

Field Test Implementation of Coordinated Ramp Metering Control Strategy: A Case Study on SR-99N

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ABSTRACT

This paper focuses on field implementation and testing of a coordinated ramp metering (CRM) algorithm based on a simplified optimal control approach. The test site was the California State Route 99 Northbound (SR-99N) corridor in Sacramento between Calvine Road and the SR-50 interchange after 12th Avenue (Abs. PostMile 290.454 - 299.467). It is a 9-mile long corridor with 11 on-ramps, to which the CRM algorithm has been applied. By comparing the vehicle-miles-travelled (VMT), vehicle-hours-travelled (VHT), and the ratio VMT/VHT (defined as system efficiency in PeMS and interpreted as average speed) during field tests in 2016 with data from 2015 in the same period, during the morning peak hours (6:00 AM-9:00 AM), VMT/VHT increased by 7.25% on average, indicating traffic efficiency improvement. During the evening peak hours (3:00 PM-6:00 PM), VMT/VHT decreased by 0.44% on average, indicating no traffic efficiency improvement. The reason was that the traffic was not heavily congested during most evening hours. Test results suggest that the CRM algorithm tested could be more effective for heavily congested traffic. The system has been deployed for daily operation along the SR-99N corridor after the test period.

INTRODUCTION

Ramp metering (RM) is the major method of freeway traffic control, a strategy for alleviating the effect of the capacity drop phenomenon, which negatively influences transportation system efficiency. In order to increase freeway efficiency, the outflow from an on-ramp into a freeway mainline is regulated to prevent mainline flow breakdown by storing surplus on-ramp vehicles in an on-ramp queue. Freeway capacity drop means that the congestion after a breakdown has an outflow lower than the free-flow capacity. When capacity drop occurs, the throughput of the freeway can be reduced by 5% to 20%, leading to a higher total travel time spent in the network.

As a result, a large amount of research has been conducted on designing effective ramp metering strategies. Different types of ramp metering strategies have been studied in field implementation tests in the past decades [1], [2]. Most Ramp Metering operations in California are fixed by time-of-day (TOD) or are locally responsive to occupancy measurements immediately upstream of the entrance ramp merge; the latter is called a local responsive ramp metering (LRRM) strategy. The locally responsive ramp metering strategy adjusts the ramp metering rate of each on-ramp independently such that traffic flow at the entrance ramp merge area is regulated. However, the performance of locally responsive metering controller is limited, because traffic on each section of a freeway dynamically affects each other section. Downstream section flow depends on the demand flow from its upstream, and downstream congestion could back-propagate to the upstream. The global behavior of the network cannot be shared between local responsive controllers if there is no communication between them. This isolated control structure cannot coordinate available on-ramp storage space between freeway upstream and downstream, and, therefore, the overall mainstream capacity may be overloaded or underutilized.

In order to mitigate the drawbacks of LRRM, coordination control strategies have been proposed in the literature to more effectively alleviate congestion. Coordinated ramp metering (CRM) is based on optimal control theory [3], [4], and it has been studied in analysis [5] and simulation [6] in several previous works, which have indicated some potential in reducing freeway congestion at recurrent bottleneck locations. Freeway corridor traffic flow is limited by bottleneck flow. If the section upstream of a bottleneck is congested, the bottleneck flow will drop well below its capacity. A logical approach to maximize flow at recurrent bottlenecks is to create a discharge section immediately upstream of the bottleneck. 

The objective of this project is to conduct a field implementation test and evaluation of a newly developed CRM algorithm [5]. This field implementation test is a collaborative project conducted by PATH research team (<http://www.path.berkeley.edu/>) and Caltrans District 3 under the framework of the Caltrans District 3 traffic management center (TMC) system. The main tasks of the project include: (1) fine tuning CRM algorithms through simulation for California State Route 99 Northbound (SR-99N) morning peak traffic [6]; (2) implementing algorithm on PATH real-time control computers and integrating them with TMC ramp metering computers; (3) implementing and refining real-time traffic state parameter estimation; (4) conducting dry-runs with PATH computers interfaced with TMC computers; (5) progressively activating the CRM control; (6) evaluating the performance of CRM. These concepts need to be tested in the field to determine whether the projected benefits could be achieved in practice in California. If the results of field testing are favorable, they could provide the basis for future widespread adoption of CRM control strategies to further improve mobility and safety and reduce energy and emissions impacts of freeway congestion.

The remainder of this paper is organized as follows. The next section introduces the test

site and available data. Then, the proposed CRM control strategy is explained. Next, field implementation of the proposed method is explained. Finally, field test results are presented. The paper concludes with a summary and a brief discussion relating to practical applications and further research.

