MODELING AND PARAMICS BASED EVALUATION OF NEW LOCAL FREEWAY RAMP METERING STRATEGY THAT TAKES INTO ACCOUNT RAMP QUEUES

Kaan Ozbay[1], Ph.D., IlginYasar[1], Pushkin Kachroo[2], Ph.D.

[1]Department of Civil&Environmental Engineering, Rutgers University
[2]Bradley Department of Electrical&Computer Engineering, Virginia Tech

Abstract: In this paper, a “feedback” based ramp metering strategy that not only regulates the ramp input into the freeway but also regulates ramp queues by explicitly modelling them as a part of the feedback based ramp metering strategy is developed. This mixed ramp metering strategy and two other ramp control strategies, namely ALINEA (Papageorgiou, 1991), New Control (Kachroo and Ozbay, 2003) are tested using PARAMICS, a microscopic traffic simulation package, on a test network located in Hayward, California. Our simulation results show that proposed Mixed Control ramp metering strategy is promising in terms of improved overall system-wide performance.

Keywords: Closed loop controller, control algorithms, nonlinear control, feedback control, performance

1. INTRODUCTION

Increasing dependence on car-based travel has led to the daily occurrence of recurrent and non-recurrent freeway congestions not only in the United States but also around the world. Ramp metering is a direct and efficient way to control and upgrade freeway traffic flow by regulating the number of vehicles entering the freeway. From previous theoretical investigations and field operational tests, it is well known that ramp metering has various positive effects such as (Papageorgiou, 1999):

- Maintain freeway operations at noncongested condition.
- Maximize mainline throughput.
- Increase travel speed (upstream and/or downstream, depending on the strategy).
- Reduce travel time.
- Reduce auto emissions and accidents due to a smoother mainline flow.

There are two major philosophies of ramp metering strategies namely, local and system-wide. Local ramp metering strategies consider an isolated section of the network consisting of a freeway section with one on-ramp, and respond only to the changes in the local conditions. On the other hand, systemwide ramp metering is the application of metering to a series of entrance ramps with the goal of coordinating the response of all the ramps in the system. Another hybrid ramp metering strategy that combines local and system-wide ramp metering is known as hierarchical ramp metering. In this approach, a system-wide model at the upper level defines the overall desired network states, while a local model at the lower level performs to adjust the metering rate to achieve system states close to the system target.

Based on their responsiveness to the traffic, ramp metering strategies can also be divided into two categories.

Pretimed Ramp Metering; Pretimed metering is the simplest form of on-ramp metering. Ramp metering rates are constant and determined based on off-line demand for particular time-of-day historical traffic observation data, without the use of real-time measurements of sensors. It can be effective in eliminating recurrent congestion, if severe incidents or sudden changes in demand that cannot be captured by the historical measurements do not occur. However, since traffic demand is not constant, it varies during day, and different days. Moreover, incidents may perturb traffic conditions in a non-predictable way. All these unexpected fluctuations in demand can render pre-timed ramp metering strategies ineffective. These pre-time ramp metering strategies may thus lead either to overload of the mainstream flow (congestion) or to underutilization of the freeway by achieving the opposite of it is trying to avoid, congested traffic conditions on the freeways. (Traffic Control Systems Handbook, 1996)

Traffic Responsive Metering; In contrast, traffic responsive metering rates are determined based on information about the state of the traffic flow on the mainline and/or on the ramp traffic conditions. Based on the prevailing traffic conditions captured by real-time traffic data, such as occupancy, flow rate on the freeway and/or ramp, the metering rate are varied over time to effectively respond to traffic fluctuations. Ramp control systems can also be categorized as open loop and closed loop. In an open-loop ramp control system (demand capacity control, upstream occupancy control, etc.), the control input (for example, ramp metering rate) is independent of the system output, the existing traffic conditions (e.g., volume, occupancy, etc.). One of the important factors in freeway control is the management of the metering queue. In fact, a ramp metering application, aiming at avoiding or reducing congestion on the freeway, may have a positive or/and a negative impact on the adjacent road network traffic. In both demand-capacity control and upstream occupancy control, ramp-metering rate is set to minimum, if the threshold values for downstream capacity are reached or exceeded; therefore, on ramp queues are not handled directly in these controls (Banks, 1990). In closed loop control, the system output is fed back, and the input is modified by an appropriate regulator to keep the output near its set value despite the influences of time-variant disturbances (for example, flow on the upstream of the ramp). One of the most widely used algorithms in this category is ALINEA (Papageorgiou et al., 1991). ALINEA is a linearized local-feedback control algorithm that adjusts the metering rate to keep the occupancy downstream of the on-ramp at a prespecified level, called the occupancy set point. ALINEA uses 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.

