Title

Evaluation of Coordinated Ramp Metering (CRM) Systems in California

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Publication Date
2021-03-30

CALIFORNIA PATH PROGRAM
INSTITUTE OF TRANSPORTATION STUDIES
UNIVERSITY OF CALIFORNIA, BERKELEY

Evaluation of Coordinated Ramp Metering (CRM) Systems in California

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California PATH Final Report
UCB-ITS-RR-2020-02

This work was performed as part of the California PATH program of the University of California, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation, and the United States Department of Transportation, Federal Highway Administration.

Final Report for Agreement 65A0693

March 30, 2021

CALIFORNIA PARTNERS FOR ADVANCED TRANSORTATION TECHNOLOGY

ABSTRACT

Freeway on-ramp metering has been extensively used as a traffic control strategy to regulate the entry of the on-ramp vehicles to prevent congestion at the freeway merging areas and preserve the freeway capacity. The report presents the research performed and findings on the evaluation of coordinated ramp metering (CRM) systems recently implemented on I-80 Smart Corridor in Caltrans District 4 and SR-99 in Caltrans District 3. The evaluation of CRM on the selected corridors based on "before" and "after" field data during the peak periods showed a 3-9% delay reduction, and 18-28% travel time reliability improvement. Recommendations are provided for implementation of CRM systems.

ACKNOWLEDGEMENTS

This work is being performed by the California Partners for Advanced Transportation Technology (PATH) Program at the University of California at Berkeley, in cooperation with the State of California Business, Transportation and Housing Agency, Department of Transportation (Caltrans), Division of Traffic Operations through the Interagency Agreement #65A0693. The contents of this report reflect the views of the author, who is responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the State of California.

The authors wish to thank the project monitor Mr. Jose Perez of Caltrans Division of Research & Innovation and Systems Information (DRISI) and the members of the technical advisory group (TAG) for their guidance and support during the project.

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EXECUTIVE SUMMARY

Objectives and Methodology

Freeway on-ramp metering (RM) has been extensively used as a traffic control strategy to regulate the entry of the on-ramp vehicles to prevent congestion at the freeway merging areas and preserve the freeway capacity. Benefits of RM include improved freeway travel times, improved travel time reliability, and accident reductions. Fixed-rate ramp metering strategies are based on historical data and implemented by time of day. Traffic responsive RM strategies are based on real time freeway traffic data provided by loop detectors at the vicinity of the on-ramp. Coordinated RM determine the metering rates at the ramps along a freeway corridor to minimize the delays or maximize the freeway throughput. The objective of this research was to evaluate the traffic performance of coordinated traffic responsive systems (CRM) currently implemented by Caltrans based on field data.

An empirical performance evaluation on two freeway corridors was performed comparing the freeway's performance "before" and "after" the CRM implementation. The selected corridors with operational CRM were the I-80 Smart Corridor, which extends from the Carquinez Bridge to the MacArthur Maze (I580/80/880 freeway interchange) in Caltrans District 4, and the SR-99 corridor, from the Grant Line Road interchange at absolute post-mile 284.62 to the US-50 freeway interchange at absolute post-mile 298.38 in Caltrans District 3. The CRM strategies implemented (along with the corridors "Before" conditions) were:

- SR-99: Local Adaptive Ramp Metering vs. CRM
- I-80: No Metering vs. CRM Fuzzy logic

A thorough review was performed of the implemented CRM strategies implemented along the two selected study corridors. The I-80 corridor's on-ramp metering system is a coordinated ramp metering algorithm based on fuzzy logic control and is active from 5:00 AM to 8:00 PM every day. The ramp metering algorithm also combines coordination with its nearby parallel arterial San Pablo Avenue to best optimize corridor level performance in the event of an incident. The SR-99 coordinated ramp metering algorithm uses a simulation model to determine the traffic speed and density on each freeway section at each time step. The simulation model is based on the cell transmission macroscopic model that estimates the number of vehicles in each cell (segment of freeway) using density in each time step.

