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CALIFORNIA PARTNERS FOR ADVANCED TRANSIT AND HIGHWAYS

Evaluation of On-ramp Control Algorithms

Interim Report

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Chapter 1

Introduction to Ramp Metering

A freeway corridor consists of the freeway and its entrance/exit ramps, the cross streets, and adjacent parallel arterial streets. It is designed to provide a generally high level of service (LOS) to their users and to the communities which they serve. However, many corridors in the country are congested, with the worst congestion problems usually arising during the two peak periods (morning and evening) (Schrank and Lomax, 1999). There are two types of traffic congestion observed: recurrent and nonrecurrent. Recurrent congestion are due to excessive peak demands and nonrecurrent congestion are due to capacity reduction caused by events such as accidents.

The control of a traffic corridor, which consists of two major components—freeway system control and arterial street system control, is aimed at improving flows on both freeway and arterial streets, and has been demonstrated as an effective mean to increase the level of service of a corridor system during peak periods. Ramp metering, or on-ramp control, which is designed to determine a metering rate for each controlled on-ramp based on traffic conditions of part or whole of the corridor, has been considered a very important component of corridor traffic control.

There exists a large number of ramp metering schemes in literature. While some of them were implemented in the real world, most of these algorithms are still awaiting further assessment. The latter is the focus of this report. It is not our intention to review every ramp metering algorithm proposed. Rather, we focus on the most popular (in terms of their usage) and theoretically attractive (according to their logic) ones from a recent comprehensive review of existing ramp metering algorithms (Bogenberger and May, 1999). According to a set of criteria, we ranked the reviewed algorithms and plan to evaluate them in more detail in the second phase of this project.

Ramp metering is designed to achieve one or more of the following non mutually exclusive goals:

- to alleviate or eliminate congestion;

- to improve freeway flow, traffic safety and air quality by the regulation of input flow to a freeway;

- to reduce total travel time and the number of peak-period accidents;

- to regulate the input demand of the freeway system so that a truly operationally balanced corridor system is achieved.

There are three types of ramp metering control systems:

1. *isolated* or *local* system, in which control is applied to an on-ramp independently of any other on-ramps;

2. *coordinated* system, in which control is applied to a group of on-ramps in a coordinated fashion, taking into consideration the traffic conditions in the whole system rather than the local conditions around independent on-ramps;

3. *integrated* system, in which different types of control measures are used, such as ramp metering, signal timing, and route guidance via variable message signs (VMS).

According to the control philosophy, there are two classes of control schemes:

1. *fixed-time/ pre-timed/ time-of-day* control, in which metering rates are fixed according to clock time. It is proven to be effective in alleviating recurrent congestion, provided severe incidents or abrupt changes in demand do not occur;

2. *traffic-responsive* control, in which real-time freeway data are used to determine the control policy, and most of modern ramp metering strategies are based on this philosophy of control.

Chapter 2

What is an Ideal Ramp Control Methodology?

Given a clear set of control objectives and technologies, an ideal control methodology should possess the following properties:

- (C1) A good system model describing freeway operations and control – The model should be able to describe both the operations and control in the freeway system accurately. It should capture major traffic flow phenomena that are critical to control design, such as criticality, shock waves, and drivers' response to controls.

- (C2) Sound theoretical foundation – i.e., reasonable assumptions and objectives, rigorous problem formulation, efficient and accurate solution methods.

- (C3) Proactive and balanced – prevent congestion rather to react to congestion, and avoid happening of spillback of queues or over-congestion concentrated in one particular part of the system.

- (C4) Accuracy and robustness – The control actions should be effective to achieve the control objective, and degrades gracefully when part of the system, such as input links, is down.

- (C5) Computational efficiency – Algorithms are easy to program, run fast, and require moderate amount of memory.

- (C6) Flexibility and expandability – The algorithm should be easy to implement, modify and expand to account for more complex and perhaps more realistic situations encountered in the freeway system.

- (C7) Ability to handle special situations, such as giving priority to high occupancy vehicles (HOV), control under bad weather, or incident conditions.

- (C8) Simplicity- Use the simplest logic structure possible to reconcile demands on realism and theoretical elegance.

