# Evaluation of New Coordinated Feedback-Based Freeway Ramp Metering Strategy Using Macroscopic and Microscopic Simulation Models

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***Abstract***

In this paper, two new feedback based coordinated ramp-metering laws, namely C-MIXCROS and D-MIXCROS, that explicitly consider ramp queues are proposed and then evaluated using both macroscopic (Rutgers Macroscopic Simulation Environment) and microscopic (PARAMICS) simulation models (on 11-mile long corridor of I-295 in South Jersey) under different demand conditions. In addition to this newly proposed coordinated ramp metering strategies, a well-known coordinated strategy (METALINE (5)) and three other local strategies (ALINEA (6), New Control (1) and MIXCROS (1)) are also implemented using the same network and results are compared. The proportional-derivative state feedback control logic and direct regulation of on-ramp queues are employed in the derivation of this new proposed coordinated ramp metering strategy. The results from the microscopic simulation were consistent with the macroscopic simulation, where D-MIXCROS and C-MIXCROS both performed better than all other control strategies tested for all the demand scenarios. The deteriorating effect of large on-ramp queues on the total travel time is especially observed for METALINE results, where the total travel time was approximately 22% larger than those of C-MIXCROS results. MIXCROS (1) was also successful in keeping the on-ramp queues at a reasonable level for each ramp. However, because it is a local ramp metering strategy, coordinated versions of MIXCROS were observed to be more beneficial both for the ramp system and at the network level.

## 1. INTRODUCTION

The continuous increase of traffic demand has led to increasingly severe congestions, both recurrent (occurring daily during rush hours) and non-recurrent (due to incidents). One of the most efficient and direct control measures that are typically employed in freeway networks is ramp metering. Ramp metering provides improvement of freeway flow by breaking up platoons, and allowing more efficient merging, reduction of accidents, fuel consumption. Freeway control can be open loop (in general time-of day dependent) or closed loop (traffic responsive). In the first case, controls are derived from a priori known such traffic data as demands, occupancies, (e.g. Demand Capacity (2), while closed loop controls directly react to existing traffic conditions (e.g., ALINEA (6), MIXCROS (1)).

Overall, there are two types of ramp metering. Local ramp metering considers an isolated section of the network consisting of a freeway section with one on-ramp, and the controller responds only to changes in the local conditions. Coordinated ramp metering is the application of ramp metering to a series of entrance ramps with the goal of coordinating the response of all the ramps in the system. The disadvantage of local ramp metering is its lack of coordination between ramps in order to work toward optimization of the freeway facility. Coordinated ramp metering, on the other hand, can become very complex and expensive to implement and maintain.

The ramp metering controls that are evaluated in this paper, namely ALINEA, New Control, METALINE, MIXCROS, and coordinated version of MIXCROS are briefly described in the following.

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) (6).

METALINE is the coordinated version of the local ramp metering strategy ALINEA. It was implemented on certain freeways in France, the United States and the Netherlands. The control logic of METALINE is Proportional-Integral state feedback. The main challenge to the success operation of METALINE is the proper choice of the control matrices and the target occupancy vector (Table 1). There is no direct consideration of queue overflows in METALINE (5).

MIXCROS, a traffic-responsive local ramp-metering control law proposed by Ozbay et al. (2004), is developed to maximize the throughput on the freeway without creating long queues on the ramp through the use of carefully calibrated weight parameters for the freeway and ramp, namely ($w_1, w_2$). The control logic of MIXCROS is Proportional-Derivative state feedback. Complete derivation of MIXCROS is given in (1). Although MIXCROS proved to be very effective in reducing the congestion on the ramp system while keeping the on-ramp queue at an acceptable level, because MIXCROS is a local feedback based ramp-metering strategy, it produced very little improvement at the network level (3).

## 2. DESCRIPTION OF THE COORDINATED VERSION OF MIXCROS

The basic model used for the design of the coordinated MIXCROS control law (Figure 1) is the following.