The primary source of field data used in the analysis was Caltrans PeMS detector data and INRIX Analytics travel time /speed data to establish performance along the freeways mainline. An analysis methodology was also developed and implemented to quantify the changes in delay and reliability for similar levels of freeway utilization, measured using Vehicle Miles Travelled (VMT).

Findings and Recommendations

The evaluation of the implementation of CRM on the selected corridors was based on "before" and "after" days where the average VMT was balanced. The results showed a 3-4% reduction in AM and PM Peak Period Vehicle Hours of Travel (VHT) for Eastbound I-80, with a 2-9% reduction in Westbound VHT for the peak periods. Overall, the I-80 study corridor showed about a 4-5% reduction in VHT. In District 3, the Northbound SR-99 study corridor showed about an 8% decline in VHT during the AM peak period. The reductions in corridor travel time reliability were 18-28% for the Planning Time Index (PTI) and in the 2-15% range for the Travel Time Index (TTI).

Both CRM strategies improved the corridor traffic performance and can be implemented in the existing Caltrans traffic management centers. However, there is not sufficient evidence to determine which strategy performed best based on the selected performance measures because of the differences in operating characteristics and “before” conditions in each corridor. The I-80 corridor was operating with no metering in the “before” period and operating a CRM Fuzzy logic strategy during the “after” period. Furthermore, CRM implementation was a component of a larger I-80 ICM implantation, which included other strategies (changeable message signs and variable speed control). The SR-99 corridor was operating a local adaptive ramp metering in the “before” period and a CRM strategy developed by UC Berkeley PATH in the “after” period.

CRM implementations will deliver sufficient gains to warrant continued study and deployment by Caltrans. There is a need to develop statewide guidelines for selecting the most suitable CRM strategy for candidate freeway corridors and the associated CRM implementation plans and performance evaluation. Further, there is a need to be aware and monitor the advances in existing and emerging CRM technologies and their underlying algorithms given the continuous developments in data sources and software.

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Freeway on-ramp metering (RM) has been extensively used as a traffic control strategy to regulate the entry of the on-ramp vehicles in order to prevent congestion at the freeway merging areas, and preserve the freeway capacity (discharge flow rate) thus avoiding the "capacity drop". Benefits of RM include improved freeway travel times, improved travel time reliability, and accident reductions. The benefits of RM depend on the geometric and traffic characteristics of the freeway corridor. Queues on metered on-ramps that exceed the on-ramp storage and interfere with the operation of the adjacent surface street network reduce the effectiveness of the RM strategy. Availability of parallel arterial streets may improve the effectiveness of RM because they accommodate short trips and reduce the traffic demand on the adjacent freeway facility.

Several RM strategies have been developed and implemented over the years. They can be classified into fixed-rate or traffic responsive RM strategies. Fixed-rate strategies are based on historical data and implemented by time of day (typically the peak periods). Traffic responsive strategies are based on real time freeway traffic data (e.g., traffic volumes and detector occupancies) provided by loop detectors at the vicinity of the on-ramp. Fixed-rate RM are generally system-wide coordinated: typically, a traffic model is used to determine the metering rates at the ramps along the corridor to minimize the delays or maximize the freeway throughput subject to on-ramp queue length constraints. Most of the traffic responsive RM strategies are local; they determine the metering rates at each on-ramp based on occupancy data from adjacent loop detectors. Popular strategies include the demand-capacity control implemented by Caltrans that uses information from detectors located upstream of the merging area and the ALINEA strategy that uses data from detectors located downstream of the on-ramp's merging area.

A number of coordinated ramp metering (CRM) strategies have been developed [8]. Examples include the Bottleneck algorithm implemented in Minneapolis, Minnesota, the Fuzzy logic algorithm implemented in Seattle, Washington, the System Wide Adaptive Ramp Metering (SWARM) algorithm implemented in Southern California, the HEuristic Ramp metering Optimization (HERO) algorithm implemented in Melbourne Australia, and the CRM algorithm developed by California PATH.