TEST SITE AND AVAILABLE DATA DESCRIPTION

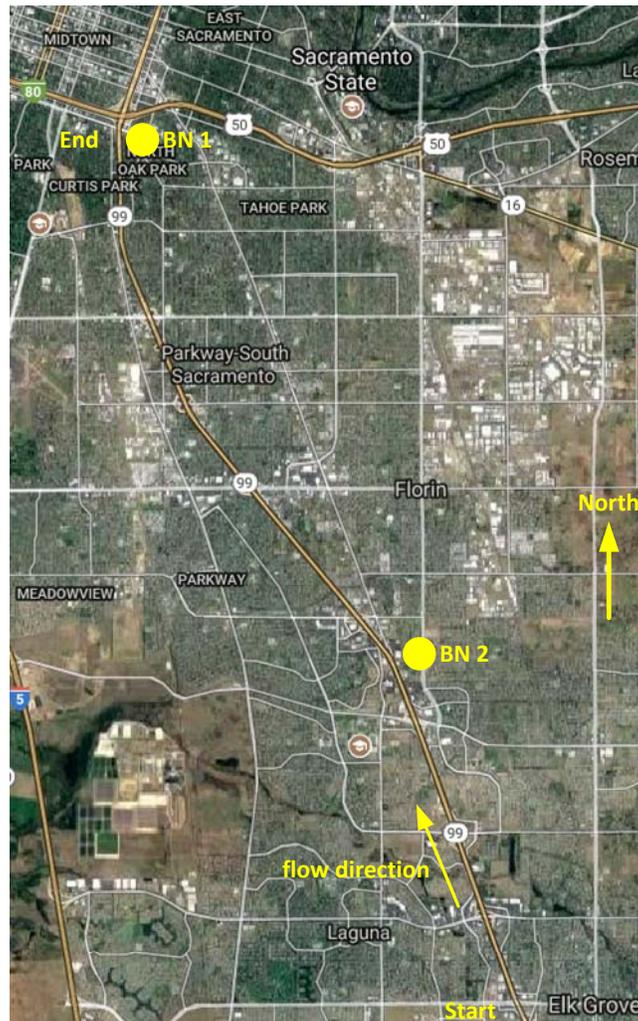


FIGURE 1 Satellite map of SR-99 N test site segment and its bottlenecks.

The test site of the field implementation is on the SR-99N from Elk Grove Boulevard at absolute postmile 287.23 to the freeway interchange point of SR-99N and U.S. Route 50 (US-50) at absolute postmile 299.467, as shown in Figure 1. The proposed CRM was deployed to on-ramps in the freeway segment on SR-99N between Calvin Road and the SR-50 interchange after 12th Avenue (abs. postmile 290.454 - 299.467). The simulation study of this test site has been conducted in previous work [6]. The field test involved activating the proposed CRM algorithm during morning peak traffic hours (6:00 AM - 9:00 AM) and evening peak traffic hours (3:00 PM - 6:00 PM). The test site is an 11-mile stretch of freeway that sustains heavy congestion during the morning and evening commutes. Morning congestion usually begins around 6:30 AM, peaks

at 8:00 AM, and finally dissipates at around 10:00 AM. Evening congestion usually begins around 3:00 PM, peaks at 4:00 PM, and finally dissipates at around 7:00 PM. The leftmost lane is a high-occupancy vehicle (HOV) lane and spans the entire mainline of the test site. The HOV lane is reserved for vehicles carrying two or more passengers, and its operational time is from 6:00 AM to 10:00 AM and from 3:00 PM to 7:00 PM. The whole test site has 16 on-ramps and 11 off-ramps. Each of these 16 on-ramps is equipped with ramp metering, which uses the immediate upstream mainline detector station for traffic responsive ramp metering control. Eleven of these 16 on-ramps have HOV lanes, which are individually metered by ramp metering. The network configuration and vehicle detection station (VDS) configuration is shown in Figure 2, where the numbered black boxes, red circles, and green circles label the indices of mainline VDS, off-ramp VDS, and on-ramp VDS, respectively. The dashed arrows in Figure 2 indicate that off-ramps 6, 7, 8, and 11 are missing. Those missing flow data were recovered by imputation [6], [7] using PeMS (<http://pems.dot.ca.gov>) historical data.

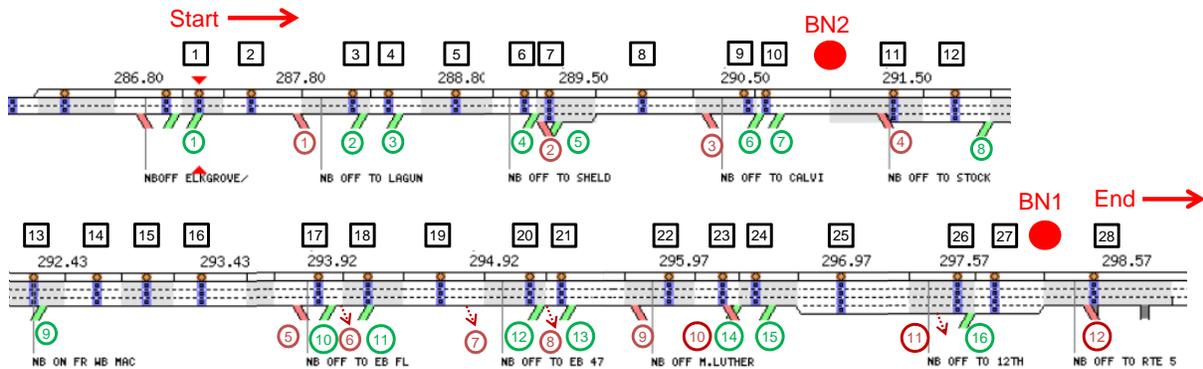


FIGURE 2 SR-99N network configuration and VDS deployment.

The field test implementation uses 30 seconds of raw data, which were directly collected from the loop detectors and 2070 traffic controllers at the test site. To monitor and control the test site, lane-by-lane mainline data (namely flow, speed, and occupancy) were collected from each loop detector. Further, lane-by-lane on-ramp and off-ramp flow and occupancy data are also collected from each loop detector. Mainline vehicle density were calculated by the speed-flow relation. These collected raw data were aggregated after outliers, abnormal data, and missing data were removed or imputed by a real-time data cleansing algorithm [8]. The aggregated data in this project were compared with data in a PeMS archive (<http://pems.dot.ca.gov>) in order to verify their correctness.