ALINEA, closed-loop ramp metering strategy, suggested by Papageorgiou, *et a*l. (1991), to be applied at the time instants $kT, k = 0,1,2,...$, for any sample time interval T (e.g., $T = 60\,\text{sec}$) is

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

Where $K_R > 0$ is a regulator parameter, $\hat{o}$ is a set (desired) value for the downstream occupancy (typically, but not necessarily, $\hat{o} = o_{cr}$ may be set, in which case the downstream freeway flow becomes close to q_{cap}, see Fig. 1), $r(k-1)$ is the last on-ramp volume, and $r(k)$ is the current ramp volume.

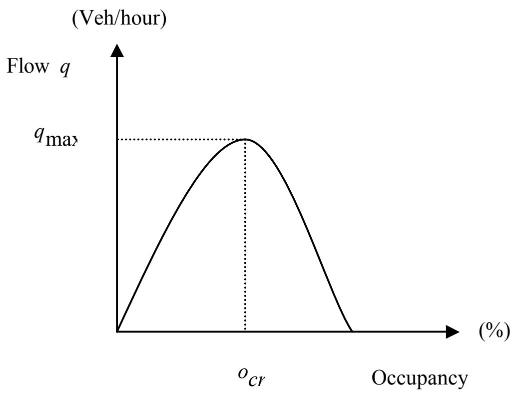

Fig. 1. The fundamental diagram (May, Adolf)

The set value, $\hat{o}$, may be changed any time, and thus ALINEA may be embedded into a hierarchical control system with set values of the individual ramps being specified in real time by a superior coordination level or by an operator.

Some of these freeway ramp metering strategies have already been field tested and implemented in the USA and Europe. Some others that are still being developed are being tested using several simulation models (e.g., H. Zhang and Stephen G. Ritchie, 1995, N.B. Goldstein and K.S.P. Kumar, 1982). A preliminary version of ALINEA and some popular previous control strategies have been implemented and tested on an on-ramp of the Boulevard Peripherique in Paris during an experimentation period of 6 months. Results of this study and other field results from current operational sites; such as, Brancion, Chatillion and Italie of the Boulevard Peripherique in Paris, showed a clear success of ALINEA in preventing congestion and increasing traffic throughput.

2. MOTIVATION

One of the major criticisms of the ramp metering has been the delay caused on the ramps due to the queues created by ramp metering strategies that are developed to just optimize traffic flow on the freeway. States like New Jersey have been reluctant to deploy ramp-metering solutions due to the concerns about queue spillovers to the local streets. Unacceptably long ramp queues can create spillover on the arterial streets by causing system-wide delays that mainly favour freeways. Moreover, the drivers who are stuck in long queues on the ramps that are metered can experience considerably high delays.

It is true that most of the ramp metering strategies proposed so far do not directly consider on-ramp queues. The most popular implementation strategy is to use override tactics that will turn off the ramp metering until the queue length is below certain threshold value.

New Control is a new nonlinear control design proposed by Kachroo and Ozbay (Book, 2003) for an isolated ramp-metering problem is shown below:

$$u(k) = -K\left[o(k) - o_{cr}\right] + \left[q_{out}(k) - q_{in}(k)\right] \qquad (2)$$

Where, $u(k)$ is the metering rate at time step k, K is the regulator parameter (constant), $o(k)$ is the current downstream occupancy at time step k, o_{cr} is the set occupancy value, $q_{in}(k)$ is the flow entering the freeway section at time step k, $q_{out}(k)$ is the flow leaving the freeway section at time step k.

This control law guarantees that $\lim_{k \to \infty} (\rho - \rho_{cr})^2 \to 0$, which is the objective of the controller. In fact, it guarantees that the rate of convergence of $o - o_{cr}$ is geometric at a rate dictated by the control gain *K*. However, this control does also not take into account ramp queues. Instead, they are handled via threshold values depending on the storage capacity of the ramp.

Since aforementioned control laws use threshold activation approach to identify ramp queue formation these ramp metering strategies are reactive rather than proactive. This type of reactive control, which depends on threshold activation, produces unwanted oscillations when it switches between trying to disperse the excessive ramp queue and trying to regulate mainline congestion. One possible way to avoid this problem is to adjust the metering rates in such a way that the overflow of ramp queues do not occur. The mixed ramp control law briefly described in the next section attempts to achieve that objective by incorporating both freeway and ramp conditions into a single control law.

