

Modeling and PARAMICS Based Evaluation of New Local Freeway Ramp-Metering Strategy that Takes Ramp Queues into Account

Kaan Ozbay, Ph.D.

Associate Professor

Associate Director, Center for Advanced Infrastructure and Transportation (CAIT)
Rutgers University, Civil and Environmental Engineering, 632 Bowser Road, Piscataway, NJ 08854-8014

Tel: 732-445-2792

Fax: 732-445-0577

Email: kaan@rci.rutgers.edu

Ilgin Yasar, M.S.

Graduate Assistant

Center for Advanced Infrastructure and Transportation (CAIT)
Rutgers University, Civil and Environmental Engineering, 632 Bowser Road, Piscataway, NJ 08854-8014

Tel: 732-445-4012

Fax: 732-445-0577

Email: ilgin@eden.rutgers.edu

Pushkin Kachroo, Ph.D

Associate Professor

Bradley Dept. of Electrical & Computer Engineering, Virginia Tech., Blacksburg, VA 24061-0111

Tel: 540-231-2976

Fax: 540-380-3383

Email: pushkin@vt.edu

Contact Person

Kaan Ozbay, Ph.D.

**Word Count is 5500+Figures+Tables
Submitted to 83rd TRB Annual for Possible Presentation and Publication**

ABSTRACT

One of the major criticisms of ramp-metering has been the delay caused on the ramps because of the queues created by ramp control strategies. However, recently, several researchers proposed strategies that explicitly take into account ramp queues when determining metering rates. In this paper, an isolated “feedback” based ramp-metering strategy using modeling is presented. In addition to the regulation of ramp input from the freeway, the strategy calls for regulation of ramp queues by explicitly incorporating them into the model. This isolated ramp-metering strategy (Mixed Control) is tested using PARAMICS, a microscopic traffic simulation package, on a calibrated test network located in Hayward, California. In addition to Mixed Control, two other ramp control strategies, namely ALINEA (Papageorgiou et al., 1991), and New Control (Kachroo and Ozbay, 2003) are implemented in PARAMICS. Because the focus of this paper is on the evaluation of the isolated ramp control strategies, change in demand caused by ramp-metering is not considered. For this isolated ramp-metering evaluation study, we defined the system as the “upstream, downstream, and ramp” links around the metered ramp (Figure 1). The performances of three ramp control strategies are compared for two freeway demand patterns (congested and fairly congested). Based on the simulation results, all the freeway ramp control strategies tested in this paper were found to be quite effective in optimizing freeway traffic conditions (reduction in mean congestion duration on the freeway downstream link, mean downstream occupancy, and travel time (upstream and downstream links)). However, Mixed Control produced the best system (upstream, downstream and ramp links) results by achieving optimal flow on the highway while keeping the queue length on the ramp small enough to prevent spillover onto the arterial network.

1. INTRODUCTION AND MOTIVATION

Increasing dependence on car-based travel has led to the daily occurrence of recurrent and nonrecurrent freeway congestions in the United States and 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. According to previous theoretical investigations and field operational tests, it is well known that ramp-metering has various positive effects such as (Papageorgiou, 1999):

- Maintaining freeway operations at noncongested condition.
- Maximizing mainline throughput.
- Increasing travel speed (upstream and/or downstream, depending on the strategy).
- Reducing travel time.
- Reducing auto emissions and accidents as a result of a smoother mainline flow.

Two major philosophies of ramp control strategies namely, local and system-wide exist. Local ramp control strategies consider an isolated section of the network (a freeway section with one on-ramp), and respond only to the changes in the local conditions. On the other hand, system-wide ramp-metering is to consider 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 the two philosophies is called hierarchical ramp-metering. In this strategy, a system-wide model at the upper level defines the overall desired network states, whereas a local model at the lower level adjusts the metering rate to achieve system states close to the system target.

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

Pretimed Ramp-metering: Pretimed metering is the simplest form of on-ramp-metering. Ramp-metering rates are constant and determined by the off-line demand for particular time-of-day historical traffic observation data, without the use of real-time measurements of sensors. It can help eliminate recurrent congestion, if severe incidents or sudden changes in demand that cannot be captured by the historical measurements do not occur. However, because traffic demand is not constant, it varies from day to day, as well as hour to hour. Moreover, incidents may perturb traffic conditions in a non-predictable way. All these unexpected fluctuations in demand can render pretimed ramp control strategies ineffective. These pretimed ramp control strategies may thus lead either to overload of the mainstream flow (congestion) or to underuse of the freeway by achieving the opposite of what 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, and flow rate on the freeway and/or ramp, the metering rates are changed 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 (e.g., ramp-metering rate) is independent of the system output, which are 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, which aims to avoid or reduce congestion on the freeway, may have a positive or and negative impact on the adjacent road network traffic. In both demand-capacity control and upstream occupancy control, the ramp-metering rate is set to minimum, whether the threshold values for downstream capacity are reached or exceeded; therefore, on ramp queues are not handled directly in these ramp control strategies (Banks, 1990). In closed loop control, the system output is fed back, and the input is modified via an appropriate regulator to keep the output near its set value despite the influences of time-variant disturbances (e.g., 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 usually is chosen to be the critical occupancy, and applies the kinematic wave theory with locally calibrated fundamental diagrams as the underlying traffic model.