Chapter 3

Categories of Existing Ramp Metering Schemes

Some of on-ramp control methodologies have been evaluated and implemented in the field, while others are still awaiting further assessment. The well-documented implemented metering algorithms include the zone ramp metering algorithm (Stephanedes, 1994), the helper ramp metering algorithm (Lipp et al., 1991), the bottleneck ramp metering algorithm (Jacobsen et al., 1989), the Sperry ramp metering algorithm (Report 1), the compass ramp metering algorithm (Report 2), the fuzzy logic ramp metering algorithm (Meldrum and Taylor, 1995), the linear programming ramp metering algorithms (Yoshino et al., 1995), the linked-ramp ramp metering algorithm (Banks, 1993), the METALINE ramp metering algorithm (Papageorgiou et al., 1990), and the ALINEA ramp metering algorithm (Papageorgiou et al., 1997). Those proposed ramp metering algorithms awaiting further assessment include the Ball Aerospace / FHWA ramp metering algorithm (Report 4, 1998; Report 5, 1998), the SWARMS ramp metering algorithm (Paesani et al., 1997; Report 3, 1996), and the coordinated artificial neural networks based ramp metering algorithm (Wei and Wu, 1996), and some of them will probably see their day in the field soon.

As we know, a freeway corridor has a hierarchic structure, formed by a mainline backbone, the freeway, and its branches, on-ramps and off-ramps, and traffic dynamics of an on-ramp generally affect traffic performance of the part of the mainline freeway downstream to the on-ramp, instead the part upstream to it, unless the on-ramp itself becomes a source of congestion. The hierarchic structure of a corridor and the influence of the on-ramps to the mainline freeway determine the designing philosophy underlying the ramp metering algorithms, and we find the ramp metering algorithms can be categorized into four types: *isolated* ramp-metering, in which the metering rates are decided solely by local traffic conditions; *cooperative* ramp-metering, in which the metering rates are first computed with the local traffic information, then adjusted according to the conditions of the entire system; *competitive* ramp-metering, in which two metering rates are computed for each ramp, one is based on local traffic conditions, and the other is based on system conditions, and the restrictive one is chosen; *integral* ramp-metering, in which local traffic conditions and system-wide traffic conditions are both used to determine metering rates. The last three types of algorithms are generally called coordinated ramp metering algorithms. A classification tree for algorithms to be reviewed is shown in Fig. 3.1, and we shall assess them based one the set of criteria developed in Chapter 2, starting with the simplest and ending with the most sophisticated metering algorithms.
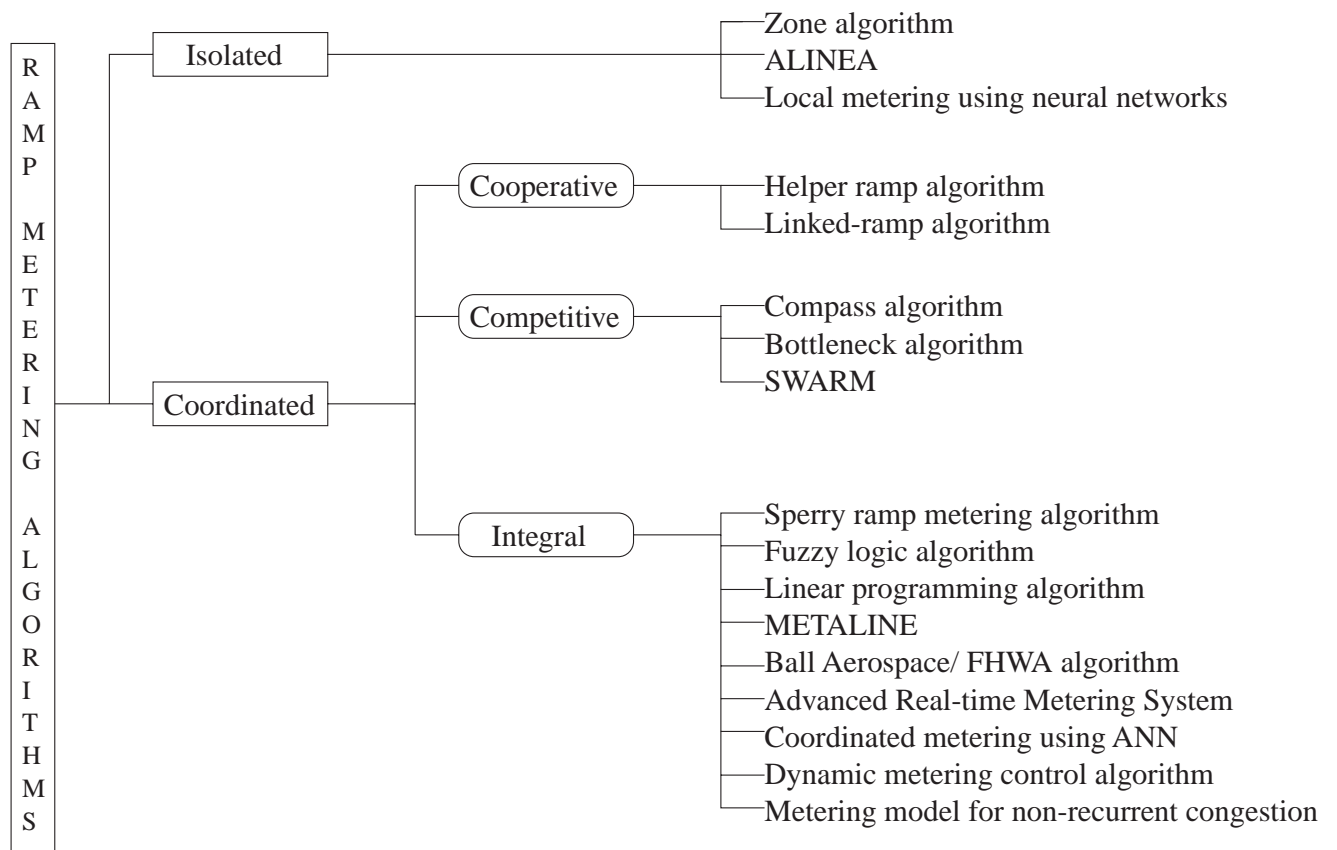
Figure 3.1: The categories of ramp metering algorithms to be assessed