3. MIXED CONTROL MODEL DESCRIPTION

The majority of the ramp metering algorithms usually give priority to freeway traffic but also give some consideration to traffic on entrance ramps when delays on entrance ramps are about to spill back onto surface streets. This creates an unstable condition on the ramp, which demands higher metering rates. Eventually, higher metering rates again put more demand on freeway, which leads to fluctuation in the freeway traffic.

To eliminate this situation, one can do a few things. The most straightforward way is to monitor the queue on the ramp and adjust the metering rate gradually to prevent the queue become critical in a smooth manner.

Hence, Mixed Control, the new “traffic responsive ramp metering control law”, is developed to maximize the throughput on the freeway without creating long queues on the ramp. This goal can be achieved by developing a ramp metering control law that considers bit queue on the ramp and traffic conditions on the freeway. This control algorithm shortens the long ramp queues, which are created by ramp metering, by calibration of the weighting parameters for freeway and ramp (w_1, w_2).

Table1 Description of system variables

Variables	Description
$f_1(k)$	The flow entering the freeway section at time step k
$f_2(k)$	The flow entering the ramp at time step k
$u(k)$	Metered ramp flow at time step k
$\rho(k)$	Freeway density for section “i”
ρ_c	The critical value of section density (veh/mile)
$q_{out}(k)$	The flow leaving the freeway section at time step k
$queue_{ramp}(k)$	Queue length on the ramp at time step k
w_1, w_2	Weight factors, $w_1 + w_2 = 1$
K	Control gain, $0 < K < 1$
T	Time step duration
Δx	Length of the freeway section

The model of a freeway section is shown in Fig. 2.

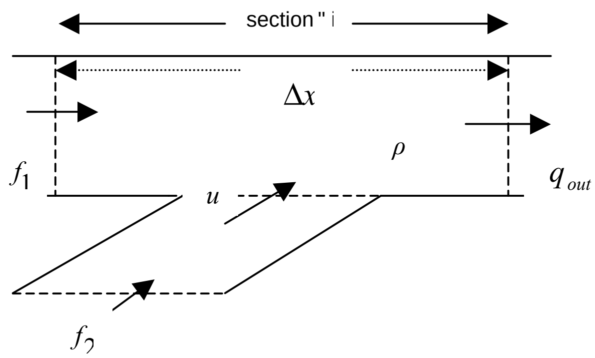

Fig. 2. Isolated Freeway Ramp

This traffic responsive ramp metering control achieves its goal, namely maximization of the throughput on the freeway without creating long queues on the ramp, by minimizing an error function.

Control Objective (3)

$$e(k) = w_1 \mid \rho(k) - \rho_c \mid + w_2 queue_{ramp}$$

The error function, which takes into account these two objectives, determines how much importance should be given to freeway density and queue length on the ramp with the help of weights w_1 and w_2. Appropriate values of the parameters, w_1 and w_2, are determined by taking the objectives of the system into consideration. The system can be in two regions. One region is where the traffic density is greater than the critical density. The other region is where the traffic density is equal to or less than the critical density. Two sub-sections can be combined to come up with a control law that is applicable in both regions. The overall control law therefore is given by

$$u = G^{-1}[-F + Ke(k)] \quad (4)$$

where

$$F = sign(\rho(k) - \rho_c) w_1 [\rho(k) - \rho_c \quad (5)$$

$$+ \frac{T}{\Delta x}(-q_{out}(k) + f_1(k))]$$

$$+ w_2 [queue_{ramp}(k) + Tf_2(k)]$$

and

$$G = [sign(\rho(k) - \rho_c) w_1 \frac{1}{\Delta x} - w_2]T \quad (6)$$

4. SIMULATION

Fig. 3 shows a screen capture of the PARAMICS model of test network located in Hayward, California, created using the available geometric and traffic demand data. Then, an Application Programming Interface (API) was written to assign demand in PARAMICS every minute in such a way that the number of vehicles generated in PARAMICS every minute closely matches with the number of vehicle counts obtained from the loop detectors. Further calibration and validation of the model were performed based on real world data from the Freeway Patrol Evaluation Project Database, conducted as a part of the PATH program at the University of California, Berkeley (Petty et al., 1995). The overall behaviour of the model was calibrated by adjusting the “mean headway”, the “mean reaction time” to obtain results close to real world data. The values of the mean target headway and the mean reaction time calibrated as 1.6 seconds and 0.4 seconds, respectively. After the model calibration, the output is observed quantitatively and qualitatively to represent field data within an acceptable level of accuracy. Therefore, the calibrated and validated model was used to simulate the traffic operations of the study site. The simulation was run with three different seeds (117,120, 125) for each scenario, and the average of the results are tabulated in the simulation results section.