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

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

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 is close to q_{cap} , capacity flow), $r(k-1)$ is the last on-ramp volume, and $r(k)$ is the current ramp volume.

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 control strategies have already been field tested and used in the USA and Europe. Some others still under development 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 for 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, clearly was a success in preventing congestion and increasing traffic throughput.

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

Most of the ramp control strategies proposed so far such as, ALINEA and a new section-based control law (New Control) proposed in Kachroo and Ozbay (2003), shown in Equation 2 do not directly consider on-ramp queues.

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

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 , and $q_{out}(k)$ is the flow leaving the freeway section at time step k .

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

Thus, the most popular implementation strategy that deals with ramp queues is the use of override tactics to turn off the ramp-metering until the queue length is below a certain threshold value. However, recently several researchers proposed strategies that explicitly take into account ramp queues when determining metering rates. For example, in a recent paper, Smaragdis, E., and Papageorgiou, M. (2003) proposed a modification to ALINEA control law (Equation 3) to control ramp-queue avoiding interference with surface traffic. They proposed a deadbeat controller, which demands the queue length at the next time step to equal its set value \hat{w} (Equation 3):

$$r'(k) = -\frac{1}{T}[\hat{w} - w(k)] + d(k-1) \quad (3)$$

Where $r'(k)$ is the flow of vehicles entering the freeway, \hat{w} is the set value chosen to be the maximum permissible queue length, $w(k)$ denotes the queue length at time-instant k , $d(k-1)$ is the demand flow entering the ramp. The proposed ramp-metering rate $R(k)$ to be finally applied is given by

$$R(k) = \max\{r(k), r'(k)\} \quad (4)$$

Where $r(k)$ is the ramp-metering rate decided by the ALINEA strategy (either the original or modified version).

Instead of using a rather rough logic for the queue threshold, a tighter ramp-queue control is used under the assumption that either a good estimate of the queue length or a measurement device, such as a video sensor, is available. With this modification, ramp-queue control is activated only when necessary and only to the extent necessary, guaranteeing full use of the ramp storage space, as well as a proper operation without oscillations.

In this paper, the authors propose and evaluate a new proactive feedback based ramp-metering law that explicitly considers ramp queues. Clearly a reactive threshold activation approach used to identify ramp queue formation can produce unwanted oscillations when it switches between the control mode that disperses the excessive ramp queue and the control mode that regulates 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 does 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.

2. MIXED CONTROL MODEL DESCRIPTION

Mixed Control, the new traffic-responsive isolated 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 both queue on the ramp and traffic conditions on the freeway. The resulting control algorithm shortens the long ramp queues, which are created by ramp-metering, through the use of carefully calibrated weight parameters for the freeway and ramp, namely (w_1, w_2) .

*****Insert TABLE 1*****

*****Insert FIGURE 1*****

The model of a freeway section is shown in Figure 1. Mixed Control can be described with the help of a block representation of the algorithm (Figure 2). The process under control is the traffic flow on a freeway section with an on-ramp (Figure 1).

*****Insert FIGURE 2*****

The system shown in Figure 1 is affected by certain process inputs, disturbances that cannot be manipulated. This control system has two input measurement disturbances, f_1 and f_2 , which are real-time data from the detectors located on the freeway upstream (freeway demand) and on-ramp upstream (ramp demand), respectively. The states of the system are functions of the disturbances, f_1 and f_2 , respectively.

The objective of this feedback control design is to make the error variable go to zero. That is:

$$\lim_{t \rightarrow \infty} e(t) = 0 \quad (5)$$

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

$$\text{Control Objective } e(k) = w_1 |\rho(k) - \rho_c| + w_2 \text{queue}_{\text{ramp}} \quad (6)$$

The error function, which takes these two objectives into account, 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. In one region is the traffic density is greater than the critical density. In the other region the traffic density equals to or less than the critical density. Two subsections can be combined to produce a unified control law that is applicable in both regions. The overall control law, therefore, is given by

$$u = G^{-1}[-F - Ke(k)] \quad (7)$$

Where

$$F = \text{sign}(\rho(k) - \rho_c)w_1[\rho(k) - \rho_c + \frac{T}{\Delta x}(-q_{out}(k) + f_1(k))] + w_2[\text{queue}_{ramp}(k) + Tf_2(k)] \quad (8)$$

And

$$G = [\text{sign}(\rho(k) - \rho_c)w_1 \frac{1}{\Delta x} - w_2]T \quad (9)$$

The complete derivation of the above control law, which is outside the scope of this paper, is offered in Kachroo and Ozbay (2003).