Chapter 4

Conceptual Evaluation of Various Ramp Metering Algorithms

4.1 Isolated ramp-metering algorithms

In isolated ramp-metering algorithms, a ramp metering rate for an on-ramp is determined based on its local traffic conditions, such as flow, occupancy, travel speed, and occasionally queue over-flow on the metered ramp. Algorithms in these category to be reviewed include the zone algorithm (Stephanedes, 1994), ALINEA ((Papageorgiou et al., 1997), and the neural control algorithm (Zhang et al., 1996; Zhang and Ritchie, 1997).

Among the three local algorithms, ALINEA and the neural control algorithm both use feedback regulation to maintain a desired level of occupancy, or the target occupancy, which is usually chosen to be the critical occupancy, and apply the kinematic wave theory with locally calibrated fundamental diagrams as the underlying traffic model.

For moderate congestion, both algorithms are effective, robust, and flexible. They are also easy to implement because the only parameters are the control gain and target occupancy. However, both algorithms do not consider queue spill-back directly, which is generally handled through overriding restrictive metering rates, and would have difficulty to balance freeway congestion and ramp queues when traffic becomes heavily congested. Moreover, the neural control algorithm is limited in adaptive control if on-line tuning is implemented.

Overall we would rank both ALINEA and the neural control algorithm as good.

In the zone algorithm, the mainline freeway is divided into several zones, and each entry ramp is affiliated with a zone. Based on traffic conservation, the metering rate for each on-ramp is computed to balance the volume of traffic entering and leaving each zone, so that traffic in each zone is moving at a desired pace. Further adjustment to the metering rate can be made based on environmental factors and other considerations. The key elements of this algorithm are the proper division of zones, the accurate estimation of bottleneck capacity, the accurate measurement of all in and out flows from a zone.

The zone algorithm has been employed by Minnesota DOT for many years and considerable experience has been gained with this particular algorithm, and is flexible due to possible adjustments for different situations. However, parameters for the algorithm have to be tuned carefully to suit local traffic and freeway characteristics, which may not be as easy as it appears because the relation between the control parameters and the control objective is not clear in the zone algorithm. Another significant drawback of the algorithm is that it does not consider the dynamic nature of traffic flow, and for this reason may not perform well under conditions as happening of an incident

when fast changes of traffic flow occur.