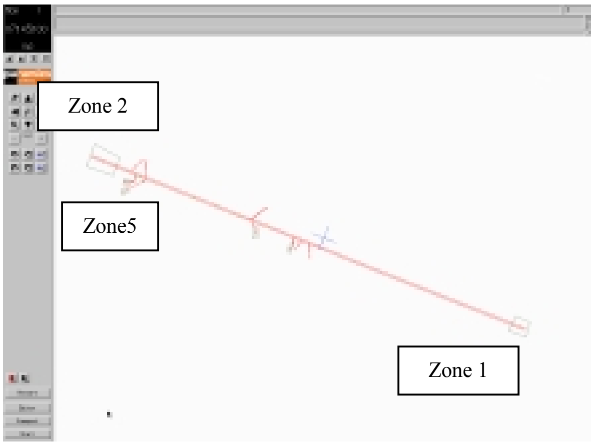

Fig. 3. PARAMICS model of the study network

The number of lanes on the 9.2 miles long study section varies between 3 to 5 lanes. The simulation was run for 3 hours and 15 minutes, allowing the initial 1 hour 15 minutes for loading the facility and 1 hour at the end to eliminate any effects from the simulation ending. Since the main goal of this paper is to test “isolated ramp metering” strategies, ramp metering was applied only to the ramp shown in zone 5 of Fig 3. The freeway section upstream and downstream of ramp consisted of 5 lanes, with 1-lane on ramp. Statistics are collected for the one-hour portion of the simulation from the detectors located 721.6 ft downstream and 468.3 ft upstream of the ramp and two additional detectors, one at the exit and one at the entrance of the ramp.

Critical occupancy of the freeway section used for control strategies implementations is found as 26% with the help of flow density curve produced using PARAMICS report data. Set occupancy for all control strategies was chosen as 25%. Free flow speed is taken as 60 mph. To be able to test the ramp metering strategies under fairly congested traffic conditions, the hourly demands from zones 2 were taken to be by 35% more and 5 (ramp demand) to zone 1 were taken to be by 3% less than the observed hourly demands from zones 2 and 5 to zone 1, that were given as 5050 veh/hr and 580 veh/hr, respectively. The vehicles file, which was generated automatically, was edited to represent the traffic on the study network (85% cars, 7.8% light goods vehicles, 3.2% ordinary goods vehicles class 1,2.8% ordinary goods vehicles class 2, 1.2% coaches). The description of characteristics of each vehicle, and assignment information for each vehicle type are presented in PARAMICS Modeller Manual.

In PARAMICS model of a network, Plan file or an API can be used to simulate actuated signals. In this study, however, we used plans file, which consists of a description of any signal plan that should be used within the network. Time step was taken as 2, the default time step, which provides that calculation are done every 0.5 seconds of simulation. In the plans file, it is made sure that the calculated green phase duration is within specified limits, i.e. minimum and maximum values are 2 and 15 seconds respectively.

The three ramp metering strategies were implemented as follows:

In ALINEA implementation, a queue override strategy that sets the green time to its maximum allowed value when the occupancy of the ramp detector exceeds a certain threshold (>45 vehicles on the ramp) is integrated into the ALINEA algorithm, to avoid interference with surface street traffic. The ALINEA regulator constant was calibrated for the study network as 208.57 veh/hr. The time interval to update the metering for all controls is equal to 20 seconds.

In New Control implementation, the similar threshold, as in ALINEA, strategy (>35 vehicles) was used for the on-ramp queue. The control gain, K, for the study network, was found as 15996 veh/hr.

In Mixed Control implementation, control gain, K, w_1 and w_2 were calibrated as 0.95 veh/hr, 0.15 and 0.85, respectively. Unlike ALINEA and New Control, Mixed Control performs satisfactorily without a queue override strategy that shuts off the ramp metering and creates unwanted fluctuations. This way of regulating smoothly the freeway and queue build-ups gives it superiority over other controls that do not explicitly consider the queues specifically created as a result of ramp metering.