3. EVALUATION OF THE MIXED RAMP-METERING STRATEGY USING MICROSCOPIC SIMULATION

Figure 3 (a) shows a screen capture of the PARAMICS model of test network located in (a section of I-880) Hayward, California, created using the available geometric and traffic demand data. An application programming interface (API) was written to assign demand in PARAMICS every minute in such a way that the number of vehicles generated every minute in the model closely matches 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, which was conducted as a part of the PATH program at the University of California, Berkeley (Petty et al., 1995). The overall behavior of the model was calibrated by adjusting the “mean headway”, and 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 a number of seeds for each scenario to obtain an estimate value, \bar{X} , with a relative error of, γ , 0.05, and a confidence level of 90%. After statistical analysis, the average of the results are tabulated in the simulation results section.

*****Insert FIGURE 3 (a)*****

*****Insert FIGURE 3 (b)*****

The number of lanes on the 9.2-mile-long study section varies between 3 to 5 lanes (Figure 3 (b)). The simulation was run for 3 hours and 15 minutes, allowing the initial 1 hour 15 minutes for loading the facility and 1 more hour to eliminate any effects from the simulation ending. Because the main goal of this paper is to evaluate “isolated ramp-metering” strategies, ramp-metering was applied only to the ramp shown in zone 5 of Figure 3 (b). The freeway section upstream and downstream of the ramp consisted of 5 lanes, with 1 lane on the ramp. Statistics are collected for the 1-hour portion of the simulation from the detectors located 721.6 ft downstream and 468.3 ft upstream of the ramp, as well as 2 additional detectors, 1 at the exit and 1 at the entrance of the ramp.

Critical occupancy of the freeway section used for control strategies implementations is found to be 18% with the help of flow density curve produced using PARAMICS report data. Set occupancy for all control strategies was chosen as 17%. Free-flow speed is taken as 60 mph. To provide a sensitivity analysis of freeway demand, calibrated network was run with 2 different freeway demands, one of which leads to fairly congested traffic on the freeway links; another results in congested traffic conditions on the same location. To test the ramp control strategies under fairly congested traffic conditions, the hourly demands from zones 2 were taken to be 35% more, and 5 (ramp demand) to zone 1 were taken to be the same as the observed hourly demands from zones 2 and 5 to zone 1, which were given as 5050 veh/hr and 560 veh/hr, respectively. Similarly, to create the congested traffic on the freeway links, the hourly demands from zones 2 were taken to be 30% more, and 5 (ramp demand) to zone 1 were taken to be the same as the observed hourly demands from zones 2 and 5 to zone 1. The “vehicles” file, which was generated automatically, was edited to represent the traffic on the study network based on the real-time calibration of the PARAMICS network (Ding, Lu, 2003).

In PARAMICS model of a network, either the “Plans” file or an API can be used to simulate actuated signals. In this study, however, we used the “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 calculations are made every 0.5 seconds of simulation. In the “plans” file, the calculated green phase duration is kept within specified limits (i.e., minimum and maximum values are 2 and 15 seconds respectively).

In No Control Scenario implementation, no ramp-metering strategy was used in the simulation. Vehicles can merge into the mainstream from the on-ramp freely, and the only restriction is the inherent gap acceptance of each individual vehicle. This scenario is used as the baseline condition to be compared with other scenarios.

The three ramp control strategies were implemented as follows:

In ALINEA implementation, a queue override strategy, which 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.

In New Control implementation, the similar threshold, as in ALINEA, strategy (> # of 35 vehicles) was used for the on-ramp queue.

During the preliminary runs for the calibration, it is observed that ALINEA tends to lead to large on-ramp queues on the ramp in expense of relieving congestion on downstream freeway links. Therefore, because of its tendency to cause large on-ramp queue formation, a larger on-ramp queue threshold (> # of 45 vehicles) was used. When lesser (> # of 35 vehicles) threshold values are used for ALINEA implementation, the threshold is reached faster, which causes green time to be set to maximum, and releasing an excessive number of vehicles on the ramp to prevent spillbacks onto arterial, resulting in fluctuations in the freeway traffic.

In Mixed Control implementation, control gain, K , w_1 , and w_2 were calibrated respectively. Unlike the other ramp-control strategy tested in this paper, Mixed Control does not need a queue override strategy that shuts off the ramp-metering and creates unwanted fluctuations.

