traffic flow and average speed, as well as a 4.5% reduction in travel time on the network. Table 4 also indicates the low variability of these estimates from one run to another.
The fourth scenario corresponds to a high demand for the on-ramp and a medium demand on the freeway. The algorithm did not show any improvement in traffic conditions for this scenario, which was expected. Ramp meters are usually turned off under such traffic conditions.

**SENSITIVITY ANALYSIS TO VARIOUS ALGORITHM PARAMETERS**

The developed algorithm was tested for 3 different percentages of penetration for the vehicle probes and for two different time steps updates.

**Impact of Penetration Rate**

One of the main concerns in applying a ramp metering strategy based on vehicle probes is the penetration rate required for the strategy to be effective. In these tests, three different penetration rates were examined: 10, 20 and 40%. Again, each scenario was tested with 5 simulation runs with different seed values.

Table 5 summarizes the results of the simulation for the four different penetration rates. The results show that the strategy’s effectiveness increased with increased penetration rates. For 10 and 20% penetration rates, the ramp metering algorithm still showed a significant improvement in all measures. The 40% penetration rate resulted in the highest reduction in travel time.

It is clear from these results that the travel time based ramp metering algorithm performs better with a higher percentage of penetration. However, more work needs to be conducted in the future for a greater understanding of the relationship between the percentage of penetration and the performance of the algorithm.
Table 5 – Summary results for different penetration rates

<table>
<thead>
<tr>
<th>Ramp Metering</th>
<th>10% Penetration Rate</th>
<th>20% Penetration Rate</th>
<th>40% Penetration Rate</th>
<th>No Ramp Metering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Percent Difference</td>
<td>Average</td>
<td>Percent Difference</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with No Ramp Metering</td>
<td></td>
<td>with No Ramp Metering</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mainline Flow</td>
<td>227</td>
<td>-5.9 %</td>
<td>219</td>
<td>-8.8 %</td>
</tr>
<tr>
<td>Network Flow</td>
<td>220</td>
<td>-1.7 %</td>
<td>213</td>
<td>-4.6 %</td>
</tr>
<tr>
<td>Mainline Speed</td>
<td>4601</td>
<td>9.6 %</td>
<td>4603</td>
<td>11.9 %</td>
</tr>
<tr>
<td>Network Speed</td>
<td>4460</td>
<td>6.7 %</td>
<td>4553</td>
<td>11.9 %</td>
</tr>
<tr>
<td></td>
<td>81</td>
<td>3.3 %</td>
<td>83</td>
<td>6.0 %</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>81.9 %</td>
<td>82</td>
<td>13.7 %</td>
</tr>
<tr>
<td></td>
<td>-4.5 %</td>
<td>-7.6 %</td>
<td>-11.9 %</td>
<td>-7.7 %</td>
</tr>
<tr>
<td></td>
<td>-0.7 %</td>
<td>13.9 %</td>
<td>-13.9 %</td>
<td>13.7 %</td>
</tr>
<tr>
<td></td>
<td>4.8 %</td>
<td>13.4 %</td>
<td>76</td>
<td>9.4 %</td>
</tr>
</tbody>
</table>

Impact of Time Steps

The proactive ramp metering algorithm was also tested under two time step intervals as the estimation steps: 30 and 60 seconds. The results show that overall the algorithm was more effective with a 30-second time step interval. The improvements caused by a shorter time step were more pronounced for medium/medium and high/medium demand traffic scenarios (i.e. scenarios 2 and 3), compared to the high/high demand traffic case (scenario 1). Table 6 shows the results for the medium/medium demand scenario.

The results in Table 6 show that the traffic condition and its optimal ramp metering rate are highly sensitive to the time step interval and would show significant improvement when the ramp metering algorithm runs at a more frequent time update. The improvement is more pronounced for medium/medium demand scenario compared to the high/high demand scenario. One possible explanation for the higher performance of the 30-second update, compared to the 1-minute 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.

Table 6 - Summary results for the algorithm time step interval under medium – medium scenario

<table>
<thead>
<tr>
<th>Ramp Metering</th>
<th>1-minute interval</th>
<th>30-second interval</th>
<th>No Ramp Metering</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average</td>
<td>Percent Difference</td>
<td>Average</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with No Ramp Metering</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mainline Flow</td>
<td>230</td>
<td>-4.5 %</td>
<td>212</td>
</tr>
<tr>
<td>Network Flow</td>
<td>222</td>
<td>-0.7 %</td>
<td>207</td>
</tr>
<tr>
<td>Mainline Speed</td>
<td>4272</td>
<td>4.9 %</td>
<td>4638</td>
</tr>
<tr>
<td>Network Speed</td>
<td>4187</td>
<td>4.8 %</td>
<td>4546</td>
</tr>
<tr>
<td></td>
<td>80</td>
<td>4.3 %</td>
<td>87</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>1.14 %</td>
<td>85</td>
</tr>
<tr>
<td></td>
<td>241</td>
<td>-11.9 %</td>
<td>224</td>
</tr>
<tr>
<td></td>
<td>224</td>
<td>-13.4 %</td>
<td>4072</td>
</tr>
<tr>
<td></td>
<td>3997</td>
<td>9.4 %</td>
<td>76</td>
</tr>
<tr>
<td></td>
<td>78</td>
<td>76</td>
<td>78</td>
</tr>
</tbody>
</table>
CONCLUSION AND CONTRIBUTIONS

This paper presented the development of a new proactive ramp metering strategy based on travel time estimated from vehicle probe technology. The algorithm computes the optimal ramp metering rate based on minimizing the system travel time, including both the travel time on the freeway – upstream and downstream of the ramp – and the wait time on the ramp. In addition, the developed model employs a dynamic weighting scheme that gives a different weight in the objective function to different freeway sections and the on-ramp. These weighting schemes are updated dynamically at every estimation step, based on the prevailing densities of the freeway sections, as well as information on queue length for the on-ramp. 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.

The developed ramp metering algorithm was tested using Quadstone Paramics microsimulation software for a simulated real ramp on Highway 2 (Deerfoot Trail) in Calgary, Canada. The developed algorithms have been rigorously examined for different traffic conditions and ramp algorithm input parameters. The results showed an overall improvement in traffic condition (i.e. average travel time, flow and speed) on 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 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 next phase of this research effort research should extend the algorithm to develop coordinated ramp metering algorithms. Furthermore, future extension of this research can compare the performance of the travel time based algorithm with ramp metering algorithms that take input from freeway detector data.

Acknowledgement

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REFERENCES


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