EVALUATION OF LOCAL AND SYSTEM-WIDE EFFECTS OF FEEDBACK-BASED RAMP METERING STRATEGIES USING MICROSCOPIC SIMULATION

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ABSTRACT

One of the most widely used control measures for freeway control is ramp metering. Ramp metering can be local and system-wide. Local controls consider an isolated section of the network and respond only to the changes in local conditions, whereas system-wide controls consider a series of entrance ramps and aim to coordinate the response of all the ramps in the system. The focus is to show local and system-wide effects of a new local ramp metering strategy, namely MIXCROS (Ozbay and Kachroo 2003), on a medium-size test network modeled using a microscopic simulation environment, PARAMICS, and compare its performance with another well-known control, namely ALINEA (Papageorgiou et al. 1991) These local controls are implemented on four on-ramps along the freeway corridor located in South Jersey.

Local controls are shown to reasonably improve traffic conditions locally. However, some negative impacts are observed downstream of the metered ramps, mainly as a result of increased flow owing to better ramp management (Zhang and Recker 1999, Nsour et al. 1992). The location of the metered ramps influences the success of the local ramp metering implementations; increase in the number of vehicles released from upstream bottlenecks leads to congestion in the downstream locations, thereby decreasing the efficiency of the local controls. Another important result from the modeling of the two local ramp controls in this and similar studies (Zhang and Recker 1999, Gardes et al. 2001, Gardes et al. 2003, Ozbay et al. 2004) is that the impact of on-ramp queue on system-wide average travel time is very significant. However, because of its proactive nature in handling on-ramp queues, the ramp metering strategy proposed and tested in this paper, MIXCROS, increases the throughput both in the ramp systems and the rest of the network while decreasing the total average travel time of the whole system.

KEY WORDS

local ramp metering, system-wide effects, ramp queue, microscopic simulation, PARAMICS [1]

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INTRODUCTION AND MOTIVATION

Ramp metering has been one of the most efficient ways of controlling and improving freeway traffic conditions since the early 1960s. In the literature, a number of studies reported successful real-world and simulation-based implementation of various ramp metering strategies. These strategies are shown to yield quantifiable improvements in the traffic conditions in the form of increased speed on the freeway, amelioration of the average travel time, and, therefore, mitigation of the congestion, on the real networks, as well as on the simulated ones (Papageorgiou 1999, Kang and Gillen 1999).

However, it has also been realized that these ramp metering strategies can have adverse effects on system-wide conditions. In other words, the congestion relief resulting from the implementation of local ramp metering controls can be inequitable; after all, "local ramp metering may reduce travel times of users on some links, whereas increasing those of others" (Yin et al. 2004). For example, by imposing large on-ramp delays to relieve the congestion on the mainline, some local controls may increase average travel times for travelers using the metered ramp links. Recently, several researchers have proposed strategies that explicitly take ramp queues into account when determining metering rates. Smaragdis and Papageorgiou (2003) proposed a modification to the ALINEA control law to regulate ramp queues so as to avoid interference with surface traffic. A deadbeat controller is designed; it uses the maximum permissible queue length as the set value, demanding the queue length at the next time step to be equal to its set value. Ramp queue control is activated only when necessary and only to the extent necessary, aiming at maximum exploitation of the available ramp storage. However, as with override tactics, the proposed improvement to the ALINEA control law results in overcritical density and reduced traffic flow in the downstream freeway section of the ramp system when the queue regulator is activated (Smaragdis and Papageorgiou 2003).

One possible solution to this issue of inequitability (also discussed by Zhang and Levinson 2003) is to adjust the metering rates in such a way that the overflow of ramp queues does not occur. MIXCROS, briefly described in the next section, attempts to achieve this objective by incorporating both freeway and ramp conditions into a single control law.

CLOSED-LOOP LOCAL RAMP METERING STRATEGIES

Ramp metering strategies can also be categorized as open loop and closed loop. In an open-loop ramp control (demand capacity control, upstream occupancy control, etc.), the control input (i.e., ramp metering rate) is independent of the system output, the existing traffic conditions (e.g., volume, occupancy, etc.). 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 (e.g., flow on the upstream of the metered 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.

Most ramp metering algorithms, including ALINEA, give priority to freeway traffic, as well as some consideration to traffic on entrance ramps when delays on entrance ramps are on the verge of spilling back onto surface streets. This creates an unstable condition on the ramp, which demands higher metering rates. Eventually, higher metering rates again place greater demand on the freeway, leading to unwanted fluctuations in the freeway traffic.