4. MEASURES OF EFFECTIVENESS

One of the measures of effectiveness is the mean congestion duration (sec) on the downstream freeway link. Mean congestion duration is the accumulated period of time during the simulation when the measured occupancy per time interval (17 sec) is larger than the critical occupancy, $o_{cr} = 18\%$.

$$\text{Mean Congestion Duration (sec)} = nT \quad (10)$$

Where n is the number of times the measured occupancy on the downstream link is larger than critical occupancy, and T is the time step interval (17 sec).

Occupancy of the freeway section (both upstream and downstream of the ramp) is gathered by means of “plans” file report for each time step (17 sec). The following formula gives one-link’s (upstream or downstream) mean occupancy based on the occupancy measurements in n time steps:

$$\text{Mean Occupancy (\%)} = \frac{\sum_{i=1}^m o_i}{m} \quad (11)$$

Where o_i is the occupancy on the downstream freeway link at time step i , m is the number of time step during the simulation.

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, which are calculated using the following equation:

$$\text{Average Link Delay (veh.hour)} = (ATT \times p) / 3600 \quad (12)$$

Where ATT (sec) is the average travel time spent on the link (downstream, upstream, or ramp link) per vehicle, which is obtained in the specific PARAMICS output file named “trips link delay”, and p (veh) is the total number of vehicles on the link during the simulation period.

The ramp queue length is the number of vehicles on the ramp per time step (17 sec). This measure is gathered through PARAMICS plans report data for each time step. Then, the average length of the on-ramp queue (on one-ramp-link) per time interval (17 sec) was found using the following equation:

$$On - ramp\ queue\ (mph) = \frac{\sum_{i=1}^m queue_{ramp_i}}{m}, \quad (13)$$

Where $queue_{ramp_i}$ is the on-ramp queue at time step i , and m is the number of time step during the simulation.

5. STATISTICAL ANALYSIS OF THE SIMULATION OUTPUT

Sequential method [12] was used for determining the number of replications required in the simulation analysis. This statistical procedure aims at obtaining the mean $\mu = E(X)$ of the selected performance measure X , within a specified precision. If we estimate \bar{X} such that $|\bar{X} - \mu|/|\mu| = \gamma$, then γ is called the relative error of \bar{X} . The specific objective of this procedure is to obtain an estimate of μ with a relative error of γ and a confidence level of $100(1 - \alpha)$ percent. If we denote the half-length of the confidence interval by $\delta(n, \alpha)$ then the sequential procedure is as follows:

0. Make n_0 replications of the simulation and set $n = n_0$
1. Compute $\bar{X}(n)$ and $\delta(n, \alpha)$ from X_1, X_2, \dots, X_n
2. If $\delta(n, \alpha)/|\bar{X}(n)| \leq \gamma'$, use $\bar{X}(n)$ as the point estimate for μ and stop. If not, replace n by $n + 1$; make an additional replication of the simulation and go to step 1.

Where, $\gamma' = \gamma/(1 - \gamma)$

Because more than one performance measures the simulation analysis are used, the largest replication value was chosen as the number of replications.

Table 2 shows the number of replications required to ascertain a 90% confidence interval (the relative error γ number is assumed as 0.05) of these performance measures using the above procedures.

*****Insert Table 2*****

6. SIMULATION RESULTS

In this section, the averages of the results of two freeway demand patterns, namely congested (Tables 3 and Figure 4 (a)) and fairly congested (Table 4 and Figure 4 (b)) were presented.

*****Insert TABLE 3*****

Simulation results (Table 3) show that both Mixed Control strategy and New Control reduce mean congestion duration on the mainline by 18.12 %, and 8.05 %, respectively, compared to No Control scenario.

ALINEA (-31.55%) performed better in reducing the mean congestion duration compared to Mixed Control (-18.12%) in the expense of large waiting times for the vehicles on the ramp.

All the ramp control strategies were able to reduce the average downstream occupancy compared to No Control scenario. ALINEA reduced the downstream occupancy by 13.90 %, whereas New Control and Mixed Control reduced the same measure by 3.74 % and 7.42%, respectively (Table 3).

From these results, it can be easily observed that freeway ramp-metering can be an effective way to reduce freeway congestion by regulating the incoming ramp demand. However, for the ramp-control strategies, which do not consider the on-ramp queue, it becomes hard to handle the on-ramp and freeway at the same time when the traffic is at 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. Thus, it is important to carefully analyze the system-wide impact of these improvements on the freeway. Table 3 shows system performance of each ramp control strategy and compares them to the “no control” scenario.

*****Insert FIGURE 4 (a)*****

ALINEA, New Control and Mixed Control mainly aim to regulate the downstream freeway link; therefore, the amount of improvement in the upstream link travel times is small for all the controls.