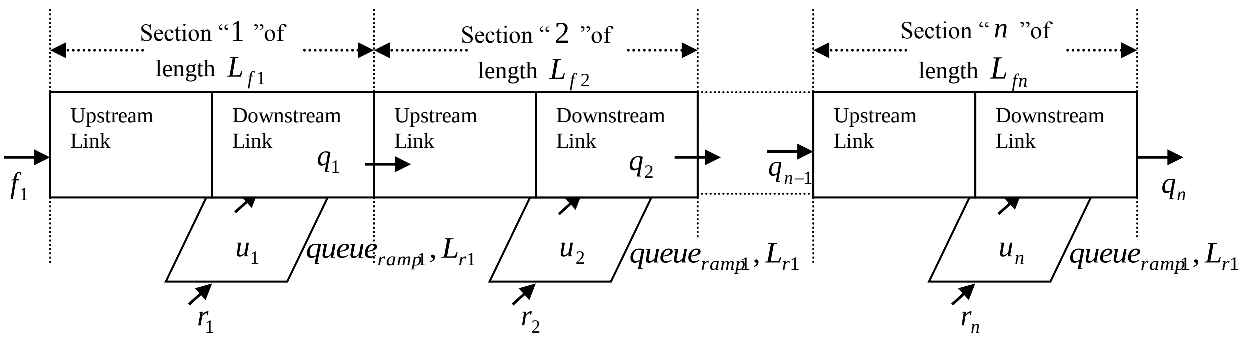


Figure 1. "$n$" Freeway sections with one on-ramp.

Where $n$ is the number of freeway sections, $f_i$ (veh/hr) is the flow entering the freeway at the first section, $q_i$ is the flow leaving the freeway section $i$ (veh/hr), $r_i$ is the flow entering the ramp (veh/hr), $u_i$ is the metered flow (veh/hr), $\rho_i$ is the freeway density (veh/mi), $\rho_{c(i)}$ is the critical density (veh/mi), $T$ is the time step duration (hr), $w_{1(i)}, w_{2(i)}$ are the weight factors ($w_{1(i)} + w_{2(i)} = 1$), $queue_{rampi}$ is the queue length on the ramp (veh/mi), $K_i$ is the control gain ($0 < K < 1$), $L_{fi}$ and $L_{ri}$ are the length of the freeway and ramp section $i$ (mi), respectively.

Coordinated version of MIXCROS is applied to a number of on-ramps in order to provide network-wide improvements, which aims to maximize the throughput on all the freeway sections without creating long queues on all the metered ramps. The proportional state feedback control logic (Equation 2) and direct regulation of on-ramp queues are employed in the derivation of this new proposed coordinated ramp metering strategy.

This coordinated traffic-responsive ramp-metering control achieves its goal by minimizing the following error function. Therefore, control objective of coordinated MIXCROS is to make the following error function go to zero as the time, $t$, goes to infinity:

$$e(t) = \sum_{i=1}^{n} \left( \left| w_{1(i)} x_{1(i)}(t) \right| + \left| w_{2(i)} x_{2(i)}(t) \right| \right)_i \tag{1}$$

Where $x_{1(i)}(t) = \rho_i(t) - \rho_{cr(i)}$, $x_{2(i)}(t) = queue_{rampi}(t)$, $i = 1,2,...n$ $i$ : section index

The error function (Equation 1) is defined as summation of the absolute values of the state variables $x_{1(i)}$ and $x_{2(i)}$. $x_{1(i)}$ is the state variable that represents the freeway section of the network, and

$x_{2(i)}$ represents the on-ramp queue. Equation 1 takes these state variables 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 $w_2$.

The control objective can be achieved by designing control law that makes the system follow the below closed loop dynamics.

$$\dot{e}(t) + Ke(t) = 0 \quad (2)$$

The system can be in $2^n$ regions, where $n$ is the number of freeway sections in the network because the first term in the error function ($\left| w_{1(i)} (\rho_i(t) - \rho_{cr(i)}) \right|$). These $2^n$ regions can be combined to come up with a control law that is applicable in all regions with the help of a function $sign$ such that

$$sign = \begin{cases} 1 & if\ \rho_i(t) > \rho_{cr(i)} \\ -1 & else \end{cases} .$$