COORDINATED RAMP METERING

The proposed CRM problem is formulated as a discrete time-optimal control problem with constraints on the decision variables over a finite horizon N_p , which is generally referred to as model predictive control (MPC). A cell transmission model (CTM) is used for the description of freeway traffic flow, constituting the modeling part of the MPC formulation. In order to increase the computation efficiency of solving optimization problems in real-time, we simplify the original nonlinear MPC problem such that it becomes a linear programming (LP) problem by assuming that average traffic speeds for each freeway section are available [5]. This assumption of having speed data is

practical since good speed measurements can be obtained from dual loop traffic detector stations in the test field [8]. These dual loop detectors are connected to 2070 controllers under the universal ramp metering system (URMS) framework in TMC, and, therefore, other traffic state parameters (flow and occupancy) can also be obtained.

Freeway Model

Considering the macroscopic traffic model, a freeway is divided into N segments such that each segment i has at most one on-ramp and one off-ramp. The following traffic quantities are defined for each segment i at each time step k :

$\rho_i(k)$: Mainline density; number of vehicles in segment i at time step k .

$\bar{\rho}_i(k)$: Estimated/measured mainline density.

ρ_i^J : Jam density of segment i .

$f_i(k)$: Mainline flow (number of vehicles per time step) of vehicles leaving upstream segment i , moving to downstream segment $i + 1$, at time step k .

$\bar{f}_i(k)$: Measured mainline flow.

F_i : Mainline flow capacity of segment i .

$w_i(k)$: Number of vehicles on the on-ramp corresponding to segment i , at time step k .

w_i^J : Jam density of the on-ramp corresponding to segment i .

$r_i(k)$: Metering flow rate; number of vehicles entering segment i through its on-ramp at time step k , determined by the controller in actuated on-ramps.

r_i^o : Maximum possible on-ramp flow for the on-ramp i .

$d_i(k)$: Estimated/measured on-ramp demand; flow of vehicles intending to enter the on-ramp belonging to segment i at time step k .

$s_i(k)$: Off-ramp flow; flow of vehicles that leave segment i through its off-ramp at time step k .

$v_i(k)$: Time mean speed of vehicles moving in segment i at time step k .

$u_i(k)$: Space mean speed of vehicles moving in segment i at time step k .

T : Sampling time or simulation time step size.

λ_i : Number of lanes in segment i .

L_i : Length of mainline segment i .

L_i^o : Queue capacity of on-ramp i ; maximum number of vehicles that the on-ramp corresponding to segment i can accommodate.

N_p : Prediction horizon.

By the law of conservation, the dynamics of freeway mainlines are described by the evolution of mainline density $\rho_i(k)$ over time:

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{\lambda_i L_i} (f_{i-1}(k) + r_i(k) - f_i(k) - s_i(k)). \quad (1)$$

Since traffic density calculated from a space mean speed $u_i(k)$ is more realistic [9], the traffic flow can be computed for each time step by

$$f_i(k) = \lambda_i \rho_i(k) u_i(k), \quad (2)$$

where space mean speed $u_i(k)$ is assumed to be given. Substituting (2) into (1) gives a linearized equation:

$$\rho_i(k+1) = \rho_i(k) + \frac{T}{\lambda_i L_i} (\lambda_{i-1} \rho_{i-1}(k) u_{i-1}(k) + r_i(k) - \lambda_i \rho_i(k) u_i(k) - s_i(k)). \quad (3)$$

Similarly, the evolution of on-ramp queue is described by the following conservation equation:

$$w_i(k+1) = w_i(k) + T(d_i(k) - r_i(k)). \quad (4)$$

Supposing that there are n_i fixed sensors (loop detectors) on segment i and $\bar{v}_l(k)$ is individual vehicle speeds (measured speed) from each sensor, the time mean speed is computed by

$$v_i(k) = \frac{1}{n_i} \sum_{l=1}^{n_i} \bar{v}_l(k) \quad (5)$$

Assuming stationary conditions, the space mean speed can be computed from $\bar{v}_l(k)$, using a harmonic mean of the measurements [9]:

$$u_i(k) = \frac{1}{\frac{1}{n_i} \sum_{l=1}^{n_i} \frac{1}{\bar{v}_l(k)}}. \quad (6)$$

Constraints

In reality, the controlled freeway is subjected to constraints for the maximum and minimum values of mainline density, on-ramp queue length, and ramp metering rate. These constraints are formulated as the following inequalities

$$0 \leq w_i(k) \leq L_i^o w_i^J, \quad (7)$$

$$r_{min} \leq r_i(k) \leq \min\{d_i(k), r_i^o, \lambda_i(F_i - \bar{f}_{i-1}(k)), \lambda_i u_i(k)(\rho_i^J - \bar{\rho}_i(k))\}, \quad (8)$$

$$0 \leq \rho_i(k) \leq \min\{\rho_i^J, \phi(u_i(k))\}. \quad (9)$$

The first inequality constraint, in (7), is the entrance ramp queue length limit, in number of vehicles; the one in (8) represents the direct constraints on ramp metering rate in which flow is the unit [veh/hr]. The low bound of on-ramp metering rate r_{min} is maintained as 300 [veh/hr] to prevent fully block an on-ramp. The upper bound of on-ramp metering rate is the minimum of the four terms in the braces: the entrance ramp demand, entrance ramp capacity, and are space available in the mainline (the last two terms). $\lambda_i(F_i - \bar{f}_{i-1}(k))$ is related to the free-flow case, and $\lambda_i u_i(k)(\rho_i^J - \bar{\rho}_i(k))$ is related to the congestion case. The third inequality, in (9) (with unit as the number of vehicles per mile), is an indirect constraint on ramp metering rate through the density dynamics. The function $\phi(u_i(k))$ describes the speed versus density, which is obtained from an empirical study of traffic speed drop [10].