One can attempt to eliminate this situation. The most straightforward way is to monitor the queue on the ramp and adjust the metering rate gradually; this smooth transition prevents the queue from becoming critical. MIXCROS, the traffic-responsive ramp metering control law described in this paper, is developed to maximize the throughput on the freeway without creating long queues on the ramp. This goal is achieved by considering both queues on the ramp and traffic conditions on the freeway. This control regulates extended ramp queues, which can be caused by ramp metering, by using a weighted average of freeway and ramp flows as its objective function.

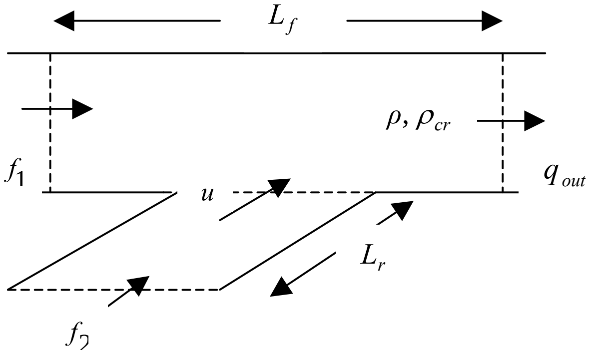


Figure 1: Isolated Freeway Ramp

The model of a freeway section is shown in Figure 1. f_1 (veh/hr) is the flow entering the freeway section, q_{out} is the flow leaving the freeway section (veh/hr), f_2 is the flow entering the ramp (veh/hr), u is the metered ramp flow (veh/hr), ρ is the density of the freeway section (veh/mi), ρ_{cr} is the critical density of the freeway section (veh/mi), $queue_{ramp}$ is the queue length on the ramp (veh/mi), and L_f and L_r are the length of the freeway and ramp section (mi), respectively.

This traffic-responsive ramp metering control achieves its goal by minimizing an error function. The control objective is defined as:

$$e(k) = w_1 \left| \rho(k) - \rho_{cr} \right| + w_2 queue_{ramp} \tag{1}$$

The error function, which takes these 2 objectives (term 1 and term 2 of Equation 1) 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 for w_1 and w_2 are determined by carefully taking the control objective of the system into consideration. The system can be categorized in 2 regions. In one region, the traffic density is greater than the critical density. In the other region, the traffic density is less than or equal to the critical density.

These two regions can be combined to devise an integrated control law (i.e., one that is applicable in both regions). The overall control law is therefore given by

$$u(k) = G^{-1}\left[-F - Ke(k)\right], \tag{2}$$

where

$$F = sign(\rho(k) - \rho_{cr})w_1\left[\rho(k) - \rho_{cr} + \frac{T}{L_f}(f_1(k) - q_{out}(k))\right] + w_2\left[queue_{ramp}(k) + \frac{T}{L_r}f_2(k)\right] \tag{3}$$

and

$$G = sign(\rho(k) - \rho_{cr})w_1\frac{T}{L_f} - w_2\frac{T}{L_r}. \tag{4}$$

T is the time step duration (hr), K is the control gain ($0 < K < 1$), $k = 0,1,...,$ is the time step. $sign(\rho(k) - \rho_{cr})$ is equal to 1 when $\rho(k)$ is greater than ρ_{cr}. Otherwise, $sign(\rho(k) - \rho_{cr})$ is equal to -1. The complete derivation of the above control law, which is outside the scope of this paper, is given in Kachroo and Ozbay (2003).

The advantages of ALINEA are listed in Papageorgiou, et al. (1991). For moderate congestion, ALINEA is effective, robust, and flexible. It is also easy to implement because the only parameters are the control gain and target occupancy. However, Banks (1991) analyzed ALINEA and found that the linear controller more effectively for regulated noncongested traffic when the nonlinearities in traffic behavior were not presented.

MIXCROS has a clear and simple algorithm compared with other known nonlinear algorithms. MIXCROS uses feedback regulation to achieve its objective, namely maximization of the throughput on the freeway without creating long queues on the ramp. This proportional-derivative state feedback control law, theoretically based on the automatic control theory, is derived from the fundamental equation of conservation of traffic flow.