The condition the control variables should satisfy is the following:

$$Gu(t) = -F(t) - Ke(t)$$

Where

$$F(t) = \sum_{i=1}^{n} \left( w_{1(i)} \times sign \times \left( \frac{1}{L_{fi}} \times (-q_i(t) + f_i(t)) \right) + w_{2(i)} \left( \frac{1}{L_{ri}} \times r_i(t) \right) \right)$$

and

$$Gu(t) = \sum_{i=1}^{n} (sign \times w_{1(i)} \times \frac{1}{L_{fi}} - w_{2(i)} \times \frac{1}{L_{ri}}) \times u_i(t)$$

The control law can be designed in a decoupled way or coupled way. The decoupled control law (D-MIXCROS) for each freeway section is:

$$u_i(t) = (sign \times w_{1(i)} \times \frac{1}{L_{fi}} - w_{2(i)} \times \frac{1}{L_{ri}})^{-1} (-F_i(t) - Ke_i(t))$$

The coupled control law (C-MIXCROS) is:

$$u_i(t) = \alpha_i \times (sign \times w_{1(i)} \times \frac{1}{L_{fi}} - w_{2(i)} \times \frac{1}{L_{ri}})^{-1} \times (-F(t) - Ke(t))$$

Where $\sum_{i=1}^{n} \alpha_i = 1$, $F = \sum_{i=1}^{n} F_i(t)$, and $e(t) = \sum_{i=1}^{n} e_i(t)$.

The complete derivation of the above control law, which is outside the scope of this paper, is offered in (1).

In Table 1, the calibration parameters for each ramp metering strategy are presented. As it seen from this table, local controls, namely ALINEA and New Control, require least amount of parameters. On the other hand, coordinated control, namely D-MIXCROS, has only 7 calibration parameters, which gives an advantage over the other coordinated control evaluated, METALINE. However, the comparison of the performances of each ramp metering strategy is provided in the simulation results section based on the macroscopic simulation environment modeling.

Table 1 Calibration Parameters for Each Ramp Control Implementation

| Ramp Metering Strategy | Calibration Parameters for Each On-ramp | Total number of Calibration Parameters for 6 On-ramps |
|---|---|---|
| ALINEA | $K_R$ | 6 |
| New Control | $K_R$ | 6 |
| MIXCROS | $K_R$ , $w_1$ and $w_2$ | 12 |
| METALINE | $K_{R1}$ and $K_{R2}$ | 12 |

| | | |
|---|---|---|
| DC MIXCROS | $K_R$ , $w_1$ and $w_2$ | 7 |
| CC MIXCROS | $K_R$ , $\alpha$ , $w_1$ and $w_2$ | 13 |

D-MIXCROS is similar to the local version of MIXCROS because it takes each on-ramp system into account separately. However, it differs from the local version because D-MIXCROS uses the same control gain $K_R$ for all the ramps, which ensures a unity in the actions of metered ramps. From implementation view, it is easier to implement D-MIXCROS than the local version of MIXCROS on a number of ramps. D-MIXCROS implementation on 6 on-ramps requires 7 parameters to be calibrated, whereas MIXCROS uses 12 calibration parameters (Table 1). Hence, it is easier to implement D-MIXCROS than both the local version of MIXCROS and C-MIXCROS on a number of ramps

In C-MIXCROS, the control effort is distributed among all on-ramps using distribution factor, $\alpha_i$, which provides the communication between on-ramp systems. With these allocation ratios, $\alpha_i$, the nature of the congestion in each ramp system can be handled in a very detailed manner. For example, if the congestion on the second ramp is propagating towards the other on-ramp locations, the allocation ratio, $\alpha_2$, for the second on-ramp can be reduced compared to the other ratios ($\alpha_2 < \alpha_1, \alpha_3$).

## 3. MACROSCOPIC SIMULATION

The proposed coordinated ramp metering controls, namely C-MIXCROS and D-MIXCROS, and ALINEA, MIXCROS, METALINE are applied at six consecutive ramps along a corridor. Each ramp system consists of a one-lane (1 mile) freeway link and a one-lane (0.5 mile) ramp link. Simulation duration for each tested case is 300 min.