Objective Function

Under the framework of optimal control, controllers are typically designed to minimize or maximize a single objective function. For ramp metering control, total time spent (TTS) and total traveled distance (TTD) are two interesting objective functions. TTS is defined as

$$\text{TTS}(k) = T \sum_{j=0}^{N_p-1} \sum_{i=1}^N L_i \lambda_i \rho_i(k+j) + \alpha_w T \sum_{j=0}^{N_p-1} \sum_{i=1}^N w_i(k+j), \quad (10)$$

where the first term of TTS is also called total travel time (TTT), the second term of TTS represents time delay due to on-ramp queue, and α_w is the on-ramp weighting parameter.

TTD is defined as

$$\text{TTD}(k) = T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N-1} L_i \lambda_i f_i(k+j) + T \sum_{j=0}^{N_p-1} L_N \lambda_N f_N(k+j). \quad (11)$$

For tractability reason, these two objective functions are combined into a single cost function

$$J = \text{TTS} - \text{TTD}_\alpha, \quad (12)$$

where subscript α represents positive weighting parameters for each segments. Choosing the weighting parameters $\alpha_{\text{TTD},N} \gg \alpha_{\text{TTD},0} > 0$ emphasizes maximizing the flow on the most downstream segment N and (12) can be written as

$$\begin{aligned} J = & T \sum_{j=0}^{N_p-1} \sum_{i=1}^N L_i \lambda_i \rho_i(k+j) + \alpha_w T \sum_{j=0}^{N_p-1} \sum_{i=1}^N w_i(k+j) \\ & - \alpha_{\text{TTD},0} T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N-1} L_i \lambda_i f_i(k+j) - \alpha_{\text{TTD},N} \sum_{j=0}^{N_p-1} L_N \lambda_N f_N(k+j). \end{aligned} \quad (13)$$

The reasons for choosing this objective function in (12) are as follows: in practice, TTS is related to vehicle-hour-traveled (VHT), and TTD is related to vehicle-miles-traveled (VMT). Both VHT and VMT are available in the PeMS archive, and, therefore, it is convenient for any freeway user to evaluate the ramp metering control performance by accessing this open data base. In addition, minimizing TTS may discourage vehicles from entering the freeway so that the mainline can have better flow when the mainline density is higher. Minimizing negative TTD is equivalent to maximizing (positive) TTD, which encourages vehicles get to enter the freeway. Therefore, to minimize the difference between TTS and TTD is to formulate the problem as a non-zero sum game. The overall effect of minimizing the objective function J is to minimize VHT and maximize VMT. In addition, since freeway efficiency (average speed) is defined as $Q = \text{VMT}/\text{VHT}$, minimizing the cost function J also lead to improved freeway efficiency Q .

Model Predictive Control schemes

Taking together the freeway model, constraints, and the cost function, the CRM controller can be formulated according to the general formulation of an MPC controller (receding horizon predictive control) [11]. At each time step k , the CRM strategy is obtained by solving the following optimization problem

$$\text{minimize}_{\rho, w, r} \quad J = \text{TTS} - \text{TTD}_\alpha$$

$$\begin{aligned} \text{subject to} \quad & \rho_i(k+j+1) = \rho_i(k+j) + \frac{T}{\lambda_i L_i} (\lambda_{i-1} \rho_{i-1}(k+j) u_{i-1}(k+j) + r_i(k+j) - \lambda_i \rho_i(k+j) u_i(k+j) - s_i(k+j)), \\ & w_i(k+j+1) = w_i(k+j) + T(d_i(k+j) - r_i(k+j)), \\ & 0 \leq \rho_i(k+j) \leq \min\{\rho_i^J, \phi(u_i(k+j))\}, \\ & 0 \leq w_i(k+j) \leq L_i^o w_i^J, \\ & r_{\min} \leq r_i(k+j) \leq \min\{d_i(k+j), r_i^o, \lambda_i(F_i - \bar{f}_{i-1}(k+j)), \lambda_i u_i(k+j)(\rho_i^J - \bar{\rho}_i(k+j))\}, \\ & \text{for } i = 1, \dots, N, j = 0, \dots, N_p - 1. \end{aligned}$$

Since this problem is a linear programming problem, it can be efficiently solved in real-time by the Simplex method [12].

FIELD IMPLEMENTATION

Concept of Operations

Figure 3 shows the overall system structure of the CRM system and signal flow of the system. The red arrow starting from the loop detector on the freeway to the PATH computer in the figure is the measurement of all available field data (flow, speed, occupancy). The blue arrow starting from the PATH computer to all cabinets (URMS controller in the field) in the figure is the calculated optimal ramp metering rate by the proposed algorithm. The yellow arrow in the figure starting from each cabinet (URMS) to its corresponding ramp metering traffic light is the on-ramp metering light control signal. The PATH CRM computer is installed in the Caltrans District 3 TMC and directly links with its intranet for data acquisition, processing, traffic state parameter estimation, calculating the optimal ramp metering rate, and sending it to the corresponding on-ramp for activation. The PATH CRM computer collects traffic data and aggregates it every 30 seconds. The benefits of using this system structure are the following. The intranet connection with 2070 controllers in the field used fixed IP addresses. Such an implementation scheme is advantageous. First, it is simple and direct. Second, there is no middle system between the PATH CRM computer and the 2070 controllers in the field; therefore, third party support is not necessary. Thirdly, the PATH computer can access all the raw field data unchanged by any middle system; therefore, the data are trustworthy. Fourth, such a direct link practically avoids any delays and data passing errors caused by middle systems.