5. SIMULATION RESULTS

All the simulations were run for three seed values for each scenario and the average of the results are presented in this section.

Simulation results (Table 2) show that both Mixed Control strategy and ALINEA reduce mean congestion duration on the mainline by 47 %, 36%, respectively, compared to No Control scenario.
New Control (-50%) performed slightly better in reducing the mean congestion duration compared to Mixed Control (-47%) in the expense of large waiting times for the vehicles on the ramp.

Table 2 Mean congestion duration on the downstream freeway link

	No Control	Alinea	New Control	Mixed Control
No of time step	125	80	62	66
Mean congestion duration (minute)	41.67	26.67	20.67	22.00
%Change	-	-36.00	-50.40	-47.20

For the controls, which do not consider the on-ramp queue, it becomes hard to handle on-ramp and freeway at the same time when the traffic is at fairly congested level. That is, when the threshold is reached, instead of improving the freeway conditions, they try to release excessive number of vehicles on the ramp to prevent spillbacks onto arterial streets by setting maximum green phase time; therefore, this results in fluctuations in the freeway traffic.

Table 3 Average downstream occupancy

	No Control	Alinea	New Control	Mixed Control
Average	0.280	0.255	0.241	0.251
%Change	-	-8.93	-13.93	-10.36

All the controls were able to reduce the average downstream occupancy compared to No Control scenario. The downstream occupancy was reduced below critical occupancy, 26%, by all three controls strategies. ALINEA reduced the downstream occupancy by 9%, whereas New Control and Mixed Control reduced the same measure by 14% and 10%, respectively (Table 3).

Table 4 Average downstream link speed and link density

	No Control	Alinea	New Control	Mixed Control
Avg.Down. Speed	32.22	37.23	39.01	37.49
%Change	-	15.57	21.08	16.36
Avg.Down. Density	48.58	42.23	41.44	42.97
% Change	-	-13.07	-14.69	-11.56

The average freeway speed, measured for the simulation period, has increased with the implementation of all the controls (Table 4). Similarly, all the controls achieved producing lesser density values on the downstream link of the freeway (Table 4). From these results, it can be easily observed that freeway ramp metering can be an effective way to reduce freeway congestion by regulating incoming ramp demand.
However, it is important to carefully analyze the system-wide impact of these improvements on the freeway. Table 5 shows system-wide performance of each ramp control strategy and compares them to the "no control" scenario.

Table 5 Link travel times of the system (vehicle.hour)

	No Control	Alinea	New Control	Mixed Control
A=Upstream	110.40	110.56	100.90	105.23
% Change	-	0.15	-8.60	-4.69
B=Downstream	343.21	325.69	308.36	310.96
% Change	-	-5.10	-10.15	-9.39
C=Ramp link	11.43	66.09	34.48	12.06
% Change	-	478.00	201.53	5.51
A+B+C	465.04	502.34	443.75	428.25
%Change	-	8.02	-4.58	-7.91
Total System	1987.19	2025.49	1950.44	1932.27
% Change	-	1.93	-1.85	-2.76

Another performance measure used to analyze the impact of ramp metering is to compare the travel times for the upstream downstream sections and ramp links. New control and Mixed control strategies resulted in decreased travel times on the upstream links. This is due to the fact that ramp demand is very close to the ramp saturation flow.

For upstream (8.60 %) and downstream (10.15 %) freeway links, New Control provided the best results in terms of achieving largest reduction in the travel time. Mixed Control was also able to reduce travel times by 4.69 % and 9.39 % in the upstream and downstream links, respectively.

However, for the ramp link, Mixed Control produced the best results among all the control strategies. Mixed Control kept the travel times almost close to the No Control case, whereas ALINEA and New Control resulted in increased ramp travel times by 478% and 202%, respectively (Table 5). Even though freeway travel time reductions were the best for New Control, Mixed Control proved to perform better by preventing larger waiting times on the ramp; and therefore resulting in better system-wide performance (upstream+downstream+ramp) level. Total system travel time, consisting of one upstream link, one downstream link and one ramp link, travel time was reduced with Mixed Control by 7.91 %; on the other hand, the corresponding travel time amelioration of New Control was only 4.58% compared to No Control scenario.