In both macroscopic and microscopic simulation models, for ALINEA, New Control and METALINE implementations, a queue threshold of 35 vehicles is used. New Control and METALINE, all versions of MIXCROS perform satisfactorily without a queue override strategy that shuts off the ramp metering and creates unwanted fluctuations. In ALINEA implementation, for the values of parameter $K_R$ above 240 veh/hr, on ramp queues are decreased, whereas ramp metering provides no improvement on the downstream traffic conditions in the ramp systems. So, the purpose of the control, which is to keep the downstream freeway section at the set level, is not met. Therefore, the regulator parameter, $K_R$, is kept between 70 veh/hr and 240 veh/hr for all the ramps.

All the tested ramp metering controls maintain the freeway outflow close to capacity, while keeping the traffic density below critical density. All the controls except D-MIXCROS and C-MIXCROS experience high fluctuations in the traffic density within first 50 min of simulation. Queue override tactics employed in these controls mainly causes this problem. That is, these controls use the storage capacity of the on-ramps, which leads to increased traffic flow on the freeway sections. This increased traffic flow results in congestion in downstream locations causing more restrictive ramp metering rates so as to serve additional throughput from the upstream ramp systems. Among all tested controls, METALINE has the largest on-ramp queues due to its restrictive metering. Decreasing freeway demand by 5.26% (Demand Scenario 1) leads to increase in the freeway maximum outflow (throughput) with each ramp metering strategy. With reduced freeway demand, each ramp metering strategy results in approximately the same total travel time. In order to observe the behavior of the controls in the presence of large ramp demand (Demand Scenario 2), ramp demand is increased by 67% compared with the base demand scenario, while lowering the freeway demand 33% due to limited capacity of the freeway segments. With this demand configuration, all versions of MIXCROS provide superior individual ramp performance results (e.g., increased average freeway downstream flow, speed and density) compared with all the controls tested. In Demand Scenario 3, where ramp demand is increased only by 33% whereas freeway demand is lowered by 33%, all ramp metering strategies, both local and coordinated, provide almost the same improvements on the network level. Due to light ramp demand, METALINE is also able to keep the on-ramp queues at reasonable levels with the help of a queue override tactic (Table 2). In the table, A refers to the total travel time on all 6 ramps (veh.hr/hr) and B stands for the total travel time in the network (veh.hr/hr).

Table 2. Overall Network Results for 4 Demand Scenarios

| | Base Demand | | Demand Scenario 1 | | Demand Scenario 2 | | Demand Scenario 3 | |
|---|---|---|---|---|---|---|---|---|
| | A | B | A | B | A | B | A | B |
| ALINEA | 13.73 | 247.17 | 13.02 | 239.58 | 19.62 | 239.70 | 15.21 | 198.29 |
| New Control | 12.70 | 246.21 | 12.22 | 238.36 | 19.24 | 239.57 | 15.29 | 198.60 |
| MIXCROS | 11.92 | 248.65 | 12.06 | 238.44 | 18.37 | 238.77 | 14.91 | 198.17 |
| METALINE | 79.87 | 314.61 | 13.44 | 243.43 | 459.95 | 680.33 | 19.55 | 201.43 |
| D-MIXCROS | 11.92 | 248.65 | 12.08 | 238.43 | 18.37 | 238.76 | 14.91 | 198.17 |
| C-MIXCROS | 11.92 | 244.56 | 12.06 | 238.44 | 18.37 | 238.77 | 14.91 | 198.18 |

## 4. MICROSCOPIC SIMULATION

PARAMICS model of the section of I-295 in South Jersey is created using the available geometric and traffic demand data. The calibrated and validated model of the 11 miles long 3-lane freeway section includes the junctions of I-295 with Route 38, State HWY 73, State HWY 70 and Berlin Rd. Each on-ramp has 1-lane. Then, an Application Programming Interface (API) is written to assign green times based on each tested control law to all 4 on-ramps in PARAMICS. In the API 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. Statistics are collected for 3-hour simulation from the detectors located downstream and upstream of the ramp and two additional detectors, one at the exit and one at the entrance of the ramp. In microscopic simulation model, the proposed ramp metering controls, namely D-MIXCROS and C-MIXCROS, ALINEA, and MIXCROS are evaluated and compared with No Control case using three demand scenarios, whose congestion levels are listed in Table 3. The congestion level is the percent of the time that the downstream link occupancy is greater than the critical occupancy. All simulations are run for 3 hr with different seed values for the statistical analysis of the results, which ensured a 95% confidence level.