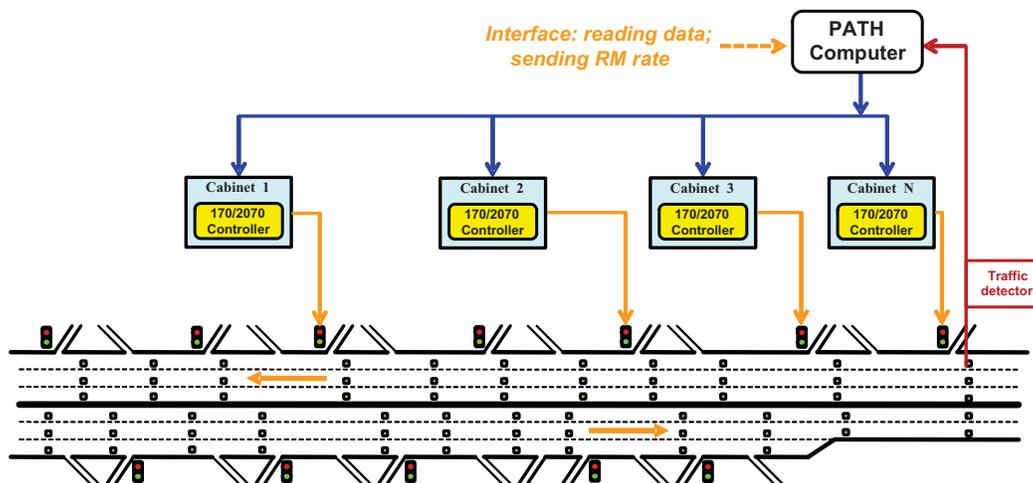


FIGURE 3 Direct interface between TMC ramp metering computer and CRM controllers; PATH computer is for data processing and calculation of CRM rate.

Progressive Implementation

All of the ramp metering in the test field use local responsive ramp metering (LRRM) originally. The LRRM uses on-ramp flow (demand) and its immediately upstream occupancy to determine the ramp metering rate. Before changing the original LRRM strategy into the proposed CRM algorithm, the implemented system runs in a dry-run mode. In this mode, the computer sends feedback

signals (from sensor measurements) from the system to the controller such that the controller generates a control signal but without implementing the control signal to the system. By investigating these control signals, one can check the correctness of control signals, and the parameters in the system can be fine-tuned. The dry-run phase of this project occurred in the week of September 19-25, 2016. During the dry-run, calculated CRM rates were saved to files instead of being sent to 2070 controllers for activation. Those saved files were carefully checked to make sure every part of the system worked correctly and robustly in the sense that, even if there was some fault in the loop detector data, historical data from the same time of a day would be used as a backup, and, therefore, sensor faults would not significantly affect the CRM calculation. In case there was a problem in the PATH computer, the 2070 controller in the field would automatically activate the default LRRM, deactivating CRM. On the day when the CRM was switched on, the project team monitored the CRM system, adjusted the parameters in the algorithm, and observed the traffic through D3 freeway traffic video systems and a Google traffic map. The comparison of CRM rates with default LRRM rates were studied.

The formal tests began on September 26, 2016, although some minor adjustments were still made in the second week. Then, the algorithm was finalized and extensive data collection began. The project team keep recording and monitoring traffic data in the field, included comparison of ramp metering rates of CRM and original local responsive ramp metering for both AM and PM peak hours, as well as some other freeway traffic parameters.

Monitoring of CRM Rate

To make sure the CRM algorithms were executed correctly, the project team monitored all traffic data obtained from 2070 controllers during the field test. Information that can be obtained from the 2070 controller include: onramp name, machine time, field RM ID, control scheme currently activated (i.e., LRRM or CRM), and cycle count. This information can be used to tell if the CRM algorithm is activated and identify the problem if is not activated. Additionally, LRRM and CRM rates were compared for everyday during the tests. Since the project team only deployed the proposed CRM algorithm in the 11 downstream on-ramps (the first 5 on-ramps used the original LRRM strategy), it was sufficient to monitor the downstream 11 on-ramps. Figure 4 presents an example comparison of ramp metering rates in morning peak traffic, and the names of those 11 downstream on-ramps are listed in Table 1. The ramp metering rates for LRRM (red lines) and CRM (blue lines) control strategies are quite different for AM peak hours. The results indicates that the proposed CRM can respond to traffic demand (green lines), since the CRM changes with time and demand differences, whereas most of the LRRMs give constant metering rates almost all the time. The LRRM metering gives a high ramp metering value in ramps 14 and 15 from 6:00 AM to 6:30 AM, since the demand is low during that time.