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 687.76 % and 237.00 %, respectively (Table 3). Even though freeway travel time reductions were best for ALINEA, Mixed Control proved to perform better by preventing larger waiting times on the ramp, and therefore, resulted in better system performance where system for the isolated case is defined as upstream, downstream and the ramp links around the ramp where ramp-metering strategy is implemented (Figure 1). Thus, total system travel time; consisting of one upstream link, one

downstream link and one ramp link, travel time was reduced with Mixed Control by 2.04 % compared to No Control scenario.

When looking at the system performance only, Mixed Control provided the better result because of efficient ramp queue management, which other controls do not include in their control law. ALINEA and New Control, however, resulted in increase of the travel time spent in the system because of 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), which also found that the improvements of traffic conditions on the mainline freeway due to ramp control did not outweigh the deterioration of the traffic performances on the on-ramps with the use of the ALINEA control strategy.

In addition to congested case, simulation results for the fairly congested case are given in Table 4.

*****Insert Table4*****

*****Insert FIGURE 4 (b)*****

Simulation results (Table 4) for the fairly congested freeway case were similar to the results obtained from the congested one. ALINEA performed better in reducing the mean congestion duration and the downstream occupancy (-13.52 % and -11.13 %, respectively) compared with Mixed Control (-5.22 % and -6 %) and New Control (0.75 % and 0.46 %) in the expense of large queues on the ramp. However, none of the controls were able to reduce the downstream occupancy below the critical occupancy (18 %) because the downstream occupancy for No Control (26.99 %) case is well above the critical occupancy.

ALINEA was able to reduce travel time on the upstream (-7.74 %) and downstream (-19.96 %) links more than other controls. However, the amelioration of traffic conditions on the mainline freeway with ALINEA control did not outweigh the travel time increase (928.06 %) of the on-ramps. Mixed Control and New Control provided some reduction in travel times on the upstream and downstream freeway links.

Mixed Control resulted in least amount of ramp link travel time among all the control strategies by keeping the queue on the ramp as close to No Control scenario as possible. However, ALINEA and New Control resulted in ramp travel time increase by 928.06 % and 234.32 %, respectively. Therefore, total system travel time; consisting of one upstream link, one downstream link and one ramp link, travel time was reduced with Mixed Control by 1.54 %, whereas the same measure was increased with New Control by 4.37 % and with ALINEA by 5.47 % compared to No Control scenario.

7. CONCLUSIONS

Because the focus of this paper is on the evaluation of the isolated ramp-control strategies, change in demand from ramp-metering is not considered. The microscopic simulation study was conducted with the assumption that both freeway and ramp demands will remain the same after the implementation of ramp control strategies. For this isolated ramp-metering evaluation study,

we define the system as the upstream and downstream and ramp links around the ramp, where ramp-metering is implemented (Figure 1). As a result of multiple simulation runs using a calibrated PARAMICS model, it was found that the system performed better after the implementation of Mixed Control compared with other ramp-control strategies. As expected, the mainline freeway experienced better traffic conditions when any of the three tested ramp-metering strategies was implemented. However, when the queue thresholds are used in ALINEA and New Control prevent the ramps from being overloaded, the system benefits of these strategies were reduced. Mixed control that significantly improved system performance compared with other two control strategies under the congested and fairly congested conditions was proven to be quite effective.

In fact, ALINEA has provided better amount of reduction than Mixed Control in mean congestion duration on the freeway. However, the major strength of Mixed Control is that it reduces the downstream occupancy (Tables 3 and 4) while preventing the number of vehicles in the queue from exceeding the ramp storage capacity (Figure 4 (a) and (b)). This feature makes Mixed Control a better option for real-world implementation.

More research is needed for the real-world implementation of this kind of ramp control strategies that can explicitly model ramp queues.

8. ACKNOWLEDGEMENT

This research was supported by the National Science Foundation's CAREER Award programs grant CAREER-CMS-9875296, New Jersey Department of Transportation, and United States Department of Transportation (University Transportation Center program). This support is both acknowledged and appreciated. The contents of this paper reflect the views of the authors who are solely responsible for the facts and the accuracy of data presented herein. The contents do not necessarily reflect the official views of NSF, NJDOT, and USDOT.