Overall, we would rank this algorithm as good.

All three algorithms would be evaluated using PARAMICS. Although none of them consider system-wide information, they may serve as building blocks of coordinated metering schemes.

4.2 Cooperative Ramp Metering Algorithms

In cooperative ramp metering algorithms, after computing the metering rate for each on-ramp, further adjustment is done based on system-wide information to avoid both congestion at the bottleneck and spillback at critical ramps. This scheme is an improvement over isolated ramp metering strategies. These algorithms, however, are still reactive to critical conditions and perform the adjustment in an ad hoc manner, and therefore traffic instability may arise when such control strategies are implemented.

4.2.1 Helper ramp algorithm

Helper ramp algorithm (Lipp et al., 1991) was first implemented in Denver area along the I-25 freeway in March 1981, and additional ramp meters were installed along several freeways in the Denver area in 1984.

In this algorithm, a freeway corridor is divided into six groups consisting of one to seven ramps per group. In the local traffic responsive metering component of the helper algorithm, each meter selects one of six available metering rates based on localized upstream mainline occupancy. In coordination part, if a ramp grows a long queue and is classified as critical, its metering burden will be sequentially distributed to its upstream ramps.

The two-level structure of the helper algorithm makes it more capable and flexible when dealing with heavy congestion. This algorithm can be and actually was modified to consider special situations such as bus bypasses and HOV lanes. Because the algorithm does not have a systematic way of designing the metering look-up table in the local level and determining the assignment rates in the coordination level, experience with local traffic patterns and trial-and-error is a must in fully utilizing the potential of this algorithm. Nevertheless, helper appears to be a quite robust strategy when accurate traffic flow models and origin-destination information are not available to the controller.

We would rank this algorithm as very good.

4.2.2 Linked-ramp algorithm

Linked-ramp algorithm (Banks, 1993) was used in the San Diego area since 1968. Before 1994, this system was partially coordinated, but now is separated into a number of local traffic responsive controllers.

This algorithm is based on the demand-capacity concept, and the local metering rate is determined based on upstream flow measurement at each location:

$$\text{metering rate} = \text{target flow rate} - \text{upstream flow rate}$$

The coordination component of this algorithm is functionally similar to that of the helper algorithm; i.e., whenever a ramp's metering rate is in one of its lowest three metering rates, then the upstream ramp is required to meter in the same rate or less, and, if necessary, the further upstream ramps are also required to do so.

This algorithm shares largely the same advantages and disadvantages of the helper algorithm, hence its ranking also. Its local control logic, however, is rather inadequate for congested traffic because the more congested the traffic is, the lower the upstream flow rate, and the higher metering rate this logic produces, which is just the opposite of what one would do.

Because of their strong resemblance, we decided to further evaluate only one of the two cooperative algorithms—the helper algorithm.

4.3   Competitive Algorithms

In the competitive algorithms, two sets of metering rates are computed based on both local and global traffic conditions, and the more *restrictive* one will be selected as the actually implemented rates. Further adjustment to the selected metering rates may also be made to account for spill-back and other constraints.

4.3.1   Compass algorithm

Compass algorithm (Report 2) was first implemented in the Toronto area, Canada in 1975.

Locally, the compass algorithm determines the metering rates from an ad-hoc look-up table, which has seventeen levels for each ramp, determined by the local mainline occupancy, the downstream mainline occupancy, the upstream mainline volume as well as some pre-defined parameters that include thresholds for local and downstream occupancies, and upstream volume. Globally, coordinated control use off-line optimization to generate metering rates based on system-wide information. The most restrictive of the two rates is selected.

The compass algorithm addresses spillback through overriding restrictive rates: if the occupancy at a ramp queue detector exceeds its threshold value, the metering rate is increased by one rate level until the detected occupancy is back below the threshold level.

The Compass algorithm is flexible, considers many types of constraints, and is straightforward to implement. However, it is not robust because of the use of look-up tables and predetermined metering rates.