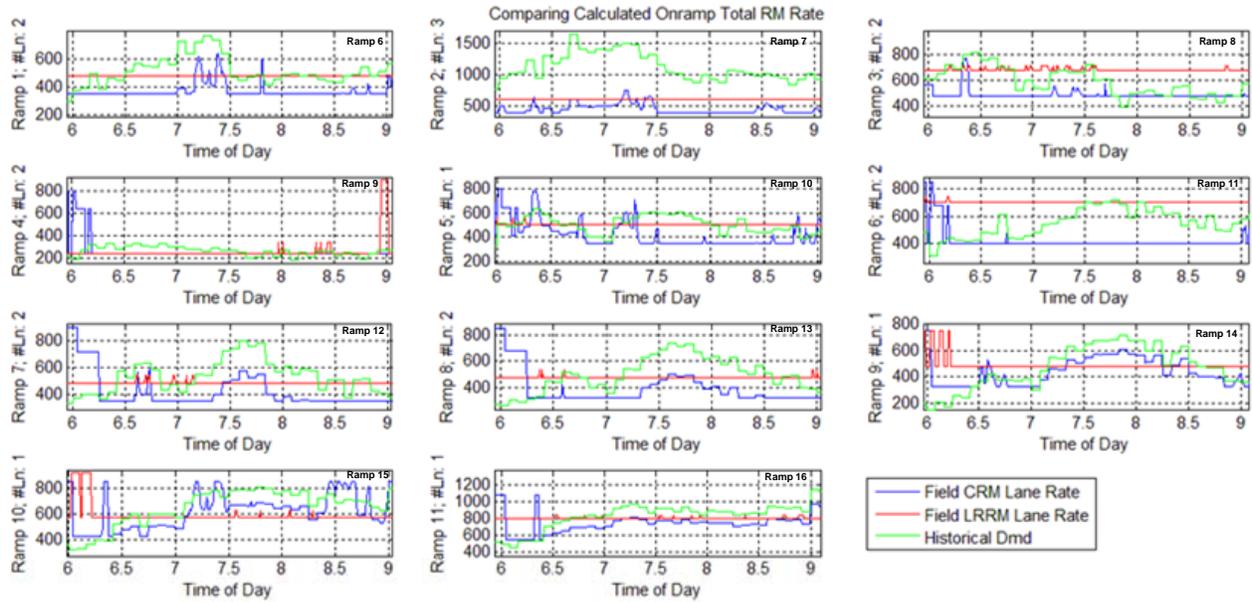


FIGURE 4 Comparison of LRRM and CRM rates for AM peak hours on Wednesday, 12 October, 2016.

TABLE 1 List of On-ramp Names

Index	Name	Control strategy	Number of lanes	Number of HOV lanes
OR 1	Elk Grove Blvd	LRRM	3	1
OR 2	EB Laguna Blvd	LRRM	1	0
OR 3	WB Laguna Blvd	LRRM	1	0
OR 4	EB Sheldon Rd	LRRM	2	1
OR 5	WB Sheldon Rd	LRRM	3	1
OR 6	EB Calvine Rd	CRM	2	1
OR 7	WB Calvine Rd	CRM	3	1
OR 8	EB Mack Rd	CRM	2	1
OR 9	WB Mack Rd	CRM	2	1
OR 10	EB Florin Rd	CRM	1	0
OR 11	WB Florin Rd	CRM	2	1
OR 12	EB 47th Ave	CRM	2	1
OR 13	WB 47th Ave	CRM	2	1
OR 14	EB Fruitridge Rd	CRM	1	0
OR 15	WB Fruitridge Rd	CRM	1	0
OR 16	12th Ave	CRM	1	0

RESULTS AND DISCUSSION

The data for performance evaluation field tests were obtained from PeMS (<http://pems.dot.ca.gov>). The data for the stretch of test site SR-99N from postmile 280 to postmile 300 are used. The sampling time of performance indexes VMT, VHT, and Q is the minimal sampling time provided

by PeMS in hours. Data from before the field test are taken from weekdays from the first week in October through the first week in November, 2015. Field test data are taken from weekdays from the first week in October to the first week in November, 2016. The AM ramp metering activation time is from 6:00 AM to 9:00 AM. The PM ramp metering activation time is from 3:00 PM to 6:00 PM. Note that the field test started from Wednesday, September 19, 2016. The traffic data from September 19, 2016, to September 30, 2016, are omitted, since the project team was adjusting system parameters during the beginning of the field test. After the duration of system tuning, the traffic characteristics become more representative, making those data meaningful for analysis. The performance indexes are compared for the same day of the week for the weeks investigated; for example, Tuesdays in 2015 are compared with Tuesdays in 2016. This is a reasonable comparison because commuter traffic patterns are similar for the same weekdays.

Freeway System Performance Indexes

Coordinated ramp metering has been introduced mainly for reducing congestion by regulating the number of vehicles entering the freeway mainline from the on-ramp. There are several congestion related indicators: freeway efficiency (average speed) [13], average travel time, duration of congestion, fuel consumption and emissions index [14]. Since the goal of this project is to evaluate the influence of ramp metering control on a freeway system, we only consider TTD, TTT (or TTS), and mean speed (MS). These traffic indices are equivalent to VMT, VHT and Q, respectively, in the PeMS archive. The calculation of these performance indices in PeMS are as follows.

VMT is the sum of distance (in miles) traveled by each vehicle on the given section of freeway over a given time period. VMT is equivalent to TTD. Consider a freeway is partitioned into N segments with length L_i for the i -th segment where each segment contains at least one loop detector. VMT is computed by

$$\text{VMT} = \sum_{i=1}^N \text{VMT}_i, \quad (14)$$

where $\text{VMT}_i(k) = \bar{f}_i(k)L_i$ and $\bar{f}_i(k)$ is flow measurement at segment i .

VHT is the sum of all trip times (in hours) spent by each vehicle on the given section of freeway over a given time period. VHT is equivalent to TTT. VHT is computed by

$$\text{VHT} = \sum_{i=1}^N \text{VHT}_i, \quad (15)$$

where $\text{VHT}_i(k) = \text{VMT}_i(k)/v_i(k)$ and $v_i(k)$ is the speed at the i -th segment.