9. REFERENCES

1. Banks, J. H. (1990). Effect of Responsive Limitations on Traffic-Responsive Ramp Metering. *Transportation Research Record* 1394.
2. Greenshields, B. D. (1935). A study in Highway Capacity. *Highway Research Board Proceedings*, Vol. 14, page 458
3. Zhang, H. and S. G. Ritchie (1995). An integrated Traffic Responsive Ramp Control Strategy via Nonlinear State Feedback. *TRB*, 74th Annual Meeting
4. Kachroo and Ozbay (2003). *Feedback Ramp Metering in Intelligent Transportation Systems*. To Be Published by Kluwer Academics.
5. Petty, K., H. Noeimi, K. Sanwai, D. Ryzdewski, A. Skabardonis P. Varaiya, and H. Al-Deek (1995). The Freeway Patrol Evaluation Project: Database, Support Programs, and Accessibility, California PATH Report.
6. Goldstein, N.B. and K.S.P. Kumar (1982). A Decentralized Control Strategy For Freeway Regulation. *Transp. Res.-B*, Vol. 16B. No4.
7. Papageorgiou, M. (1999). *Traffic Control*. In *Handbook of Transportation Science*, R.W. Hall, Editor, Kluwer Academic Publishers, Boston
8. Papageorgiou M., H. S. Habib, and J. M. Blossville (1991). ALINEA: A Local Feedback Control Law for On-ramp Metering, *Transportation Research Record*, 1320, pp. 58-64
9. Smaragdis, E., and M. Papageorgiou (2003). A Series of New Local Ramp Metering Strategies, *Transportation Research Board 82nd Annual Meeting*, January 12-16

10. Traffic Control Systems Handbook, U.S. department of Transportation, Federal Highway Administration, February 1996
11. Gardes, Y, A. Kim, and A. May (2003). Bay Area Simulation and Ramp Metering Study-Year 2 Report, California PATH Report
12. Law, A.M. and W. David Kelton. Simulation Modeling & Analysis. McGraw-Hill, Inc., Second Edition
13. PARAMICS Modeller Manual

List of Tables

- TABLE 1 Description of System Variables
TABLE 2 Numbers of Replications
TABLE 3 Simulation Results for Congested Case
TABLE 4 Simulation Results for Fairly Congested Case

List of Figures

- FIGURE 1 Isolated freeway ramp
FIGURE 2 The proposed traffic-responsive ramp-metering control system
FIGURE 3 (a) PARAMICS model of the study network (b) Layout of the freeway segment (not drawn to scale) (5)
FIGURE 4 (a) Time-dependent ramp queue plot for fairly congested traffic conditions, (b) Time-dependent ramp queue plot for congested traffic conditions.

TABLE 1 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

TABLE 2 Numbers of Replications

Scenario	Number of Replications
No Control with fairly congested demand	25
No Control with congested demand	16
ALINEA with congested demand	25
ALINEA with congested demand	25
New Control with congested demand	34
New Control with congested demand	32
Mixed Control with congested demand	14
Mixed Control with congested demand	18

TABLE 3 Simulation Results for Congested Case

	No Control	ALINEA	New Control	Mixed Control
No of time step	149	102	137	122
Mean congestion duration (minute)	42.22	28.90	38.82	34.57
%Change		-31.55	-8.05	-18.12
Average Downstream Occupancy	21.15	18.21	20.36	19.58
%Change		-13.90	-3.74	-7.42
A: Upstream link travel time (veh.hour)	129.67	127.45	128.82	127.98
% Change		-1.71	-0.65	-1.31
B: Downstream link travel time (veh.hour)	269.60	228.07	259.58	249.29
% Change		-15.4	-3.72	-7.53
C: Ramp link travel time (veh.hour)	11.37	89.55	38.31	24.98
% Change		687.76	237.00	119.75
A+B+C (veh.hour)	410.64	445.08	426.71	402.25
%Change		8.39	3.91	-2.04

TABLE 4 Simulation Results for Fairly Congested Case

	No Control	ALINEA	New Control	Mixed Control
No of time step	197	171	199	187
Mean congestion duration (minute)	55.90	48.34	56.32	52.98
%Change		-13.52	0.75	-5.22
Average Downstream Occupancy	26.99	23.99	26.50	25.37
%Change		-11.13	0.46	-6.00
A: Upstream link travel time (veh.hour)	145.93	134.63	142.93	140.62
% Change		-7.74	-2.06	-3.64
B: Downstream link travel time (veh.hour)	339.34	271.62	337.22	326.36
% Change		-19.96	-0.62	-3.83
C: Ramp link travel time (veh.hour)	11.44	117.62	38.25	22.10
% Change		928.06	234.32	93.15
A+B+C (veh.hour)	496.71	523.87	518.4	489.34
%Change		5.47	4.37	-1.54

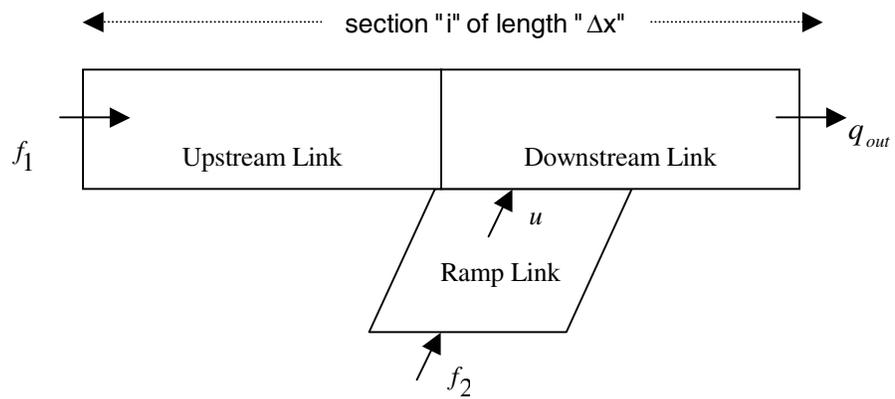


FIGURE 1 Isolated freeway ramp.