Table 3. Congestion Levels on Each Ramp

| | 1st Ramp | 2nd Ramp | 3rd Ramp | 4th Ramp |
|---|---|---|---|---|
| 1st Demand Level | 27% | 60% | 68% | 20% |
| 2nd Demand Level | 53% | 39% | 58% | 9% |
| 3rd Demand Level | 0% | 17% | 35% | 24% |

Ramp metering controls seem to be more effective under certain demand patterns than others. As traffic demand increases, ramp metering tends to be more effective in reducing system travel time. The reason for reduced ramp metering performance for the third demand scenario is the low level of congestion on each ramp system. It was also claimed in other studies that the effectiveness of ramp control varies over the severity of congestion (11). Table 4 summarizes the main findings of this implementation. All controls tested except ALINEA reduced the average travel time regardless of the demand scenario compared with No Control.

For the demand scenarios tested, both C-MIXCROS and D-MIXCROS lead to maximum improvement for all the performance criteria.

Table 4. Overall Network Results for 3 Demand Scenarios

| | Demand Scenario 1 | | Demand Scenario 2 | | Demand Scenario 3 | |
|---|---|---|---|---|---|---|
| | Tot. Travel Time (veh.hr) | Mean Speed (mph) | Tot. Travel Time (veh.hr) | Mean Speed (mph) | Tot. Travel Time (veh.hr) | Mean Speed (mph) |
| No Control | 3723.57 | 55 | 4119.18 | 49.6 | 3408.15 | 57.8 |
| ALINEA | 3901.73 | 52.13 | 4137.14 | 49.43 | 3368.08 | 58.23 |
| Change (%) | 4.78 | -5.23 | 0.44 | -0.35 | -1.18 | 0.74 |
| MIXCROS | 3674.04 | 55.63 | 3976.06 | 51.4 | 3354.74 | 58.25 |

| | | | | | | |
|---|---|---|---|---|---|---|
| Change (%) | -1.33 | 1.14 | -3.47 | 3.63 | -1.57 | 0.78 |
| D-MIXCROS | 3552.71 | 57.28 | 3801.35 | 54.1 | 3394.75 | 57.83 |
| Change (%) | -4.59 | 4.14 | -7.72 | 9.07 | -0.39 | 0.43 |
| C-MIXCROS | 3546.94 | 57.25 | 3938.86 | 52.15 | 3354.98 | 58.05 |
| Change (%) | -4.74 | 4.09 | -4.38 | 5.14 | -1.56 | 0.43 |

## 5. CONCLUSION

Evaluation of the new coordinated ramp metering control is performed to demonstrate its characteristics and eventually its impact on the ramp system and whole network in two phases. The first phase includes the macroscopic testing of the proposed coordinated ramp metering controls using RMSE (Rutgers Macroscopic Simulation Environment) to compare it with three local (ALINEA, New Control and MIXCROS) and one coordinated ramp metering control (METALINE) under the various demand scenarios. The second phase involves evaluating the proposed methodology using a microscopic simulation environment (PARAMICS) under three different demand scenarios.

From these implementations, it is found that the system performed better after the implementation of coordinated version of MIXCROS (1), namely C-MIXCROS and D-MIXCROS compared with other ramp metering controls. As expected, the mainline freeway experiences better traffic conditions when any of the tested ramp metering controls is implemented. However, when the queue thresholds are used in ALINEA, New Control and METALINE to prevent the ramps from being overloaded, the system benefits of these strategies are reduced. C-MIXCROS and D-MIXCROS significantly improve system performance compared with other controls under various demand conditions and they are proven to be quite effective.

Well tuned parameters are critical for good ramp metering performance. Compared to some coordinated ramp metering controls that employs optimization techniques, parameter calibration for C-MIXCROS and D-MIXCROS is not burdensome.

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