Overall we would rank this algorithm as good.

4.3.2   Bottleneck algorithm

The Seattle bottleneck algorithm (Jacobsen et al., 1989) was developed by the Washington Department of Transportation (WSDOT), and has been used to control a portion of I-5, north of the Seattle Central Business District.

This algorithm also has a two-level structure. At the local level, a control strategy compares the upstream demand with the down stream supply (that is, the real-time capacity), then takes the difference of them as the locally determined metering rate. At the global level, a coordinate control strategy first identifies bottlenecks, decides the volume reduction for the bottleneck based on flow conservation, and then distributes the volume reduction to upstream ramps, the coordination determined metering rates, according to predetermined weights. The restrictive of the locally and globally determined rates is selected to be realized.

The Seattle bottleneck algorithm is conceptually one of the best heuristic ramp metering algorithms implemented in the field. It is real-time, coordinated, yet logically simple (based on supply-demand and flow conservation) and flexible (only a few adjustable parameters). Field operations with this control also show markable improvement in traffic conditions.

Nevertheless, the Seattle algorithm can be improved by adopting a more robust local control strategy such as ALINEA, and real-time adjustment of volume reduction weights based on current O-D information. Further consideration of ramp queue spill over is also needed.

The overall ranking of this algorithm is very good.

4.3.3   System wide adaptive ramp metering (SWARM)

SWARM (Paesani et al., 1997; Report 3, 1996) is developed by NET and is expected to be tested in Orange County, California.

Like other heuristic coordinated control algorithms, SWARM also operates at two levels: the local control decides ramp metering rates based on local density; the global control decides the overall volume reduction from ramps upstream a critical bottleneck, and then distributes them to upstream ramps according to a set of predetermined fractions to obtain a new set of ramp metering rates; the most restrictive of the two is selected for each ramp.

SWARM has a built-in failure management module to clean faulty input data from detectors. It also allows further adjustment to accommodate queue spill-back handling. Both features enhance its robustness.

Unlike previous two-level algorithms, SWARM identifies bottlenecks based on predicted traffic conditions rather than measured traffic conditions. Therefore it has the potential to nail congestion in the bud. On the other hand, it could also produce worse results than other non-anticipating algorithms (such as the Seattle Bottleneck Algorithm) if its predictions are poor. Good prediction models and accurate OD information are two key elements in the successful implementation of SWARM.

Overall we would rank this algorithm as very good.

4.4   Integral Ramp Metering Algorithms

Integral ramp metering algorithms have a clear control objective(s) that is explicitly or implicitly linked to the control action. The objective is usually travel time, or throughput of the entire system. They decide ramp metering rates through optimizing the objective while considering system constraints, such as maximum allowable ramp queue, bottleneck capacity, and so forth. As in other algorithms, further adjustments to the computed metering rates can be done to deal with special scenarios, such as ramp queue overflow. This, however, is mostly done in an ad hoc manner.

Conceptually this class of algorithms is most appealing because of their solid theoretical foundation and their capability of handling various types of metering and modeling constraints. However, these algorithms are also invariably more complex in logic and more demanding in computation. Their performance is heavily dependent on the quality of input data (such as O-D tables, estimated bottleneck capacity, and predicted demands), and the traffic models used.

4.4.1   Sperry ramp metering algorithm

The Sperry algorithm (Report 1) was developed by Virginia Department of Transportation. It was used to control 26 ramp meters along I-395 in northern Virginia.

We have found only a sketchy description of this algorithm. Thus it is not possible to rate the Sperry algorithm at this moment. We are attempting to locate further documentation of this algorithm.

4.4.2 Fuzzy logic algorithm

Fuzzy logic based ramp control (Meldrum and Taylor, 1995) has been implemented in Seattle and the Netherlands.

Fuzzy logic algorithms convert empirical knowledge about traffic flow and ramp control into the so-called fuzzy rules. Traffic conditions, such as occupancy, flow rate, speed, and ramp queue are divided into finite categories, such as small, medium, and big, and then rules are developed to relate traffic conditions with metering levels. For example, a rule can be: *if the local occupancy is small, and ramp queue is small, then metering rate is high.* Finally the categorical values of small, big, etc. are converted into crisp numbers according to membership functions.