When looking at the system performance only, the benefit of Mixed Control and New Control, measured in terms of total vehicle travel time reduction, is found to be 2.76 and 1.85 percent, respectively. Mixed Control provided the better result due to efficient ramp queue management, which New Control does not include in its control law. ALINEA, however, resulted in slight increase of the travel time spent in the system due to large queues on the ramp. ALINEA results obtained from our simulation study for the overall system showed resemblance to another study by Gardes et al. (2003) that also found that the improvements of traffic conditions on the mainline freeway due to ramp control did not overweigh the deterioration of the traffic performances on the on-ramps with the implementation of ALINEA control strategy.

Looking at the system-wide statistics, in terms of travel time spent in the system, it was found that the system did perform better after the implementation of Mixed Control compared to other controls. As expected, the mainline freeway did experience better traffic conditions when the metering system was implemented; in addition, the level of benefits obtained on the freeway exceeded the additional delay experienced on the ramps.

The queue thresholds are used in ALINEA and New Control strategy to try to prevent the ramps from being overloaded. When queue thresholds are activated, the metering rate switches to the maximum metering rate so that more vehicles can enter the freeway. Queue control is critical to ensure that the ramp delays do not reach unacceptable levels (Fig. 4). However, it reduces the potential of the freeway control strategy to adjust the metering rates so as to obtain optimised traffic conditions on the freeway.

Although New Control has provided slightly better amount of reduction than Mixed Control in terms of mean congestion duration on the freeway, the major strength of Mixed Control comes from the fact that it maintains the occupancy below the set value (Table 3) while preventing the number of vehicles in the queue from exceeding the ramp storage capacity (Fig. 4). This feature makes Mixed Control a better option for real-world implementation. Furthermore, this feature differentiates Mixed Control from other freeway ramp control strategies.

Even though, all the freeway ramp metering strategies tested in this paper proved to be effective in terms of optimizing freeway traffic conditions, Mixed control which explicitly considers the ramp queues in its control law showed promise in terms of improved overall system-wide performance. Thus, more research is needed for the development and implementation of this kind of ramp metering strategies that can take the ramp queues into account as part of its control strategy.

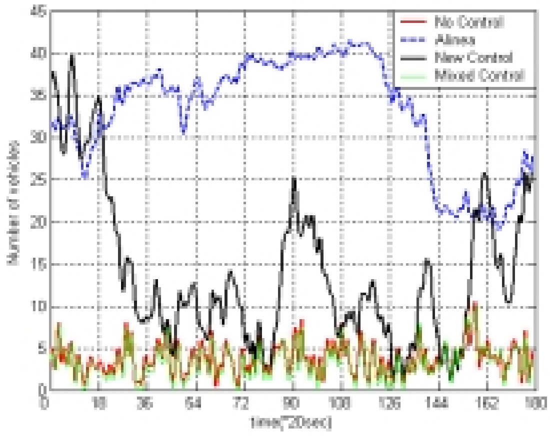

Fig. 4. Time Dependent-ramp queue plot

6. REFERENCES

Banks, J. H. (1990). Effect of Responsive Limitations on Traffic-Responsive Ramp Metering. *Transportation Research Record 1394.*

Greenshields, B. D. (1935). A study in Highway Capacity. *Highway Research Board Proceedings*, **Vol. 14**, page 458

Zhang, H. and S. G. Ritchie (1995). An integrated Traffic Responsive Ramp Control Strategy via Nonlinear State Feedback. *TRB*, 74th Annual Meeting

Kachroo and Ozbay (2003). *Feedback Ramp Metering in Intelligent Transportation Systems*. To Be Published by Kluwer Academics.

Petty, K., H. Noeimi, K. Sanwai, D. Rydzewski, A. Skabardonis P. Varaiya, and H. Al-Deek (1995). *The Freeway Patrol Evaluation Project: Database, Support Programs, and Accessibility*, California PATH Report.

Goldstein, N.B. and K.S.P. Kumar (1982). A Decentralized Control Strategy For Freeway Regulation. *Transp. Res.-B,* **Vol. 16B. No4**.

Papageorgiou, M. (1999). *Traffic Control. In Handbook of Transportation Science*, R.W. Hall, Editor, Kluwer Academic Publishers, Boston

Papageorgiou M., H. S. Habib, and J. M. Blosseville (1991). ALINEA: A Local Feedback Control Law for On-ramp Metering, *Transportation Research Record*, 1320, pp. 58-64

Traffic Control Systems Handbook, U.S. department of Transportation, Federal Highway Administration, February 1996

Gardes, Y, A. Kim, and A. May (2003). *Bay Area Simulation and Ramp Metering Study-Year 2 Report*, California PATH Report