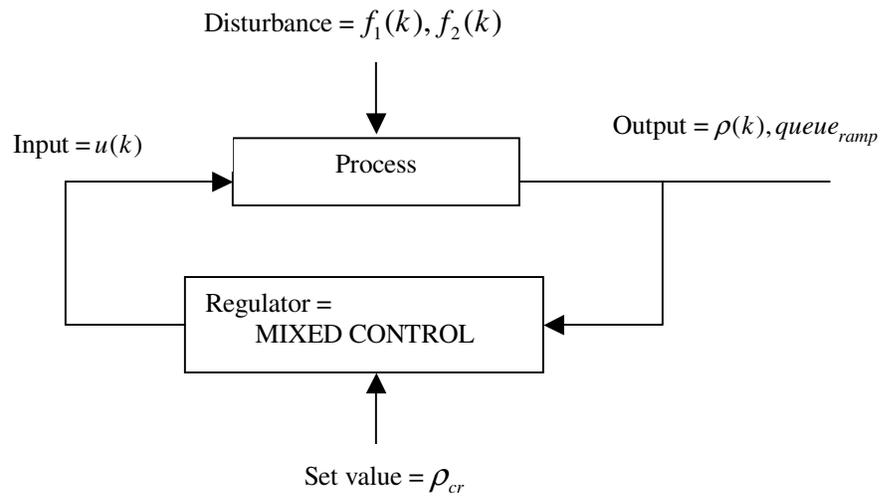
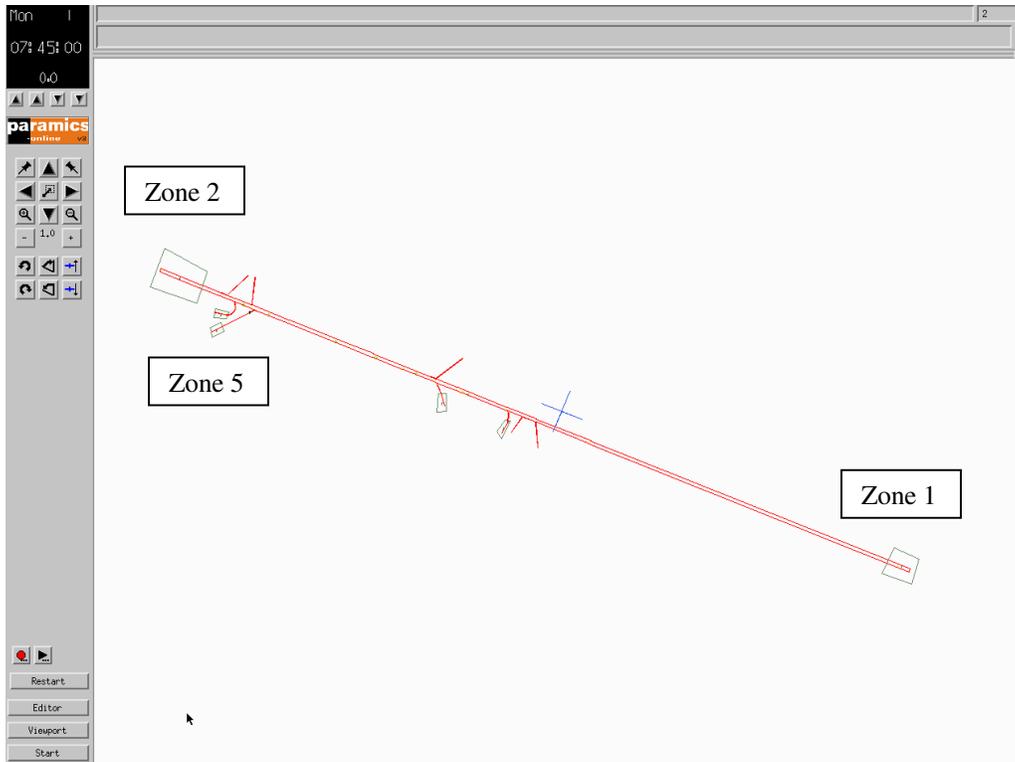
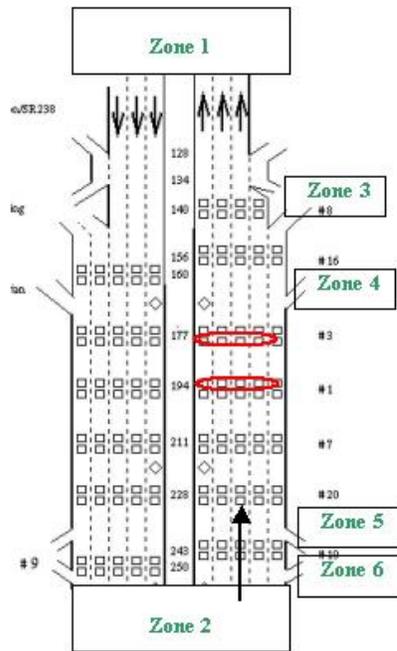