In a way a fuzzy logic algorithm is like an expert system. It is very powerful and robust if the right type of rules are used. Often only a few rules are needed for local control strategies. For system-wide control, the rule base can be quite complex. Developing a consistent set of rules that embodies the objective of control is not always straightforward. Moreover, it often takes great amount of effort to calibrate the parameters (tuning the rules and membership functions), which may work well under the set of conditions that the parameters are calibrated but perform poorly when traffic conditions have changed. Weighing its theoretical attractiveness and practical complexity, we would rank this algorithm as good.

4.4.3 Linear programming algorithm

Linear programming based ramp control algorithms (Yoshino et al., 1995) are among the oldest in both research and practice. It was widely used in developing time-of-day ramp metering rates before automatic control based dynamic algorithms were introduced. The particular linear programming algorithm that we evaluate here, which was developed and implemented in Japan, has a few unique features. First, it maximizes the weighted sum of ramp flows where the weights are selected by the user to reflect his belief in the varying importance of the ramps. Secondly, it computes a real-time capacity for each road segment. This allows the algorithm to work under congested road conditions. Constraints on ramp queue length and metering bounds are easily incorporated in and is integral to the linear programming formulation of ramp metering.

Although mathematically more complex than most of the other algorithms that we have discussed thus far, the linear programming ramp metering algorithm can be solved very efficiently using canned linear programming solvers. The drawbacks of this algorithm are 1) its performance is heavily dependent on accurate O-D data, and 2), it is static, i.e., it neglects the variation of travel time in its computation of ramp metering rates. Overall we would rank this algorithm as good.

4.4.4 METALINE algorithm

METALINE (Papageorgiou et al., 1990 is an extension of the local control algorithm ALINEA. It was implemented on certain freeways in France, the United States and the Netherlands.

The control logic of METALINE is Proportional-Integral state feedback. The metering rate of each ramp is computed based on the change in measured occupancy of each freeway segment under METALINE control, and the deviation of occupancy from critical occupancy for each segment that has a controlled on-ramp:

$$\vec{r}(k) = \vec{r}(k-1) - \mathbf{K}_1(\vec{o}(k) - \vec{o}(k-1)) - \mathbf{K}_2(\vec{O}(k) - \vec{O}^c)$$

where, $\vec{r}(k) \in \mathbb{R}^m$ is the vector of metering rates for the m controlled ramps at time step k; $\vec{o}(k) \in \mathbb{R}^n$ is the vector of n measured occupancies within the directional freeway segment at

time step k; $\vec{O}, \vec{O}^c \in \mathbb{R}^n$ are respectively the measured and desired occupancy downstream of m controlled ramps. $\mathbf{K}_1, \mathbf{K}_2$ are two gain matrices.

Like the ALINEA algorithm, the METALINE algorithm is theoretically sound, robust, and easy to implement. The main challenge to the success operation of METALINE is the proper choice of the control matrices $\mathbf{K}_1, \mathbf{K}_2$ and the target occupancy vector $\vec{O}^c$. There is no direct consideration of queue overflow, HOV/bus priority, and bottleneck effects in METALINE. One can, however, adjust in an ad hoc manner the METALINE metering rates to partially address these constraints.

Overall we would rank this algorithm as very good.

4.4.5   Ball AEROSPACE / FHWA ALGORITHM

Funded by the Federal Highway Administration, Ball AEROSPACE is developing a corridor control system in which system-wide ramp metering is one component (Report 4, 1998; Report 5, 1998). At the moment, the algorithm is still under development and no algorithmic detail but a few sketches of conceptual flow charts are available. Judging from these charts, it appears that Ball AEROSPACE attempts to develop a fairly comprehensive ramp metering system whose logical structure is quite complex. We await further documentation of this algorithm to perform a thorough evaluation.

4.4.6   Coordinated Metering using Artificial Neural Networks

The coordinated artificial neural networks based ramp metering algorithm (Wei and Wu, 1996) uses artificial neural networks to learn and memorize the metering plans generated by a traffic simulation model (FREEQ10PC) and a ramp control expert system. As such, the full capability, such as adaptive learning, of artificial neural networks is not fully exploited by this algorithm. Basically it does whatever the ramp control expert system does.