For the implementation of MIXCROS, four detectors are required. They measure freeway traffic flow upstream of ramp f_1, traffic volume demand on ramp f_2, freeway traffic flow downstream of ramp q_{out}, and metered flow from ramp u.

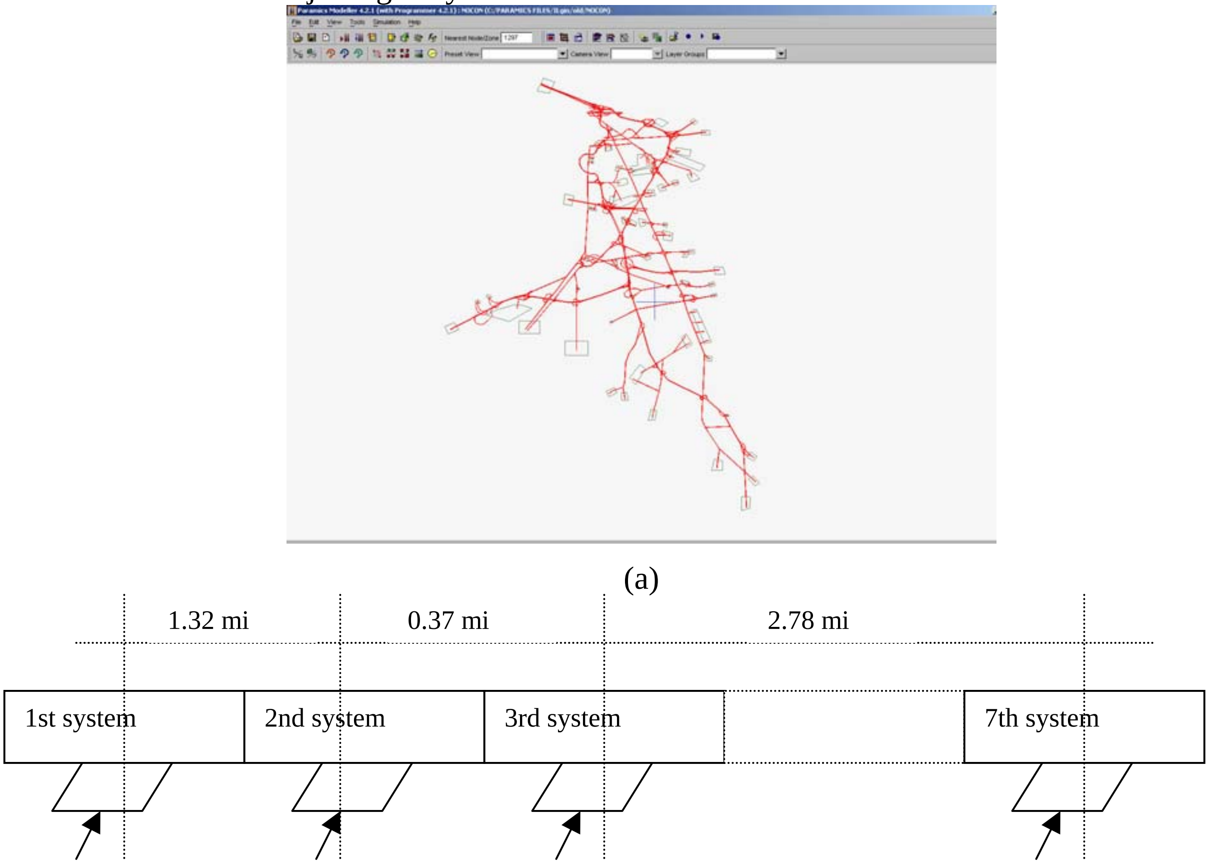
Because of its nonlinear nature, MIXCROS is effective for regulating both noncongested and congested traffic when the nonlinearities in traffic behavior are present (Ozbay et al. 2004).

MIXCROS regulates on-ramp queues via the calibration of the weight parameters for the freeway and the ramp. Therefore, no overriding tactics similar to the ones used by ALINEA (Papageorgiou et al. 1991) for preventing interference of the on-ramp queue with the surface traffic are needed.

DESCRIPTION OF MICROSCOPIC SIMULATION MODEL

South Jersey highways have already reached high traffic congestion levels, especially during the morning peak hours owing to the demand originating from Camden County to the Philadelphia business district.

A PARAMICS model (Figure 2a) of the South Jersey test network is developed using the USA network available in Arc View GIS software data files. The area that is modeled is approximately 90 square miles with 1,215 nodes and 59 zones. Only major highways and freeways are included in the model, whereas the secondary roadways are modeled as demand connectors to the major highways.