FIGURE 2 The proposed traffic responsive ramp metering control system.

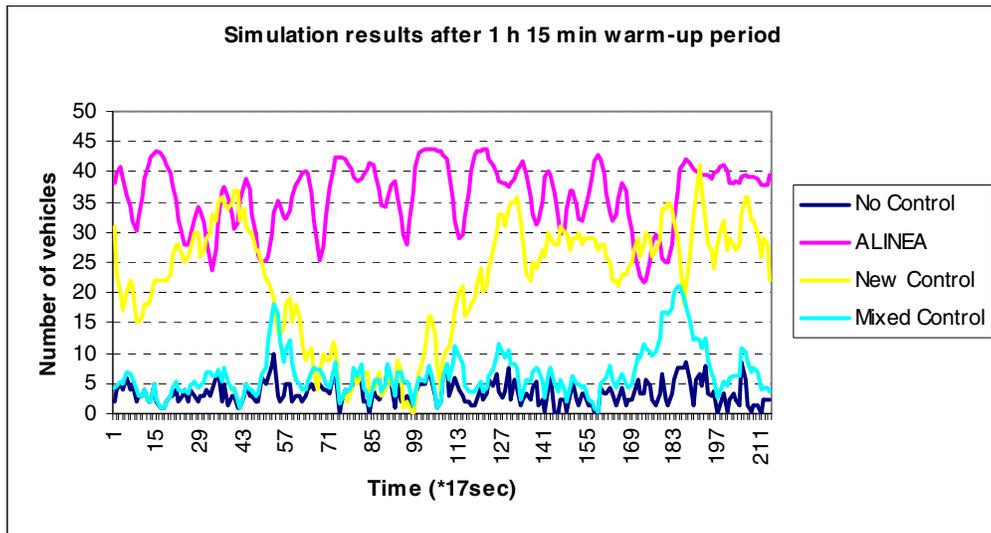


(a)

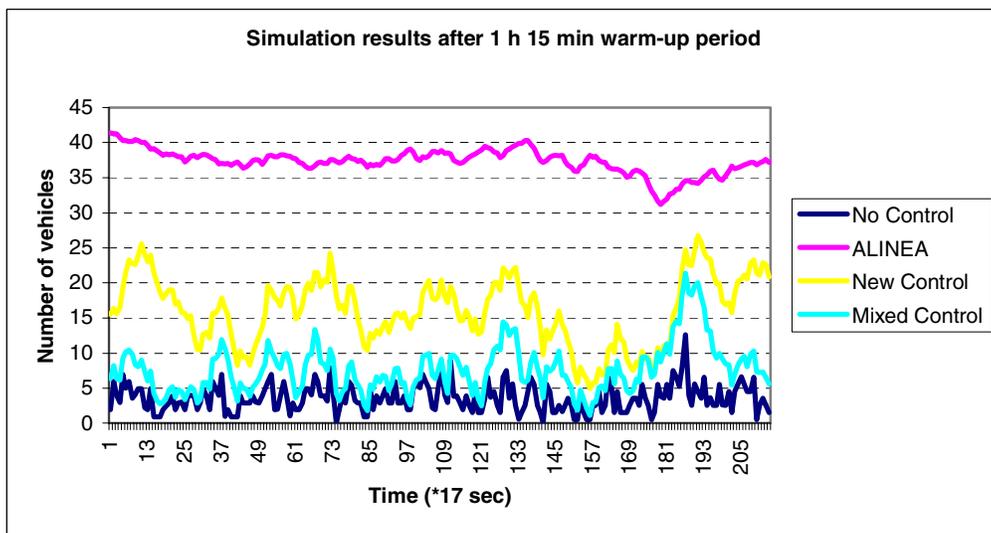


(b)

FIGURE 3 (a) PARAMICS model of the study network. (b) Layout of the freeway segment (not drawn to scale) (5).



(a)



(b)

FIGURE 4 (a) Time-dependent ramp queue plot for fairly congested traffic conditions, (b) Time-dependent ramp queue plot for congested traffic conditions.