There are better coordinated neural control algorithms, one of which was developed with the support of Caltrans (Zhang 1995). These algorithms are typically adaptive algorithms in the sense that the neural network controllers adjust their control gain in real-time.

We would rank this version of a neural network ramp metering algorithm as fair.

4.4.7   Advanced Real-time Metering System (ARMS)

ARMS (Liu et al., 1993), developed by researchers from Texas Transportation Institute, works on two levels. In the first level, a system-wide control policy is to maintain free flow conditions. The total metering volume is obtained by maximizing an objective function that includes throughput, and innovatively the risk of congestion, then distributed to each ramps using O-D information. A prediction and pattern recognition algorithm is also developed to predict in real time the potential occurrence of recurrent congestion. In the second level, the algorithm works to resolve congestion once it develops. It does this by minimizing the congestion clearance time and queues on the controlled ramps. Again the total metering volume obtained from the second level is distributed to each ramp based on O-D information.

The novelty of this algorithm is that it incorporates a congestion risk factor into its formulation. It also projects traffic conditions to decide potential bottlenecks, which makes the algorithm proactive. Although this algorithm is relatively more complex, the aforementioned attractive features of the algorithm makes it standing out as a very good algorithm.

4.4.8 Metering model for non-recurrent congestion

Metering model for non-recurrent congestion (Chang et al., 1994) has nearly all the elements of a good ramp control algorithm: the whole process is set up as an optimal control problem, it has a dynamic traffic flow model (the kinematic wave traffic model) to describe the traffic flow process, explicitly links control with a clear set of objectives (i.e., maximizing throughput), takes into account system-wide physical and environmental constraints (e.g., maximum ramp queue) and projected traffic conditions (e.g., capacity reduction, future demand), and uses a rigorous yet straightforward solution procedure (successive linear programming) to obtain real-time metering rates. The performance of this algorithm, as indicated from the simulation results reported in (Chang et al., 1994), is quite good.

Nevertheless, one can do a few things to improve this algorithm. First, its numerical approximation of the kinematic wave model is not the most accurate. By using a more accurate approximation procedure (i.e., the Godunov scheme), one can both improve the accuracy of the flow predictions and eliminate the complicated Kalman filtering process, thus significantly speeds up the computation of ramp metering rates. Second, this algorithm takes the capacity reduction (caused by incidents) factor as given and fixed. In reality, this factor is not known in real-time and may also change over time. One can, however, devise ways to estimate how much capacity reduction takes place in real-time. Third, the algorithm does not explicitly consider OD flow. Rather, it uses exit fractions to capture time-varying OD demands. This limits its ability to handle traffic diversions in an optimal way. Actually diversions in this algorithm are part of the inputs, not something to be optimized by the algorithm. This can be changed if a multi-commodity traffic flow model is used.

Overall, the algorithm is theoretically appealing and can be ranked as very good.

4.4.9 Dynamic metering control algorithm

The dynamic ramp metering model developed by Chen, Hotz and Ben-Akiva (1997) has four elements: local control, area-wide control, state estimation and O-D prediction. Local control attempts to maintain traffic conditions close to the target traffic conditions that are provided by area-wide control. The area-wide control in the dynamic ramp metering model is a predictive (rolling horizon) optimal control algorithm. It obtains metering rates through minimizing the total system travel time that includes travel time on freeway and delay on ramps, subject to demand and queue capacity constraints. To know future travel demand and traffic conditions, a state estimation model and a O-D prediction model are also developed. In the end, the two controls are combined in the following way:

$$r_t = \bar{r}_k - K(o_t - \bar{o}_k)$$

where r_t and o_t are respectively the local ramp metering rate and occupancy at time t, while $\bar{r}_k$ and $\bar{o}_k$ are respectively the ramp metering rate and occupancy set by the area-wide control algorithm.

Overall this is perhaps the most complex and comprehensive ramp metering algorithm that we have reviewed in this report. It contains essentially all the elements that an ideal ramp metering algorithm has. It is system-wide, adaptive and predictive. Initial simulation by Chen, Hotz and Ben-Akiva (1997) indicates that the combined local/area-wide control model is more effective than each control model operating alone. It is yet to be seen, however, how smooth this control model will operate in the real world because its effectiveness depends heavily on the accuracy of the state estimation and O-D prediction models.