(a)

(b)

Figure 2: (a) South Jersey highway modeled in PARAMICS, (b) Distance between the controlled on-ramps on the corridor.

South Jersey – Philadelphia highway travel demand matrices for different time periods of the day and the corresponding zone locations are generated using the data provided by Delaware Valley Region Planning Committee (DVRPC). The 10.2-mile corridor chosen for the study includes 11 on-ramps, at 4 of which local-feedback ramp metering strategies, namely ALINEA and MIXCROS, are implemented (Ozbay and Bartin 2003). In Figure 2b, the schematic view of the location of the controlled on-ramps is presented. The freeway sections upstream and downstream of the ramp consisted of 3 lanes for the 1st 3 on-ramps till the 7th on-ramp upstream freeway link, with 1 lane on the ramp. For the 7th on-ramp, the upstream freeway section has 4 lanes and the downstream freeway section has 5 lanes with 1 lane on the ramp. The other ramps were not metered because extensive simulation studies showed that metering these ramps would not be productive regarding traffic management objectives.

CALIBRATION OF THE PARAMICS MODEL

A great deal of effort is spent to calibrate PARAMICS input parameters and make necessary modifications in the demand matrix (Ozbay and Bartin 2003). Various simulation runs are performed to verify that the simulation model produces reasonable results given the modeled network characteristics with each input parameter calibrated. In these calibration runs, vehicle counts have been utilized as network outputs. The data sources of vehicle counts are NJDOT online data resources (http://www.state.nj.us/transportation/) and ground truth data for the South Jersey test network obtained by the Rutgers team using traffic sensors deployed along I-76 and I-676 at 5 different locations for the PM period (Ozbay. et al. 2004).

In “No Control Scenario”, no ramp metering strategy is implemented 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.

After implementing ALINEA and MIXCROS using plans and phases files within PARAMICS Modeller, a series of simulation runs are carried out to determine the gain parameter K; it is complicated to analytically determine the K value that produces desirable performance for each ramp metering control law. The approach used in this study is similar to the one adopted by Zhang et al. (2001). The weight ratios w_1 and w_2 used in MIXCROS implementation are determined in the same manner. The calculated green phase duration is kept within prespecified limits (i.e., minimum and maximum values are 2 and 15 seconds, respectively). The critical occupancy values for each metered ramp is determined using occupancy flow plots obtained from the simulated data generated using PARAMICS. According to these plots, for each lane on the downstream of the on-ramp, the critical occupancies for the 1st, 2nd, 3rd, and 7th ramps are found to be 20%, 25%, 17%, and 33%, respectively. These values are kept constant during the course of the simulation for each scenario. The changes in the capacity experienced in real-world operation are taken into account in another study conducted by the authors of this paper.

SIMULATION RESULTS

All simulations are run for 3 hours for the afternoon peak-hour demand using different seed values for the statistical analysis of the results at a 95% confidence level. Table 1 displays summarized simulation results for each controlled on-ramp and overall South Jersey test network. The measures of effectiveness used to evaluate ramp metering strategies are the following:

A is the average travel time of the upstream freeway section (sec), B is the average travel time of the downstream freeway section (sec), and C is the average travel time of the ramp section (sec); therefore, A+B+C is the average travel time of the ramp system (sec), D is the average throughput of the upstream freeway section (veh), E is the average throughput of the ramp system (veh), F is the average on-ramp queue (veh / 17 sec), and G is the maximum on-ramp queue (veh / 17 sec).

Table 1:

Simulation Results for the Controlled On-ramps and the Total Network Results

1st ramp	**A**	**B**	**C**	**A+B+C**	**D**	**E**	**F**	**G**
No Control	45.81	42.54	29.89	118.24	3343.93	3321.33	3.71	25.8
ALINEA	48.86	41.04	27.15	117.04	3116.6	3110.33	3.06	22
Change (%)	6.65	-3.53	-9.17	-1.01	-6.8	-6.35	-17.59	-14.73
MIXCROS	42.33	36.84	28.19	107.36	3450	3437.67	2.75	13.4
Change (%)	-7.59	-13.4	-5.68	-9.2	3.17	3.5	-25.8	-48.06
2nd ramp	**A**	**B**	**C**	**A+B+C**	**D**	**E**	**F**	**G**
No Control	36.7	22	27.01	85.7	3801.2	3792.73	3.38	21.4
ALINEA	31.9	18.76	26.31	76.97	3642.67	3631.80	4.63	29.4
Change (%)	-13.06	-14.74	-2.59	-10.19	-4.17	-4.24	37.21	37.38
MIXCROS	39.61	25.55	26.78	91.94	3887.33	3885.67	3.67	17.4
Change (%)	7.94	16.13	-0.83	7.28	2.27	2.45	8.6	-18.69
3rd ramp	**A**	**B**	**C**	**A+B+C**	**D**	**E**	**F**	**G**
No Control	14.80	23.59	14.66	53.05	3758	4212.13	3.37	18.6
ALINEA	13.22	29.04	18.39	60.65	3582.13	3997.87	3.61	19
Change (%)	-10.69	23.11	25.46	14.33	-4.68	-5.09	7.31	2.15
MIXCROS	17.98	27.47	14.15	59.61	3852	4384.67	2.38	16.4
Change (%)	21.50	16.48	-3.48	12.36	2.5	4.1	-29.36	-11.83
7th ramp	**A**	**B**	**C**	**A+B+C**	**D**	**E**	**F**	**G**
No Control	45.04	42.82	17.68	105.55	5664.47	5632.93	10.01	39.4
ALINEA	38.05	34.5	18.16	90.71	5410.8	5399.07	9.22	43.6
Change (%)	-15.52	-19.44	2.68	-14.06	-4.48	-4.15	-7.88	10.66
MIXCROS	34.08	27.02	21.85	82.95	5789.00	5773.67	15.15	42
Change (%)	-24.33	-36.91	23.57	-21.41	2.2	2.5	51.36	6.6
System-wide Results				**No Control**	**ALINEA**	**Change (%)**	**MIXCROS**	**Change (%)**
Tot travel time (veh.hr)				15398.26	15176.47	-1.44	14504.24	-5.81
Mean veh. speed (mph)				38.62	39.1	1.24	41.1	6.42

After various test runs, metering of all the ramps is found to be infeasible because of the demand and geometric characteristics of the test network. In fact, if these ramps are metered, the level of congestion is observed to increase considerably with very heavy ramp queues. Thus, only ramps “1, 2, 3, and 7” are selected as the best candidates for ramp metering in this corridor and the other ramps are left out of this study (Ozbay and Bartin 2003). Ramp system is defined as the upstream-downstream freeway and on-ramp links. System-wide results cover all the ramps along the corridor, as well as major highways and freeways included in the PARAMICS model (Figure 2a).

It is important to look at the throughput values and travel times together to get a real sense of the system-wide benefits of the ramp metering. For example, increased vehicle-hours do not necessarily show degradation in system performance because average vehicle travel time can be less than or equal to travel time before the implementation of ramp metering. However, a significant increase in the number of vehicles using the system can definitely increase the total vehicle-hours.

In this study, increase in the 1st ramp system throughput lead to an increase in average travel times on the downstream ramp systems and nearby links, which can also be the reason for the average travel time increase at the 2nd and 3rd on-ramp systems for the MIXCROS implementation. Moreover, 2nd and 3rd on-ramps are located only 0.37 mile apart. Therefore, any throughput increase owing to upstream on-ramp regulation can further deteriorate the conditions on the downstream on-ramp systems. However, the benefit of implementing ramp metering strategies can be demonstrated by the fact that one additional vehicle served in the system causes less marginal increase in the average travel time. Average travel time in the 1st ramp system is decreased by 9.2%, while increasing the throughput by 3.5%, compared with “No Control” scenario. In addition, with efficient ramp queue handling, the average on-ramp queue is decreased by 25.8% compared with the “No Control” case. Using MIXCROS leads to an increase in the average travel time in the 2nd and 3rd ramp systems by 7.28% and 12.36%, respectively. Nevertheless, it leads to increase in the throughput in all metered ramp systems by 3.5%, 2.45%, 4.1%, 2.5%, respectively. Thus, this increase in average travel time can be attributed to reasons noted above, and it does not necessarily imply a worsening of performance measures. ALINEA produces similar results on the 1st, 2nd and 3rd ramps; that is, while decreasing average travel time on the 1st and 2nd ramp systems by 1.01% and 10.19%, respectively, it increases the average travel time by 14.33 % for the 3rd ramp system. Unlike MIXCROS, using ALINEA results in decrease in the throughput for all the ramp systems by 6.8%, 4.17%, 4.68%, and 4.48%, respectively.