Freeway efficiency (mean speed) is expressed in miles per hour (MPH) and is defined as

$$Q = \frac{\text{VMT}}{\text{VHT}}. \quad (16)$$

From the definition of Q in (16), VMT is in the numerator of the Q value and VHT is in the denominator, so increasing VMT or decreasing VHT can make Q increase, which is consistent with the control objective: maximize TTD or minimize TTS. Therefore, higher Q values not only indicate better control performance, but also better freeway efficiency.

There is another way to interpret the freeway efficiency Q . Since the unit of Q is the same as flow over vehicle density (f/ρ), freeway efficiency can also be interpreted as the mean speed

of all trips of the freeway during a period of time. Higher Q values indicate that the drivers on the freeway gain higher speed on average. Therefore, high Q values indicate high freeway efficiency. In addition, from a traffic engineering perspective, higher VMT values indicate that the freeway can be used by more drivers. Lower VHT values indicate the driver can spend less time travelling on the freeway. Increasing VMT or decreasing VHT can increase Q, which is equivalent to increasing freeway usage or to reducing travel time. Therefore, Q is an index of freeway efficiency for both traffic engineers and drivers.

Field Test Results

By comparing the traffic performance indexes before and after the field test, the improvement resulting from the proposed CRM strategy can be observed. The improvement of an index x is computed by

$$\Delta x = \frac{x_{\text{after test}} - x_{\text{before test}}}{x_{\text{before test}}} \quad (17)$$

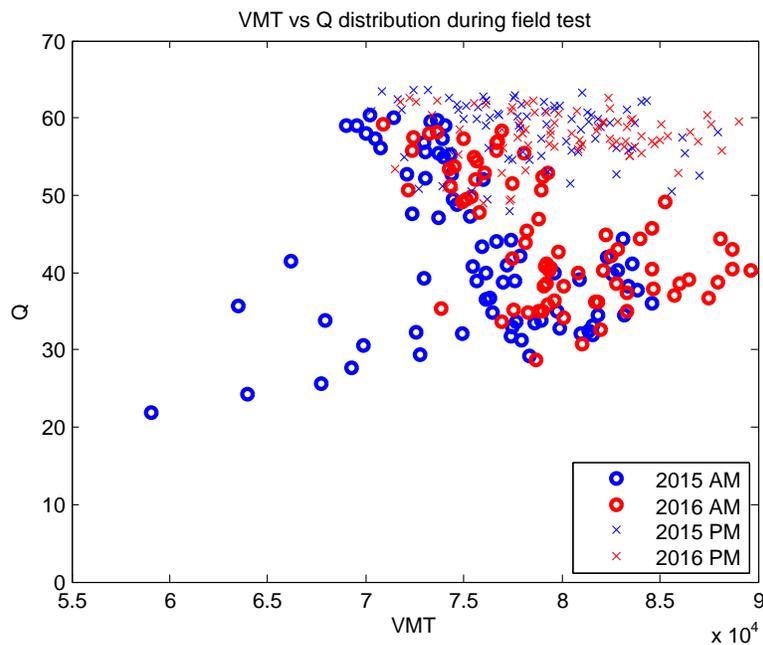


FIGURE 5 VMT versus Q distribution: Blue and red circles are AM traffic data in 2015 and 2016, respectively. Blue and red crosses are PM traffic data in 2015 and 2016, respectively.

Figure 5 shows the VMT versus Q distribution, where circles represent the data from morning traffic and crosses represent data from evening traffic. The figure shows that the circles are more scattered than the crosses, indicating that the VMT values have larger variation during the morning traffic than during the evening traffic. Red circles represent 2016 field test, while blue circles represent 2015 pretest field data. Compared with the blue circle data cluster, the red circle cluster lies on the right of the VMT axis and above the Q axis. This comparison indicates the improvement of

freeway efficiency indexes Q and VMT, since more red circles move toward positive Q and positive VMT directions, and it means the field test increased the freeway efficiency (average speed) Q by increasing VMT (usage of freeway or increasing demand). Conversely, the scatter of crosses in the figure is more concentrated than that of circles, which means the evening traffic did not change much after the CRM control. Therefore, the CRM control increased both the freeway efficiency and usage during morning traffic more significantly than it did during evening traffic.

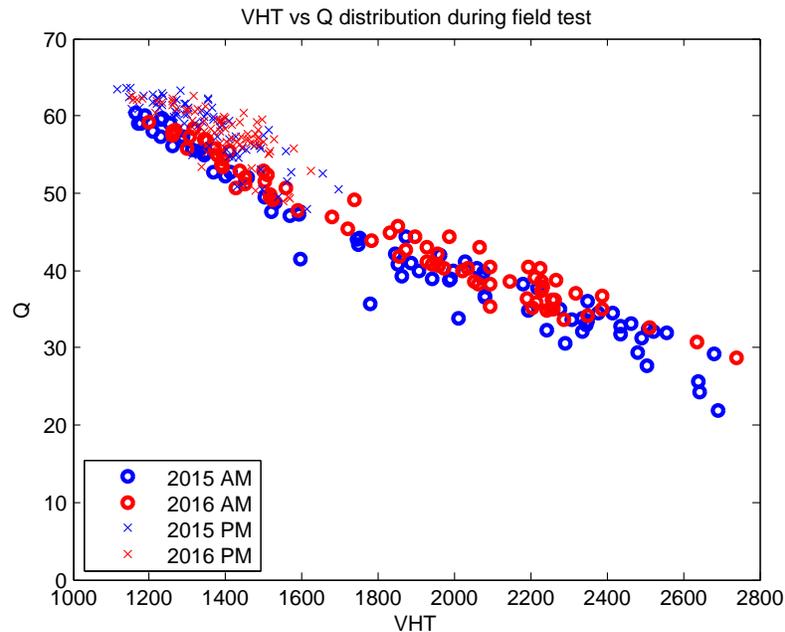


FIGURE 6 VHT versus Q distribution: Blue and red circles are AM traffic data in 2015 and 2016, respectively. Blue and red crosses are PM traffic data in 2015 and 2016, respectively.