We would rate this algorithm as very good.

Chapter 5

Discussions

Over the years, many ramp metering algorithms have been proposed. We have in this report reviewed a sample of these algorithms that we consider to be representative. Prior to our review, we developed a classification scheme and a set of evaluation criteria to aid the categorization and qualitative assessment of the selected metering algorithms. The findings are reported in Chapter 4 and we do not intend to repeat them here. Instead, we make a few remarks about possible improvements and further directions of research in ramp metering.

Ramp metering improves freeway traffic flow because it 1) breaks up vehicle platoons from entrance ramps so as to reduce the chance of traffic breakdown due to merging, and 2) distributes traffic more evenly over time and space to avoid saturation pressure on bottlenecks. When the demand pressure is not high, ramp metering can completely eliminate freeway congestion with a moderate price: some delays on the metered ramps. This, however, is not always achievable when demand pressure exceeds certain thresholds. When this happens, one can either give priority to the freeway and meter the ramps as heavily as one can so as to maintain free flow on the freeway (freeway-first policy), or balance the interests of traffic on the freeway, ramps and feeder streets and meter the ramps at such a level that it improves freeway flow but also does not create long queues on ramps or gridlock on feeder streets (balanced policy).

Among the ramp metering algorithms reviewed in this report, the majority falls inbetween the two kinds of policies. That is, they usually give priority to freeway traffic but also give some consideration to traffic on entrance ramps and arterial streets when delays on entrance ramps become excessive or queues on entrance ramps are about to spill back onto feeder streets. When the sizes of queues on metered ramps become critical, it is customary for these algorithms to raise the entrance flow from ramps to a higher level till the critical queues subside. This often creates a "boom-and-bust" cycle in ramp metering: under high demand pressure, critical conditions on the freeway demand lower metering rates, which often leads to long queues at metered ramps. This makes the ramps become critical that in turn demands higher metering rates. Higher metering rates again put more demand pressure on freeway bottlenecks. The cycle goes on till demand pressure subsides to a sufficient low level.

To eliminate the "boom-and-bust" cycle, one can do a few things. The most straightforward is to monitor the queues on various ramps and adjust the metering rates gradually to prevent the queues become critical in a smooth manner. This can be done effectively when the demand pressure is moderate at most ramps and high at only a few ramps. When the demand pressure is high across board, it may no longer be feasible to maintain free flow conditions on the freeway while keeping the ramp queues undercritical (Zhang, Ritchie and Recker 1996, Zhang and Recker 1999). Under such situations, truly system-wide adaptive control is called for. Such controls should have a well defined objective that balances the interests of freeway, ramp and feeder streets operations, and

links the performance of the system with traffic conditions and ramp control actions. Among all reviewed algorithms, only two (Ball Aerospace and Dynamic metering control algorithm) belong to this category. Although this kind of algorithms are potentially more effective in improving overall system performance, they are also inherently more complex, therefore require a more sophisticated understanding of traffic systems for their successful implementations. As a result, no such ramp metering systems, to the best of our knowledge, have been implemented in the field. The situation can be improved if a testing facility is available to systematically test and refine such complex ramp metering systems before they are put into daily operations. In this way both system developers and operators gain experience and confidence in implementing and operating such complex systems. We believe that this project and the Testbed facility at UC Irvine would facilitate this effort.

We also want to emphasize the importance of accurate O-D information and predictions of traffic conditions in successful ramp metering. O-D information plays a critical role in managing ramp queues and traffic diversions to feeder streets, and the knowledge of future traffic conditions allows proactive actions be taken to prevent traffic congestion rather than cope with it after it has already occurred. Another important factor that a successful ramp metering system has to consider is the response of drivers to ramp metering in both short and long terms. This aspect is almost completely ignored by nearly all reviewed metering algorithms. Drivers' responses to ramp metering have significant implications to both temporal and spatial distributions of demand to entrance ramps, thus play a critical role in determining metering and infrastructure expansion policies in the long range time scale.

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