Because of the nature of the demand matrix (low ramp demand), there are no excessive queues. The average values of the on-ramp queues remained similar to the “No Control” scenario for both the controls. Nevertheless, ALINEA increases the average and maximum on-ramp queue on all the ramps, except the first on-ramp, compared with the “No Control” case.

Both MIXCROS and ALINEA provide the best improvements (i.e., decrease in average travel time by 21.41% and 14.06%, respectively) in the 7th ramp system. This holds true because the ramp is located further away from other controlled on-ramps (Figure 2b); therefore, it is free from any fluctuations in the traffic state caused by previous on-ramp vehicles.

System-wide results indicate that MIXCROS decreases the average travel time by 5.81% and increases the mean vehicle speed by 6.42%. ALINEA, on the other hand, has quite insignificant effects on the system-wide performance measures; it decreases the throughput along the corridor, leading to increase in travel time in other bottleneck locations in the whole network (Figure 2a).

CONCLUSIONS

Two local feedback ramp control strategies ALINEA and MIXCROS are implemented and evaluated on 4 on-ramps in the carefully calibrated and validated South Jersey test network. The network used for simulation includes parallel surface streets around the corridor, thereby considering the network-wide average travel times and throughput.

One important result of this and similar studies (Ozbay et al. 2004, Gardes et al. 2001, Gardes et al. 2003) is that the impact of the on-ramp queue on overall system-wide average travel time is found to be very significant. In other words, amelioration on the freeway links can hardly balance waiting times on the ramp when the on-ramp queues are large. Though average on-ramp queue values of both control strategies are not dissimilar, the proactive nature of MIXCROS results in greater improvements on system-wide average travel times (5.81% reduction) and mean vehicle speeds (6.42% increase) for the entire simulated network.

Another significant finding of this study is that the location of the metered ramps has an impact on the success of the local ramp metering implementations; increase in the number of vehicles released from upstream bottlenecks can lead to severe congestion in the downstream locations and therefore reduce the efficiency of the local controls. Similarly, in Ozbay et al. (2004), it is shown that when the congestion level is increased as a result of heavier travel demand on the freeway, the local controls such as ALINEA (Papageorgiou et al. 1991), New Control (Kachroo and Ozbay 2003), and MIXCROS (Kachroo and Ozbay 2003) provide lesser improvements.

The 3rd and most important discovery is that it is necessary to analyze the effects of the local ramp metering implementations not only at the ramp system level but **also at the system-wide level;** a successful ramp metering implementation causes an apparent increase in the throughput at each ramp system. This increase would eventually increase the number of vehicles on the remaining links. In fact, although MIXCROS increases the throughput both in the ramp systems and the rest of the network, it is still able to reduce the total average system-wide travel times. This can be explained by the first conclusion of the paper; i.e., MIXCROS offers proactive control, which is largely attributed to the fact that MIXCROS uses derivative control action. One advantage of using derivative control action is that it responds to the rate of change of the error (Equation 1) and can produce a significant correction before the magnitude of the error becomes unmanagable. Derivative control thus anticipates the actuation error, initiates an early corrective action, and tends to increase the stability of the system. On the other hand, in ALINEA implementation, the average travel times are decreased with the decrease in the throughput along the corridor (Table 1). Because the freeway links are the part of the whole network, the diversion is only beneficial when the alternate routes have sufficient capacity to carry the diverted traffic. As stated in Cassidy and Rudjanakanoknad (2002), the few system-wide benefits observed when ramp metering is implemented and evaluated at a system level, can be mainly traced to vehicles diverting from the freeway to other routes with bottlenecks. In the ALINEA implementation studied in this paper, similar diversion behavior to other routes is also observed by specifically keeping track of individual vehicles. It is clear that the results presented in this paper are network and demand specific and should be generalized. However, system-wide impacts of these ramp control strategies constitute an important topic that is also raised by various other researchers (Zhang and Recker 1999, Pooran et al. 1994). The results presented in this paper clearly demonstrate the need for microscopic simulation-based analysis of ramp metering strategies for a fair and accurate evaluation of their overall benefits. Thus, the analysis of the impacts of ramp metering both at the local and network-wide levels presented in this paper helps us better understand the real benefits of this favorite freeway control strategy from a system perspective.

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