The VHT improvement can also be observed by plotting VHT versus Q for both before and after the field test, as shown in Figure 6. In this figure, circles represent the data from morning traffic, and crosses represent data from evening traffic. The circles are more scattered than the crosses, indicating that the VHT values have larger variation during the morning traffic than during the evening traffic (the variation of travel time in AM is larger than in PM). Again, compared with the blue circle data cluster, the red circle cluster slightly moves to the left of the VHT axis and above the Q axis. This confirms the finding that the CRM control resulted in greater improvement in the morning than in the evening.

TABLE 2 Summary of both AM and PM hourly performance comparison

	6-7 AM	7-8 AM	8-9 AM	3-4 PM	4-5 PM	5-6 PM
2015 VMT	80118.58	74488.19	71804.62	78513.72	75687.66	69856.27
2016 VMT	83900.23	79286.52	75408.84	80324.92	76949.2	72439.83
2015 VHT	2324.12	2020.70	1366.42	1331.05	1305.34	1180.34
2016 VHT	2210.69	1973.29	1398.04	1410.57	1317.57	1206.86
2015 Q	34.47	36.86	52.54945	58.99	57.98	59.18
2016 Q	37.95	40.18	53.93897	56.95	58.40	60.02
Δ VMT	4.72 %	6.442 %	5.019 %	2.307 %	1.667 %	3.698 %
Δ VHT	<i>-4.881 %</i>	<i>-2.346 %</i>	<i>2.314 %</i>	<i>5.974 %</i>	<i>0.937 %</i>	<i>2.247 %</i>
Δ Q	10.093 %	8.999 %	2.644 %	<i>-3.460 %</i>	0.723 %	1.420 %

A summary of the PeMS data comparing average VMT, VHT, and Q before and after the field test is contained in Table 2, where **bold text** indicates improvement of the networks performance and *italic text* means deterioration of performance. Morning ramp metering performance is summarized as follows:

- VMT increased by 5.39% on average.
- VHT decreased by 1.64% on average.
- Q increased by 7.25% on average.

Since VMT and Q increased, we conclude that CRM improved the traffic during morning peak hours.

Evening ramp metering performance is summarized as follows:

- VMT increased by 2.56% on average.
- VHT increased by 3.04% on average.
- Q decreased by 0.44% on average.

Since the change in both VMT and Q was marginal, we conclude that CRM did not improve traffic during the evening peak hours.

CONCLUSIONS

In this article, we presented the results of a field test of CRM based on MPC. The stretch of SR-99N between Elk Grove Street and the interchange with SR-50 was used as the test site. Previously, LRRM was used for the operation along that corridor in peak hours, and LRRM was still used for the first five upstream on-ramps in this project. The proposed CRM was implemented for the 11 downstream ramp meters. CRM is essentially different from LRRM in the sense that LRRM determines on-ramp metering rates based only on local mainline occupancy/flow data from its immediate upstream detector, whereas CRM determines ramp metering rates by using mainline occupancy/flow/speed data of the whole freeway and the demands of all on-ramps. Mathematically, centralized optimization is implemented for this small freeway using an efficient linear programming solver. Physically, the implemented algorithm controls the SR-99N corridor as a long discharging section in the sense that the most downstream is close to its capacity flow, and any section is not more congested than its upstream section. We believe that this is the best strategy to alleviate traffic congestion on freeway.

After the control system was implemented, a progressive test procedure was conducted for the field tests. First, a dry-run was conducted for the first 2-3 weeks to verify that the overall system was running well. Then, after 5 weeks of tests and data collection, PeMS hourly VHT and VMT data were used for performance evaluation. It is noted that PeMS data are completely independent from the data in PATH computer obtained directly from the 2070 controllers in the field. By using PeMS data, the project team intended to obtain objective performance results to the extent possible. To address demand fluctuation, freeway efficiency (VMT to VHT ratio) was used as the performance parameter, which could be understood as the average speed. We believed that this ratio could reasonably accommodate traffic demand fluctuation. The aggregated data over five weeks for VMT/VHT increased by 7.25% for morning peak hours, indicating improvement in congested traffic. For evening peak hours, the CRM algorithm did not improve traffic, since the traffic is not heavily congested at that time. This suggests that the algorithm is effective for congested traffic caused by high demand.

Future research includes combined implementation of variable speed advisory (VSA) [15] and CRM [5]. VSA is another strategy for reducing traffic congestion by directly regulating freeway mainline flow, which can be seen as a mainline version of ramp metering control. Similar to the coordination structure of CRM, VSA signs can be installed along the freeway from upstream to downstream, such that speed harmonization can be achieved by coordinating all VSA signs on a freeway. By adding VSA devices into a freeway system with an existing RM system, a coordination control strategy combining VSA and CRM could improve freeway efficiency and safety.

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