CRM has potential to further improve the freeway performance compared to existing local ramp metering algorithms. CRM can be implemented in the Advanced Traffic management System (ATMS) of most Caltrans districts; CRM is currently operational on three corridors in three different Caltrans districts. Each of the implemented CRM systems has its own unique algorithm characteristics and implementation protocols. There is no current information based on field data on the performance of each system, and there is no guidance on which CRM should be recommended for implementation in other Caltrans districts.

There is a need to evaluate the different CRM systems to provide a better understanding for needed corridor/system wide improvements and strategies with the purpose of improving corridor safety, efficiency, and reliability.

The objective of this research was to conduct an evaluation of the performance of CRM systems currently implemented in these three Caltrans districts. Using field data "before" and "after" the CRM implementations, the study will determine which CRM system provides the best overall performance. The study's goal was to provide answers to the following: a) what are the advantages and disadvantages for each CRM system, b) which CRM system provides the best overall performance in terms of system throughput, corridor travel time, queue reduction and related measures, c) what are the commonalities and what are the unique features/elements for each CRM system, and d) which CRM is easiest to implement on a new freeway corridor. The proposed end products of this project were evaluation reports on algorithm performance for each Caltrans District, and recommendations for CRM implementations in Caltrans Districts.

1.2 Report Organization

This document is the final report for the study. It describes the worked performed, presents the study findings and provides recommendations for implementation of CRM systems. Chapter 2 describes the selected study corridors including their design and operational characteristics and the CRM algorithms implemented. Freeway performance measures are discussed in Chapter 3. The empirical RM evaluation plan and the associated results are presented in Chapter 4. Chapter 5 (the final chapter of this report) contains a summary of the findings, lessons learned and recommendations.

CHAPTER 2
SELECTED CRM SYTEMS

Recently, CRM systems have been implemented along specific freeway sections in three Caltrans districts, as outlined below:

- SR-99: Local Adaptive Ramp Metering vs. CRM
- I-80: No Metering vs. CRM Fuzzy logic
- I-110: Local Adaptive Ramp Metering/SWARM vs. DCRM

Following discussions with District 7, it was determined that the CRM version was not implemented along the I-110 corridor. A partial implementation of CRM occurred in 2017 followed by a field evaluation [19]. It is planned to implement CRM on the I-405 travel corridor at a later date. Therefore, the District 7 corridors are not included in these evaluations. Information on the District 7 corridors and features of the CRM collected through the literature [5] and discussions are included in Appendix C of this document.

2.1 State Route (SR) 99 Corridor – District 3

CRM in District 3 is being implemented on a section of SR-99, from the Grant Line Road interchange at absolute post-mile 284.62 to the US-50 freeway interchange at absolute post-mile 298.38, for a total length of 13.76 miles (see Figure 2.1). As indicated by the arrows in Figure 2.1, there are 13 interchanges with local arterial streets: 6 partial cloverleaf interchanges, 3 full cloverleaf interchanges, 3 diamond interchanges with the local arterials, and a four-level stacked interchange with the US-50 freeway.

Figure 2.2 shows the detailed freeway lane configurations. There are two general purpose lanes and one high Occupancy Vehicles lane (HOV) lane upstream of the Stockton Boulevard off-ramp. There are three general purpose lanes and one HOV lane downstream of the Stockton Boulevard off-ramp.

The freeway corridor is equipped with loop detectors are connected to 2070 controllers under the universal ramp metering system (URMS) framework in the District 3 Traffic Management Center (TMC). There are dual loop detectors on the freeway mainline that directly measure vehicle speeds and single loop detectors on the ramps. There are 32 mainline detectors and 29 HOV lane detectors, as indicated by the blue numerical labels (Figure 2.2). There are also detectors placed at the on-ramps and off-ramps, as indicated by the green numerical labels and red numerical labels for on-ramps and off-ramps, respectively. The off-ramps to Westbound Florin Road, Eastbound 47th Avenue, Westbound 47th Avenue, and 12th Avenue do not have detectors. Also, detectors with numerical labels circled in red are currently non-operational and cannot provide any data. Table B.1 in Appendix B shows a list of the on-ramp and off-ramp detectors and their status.

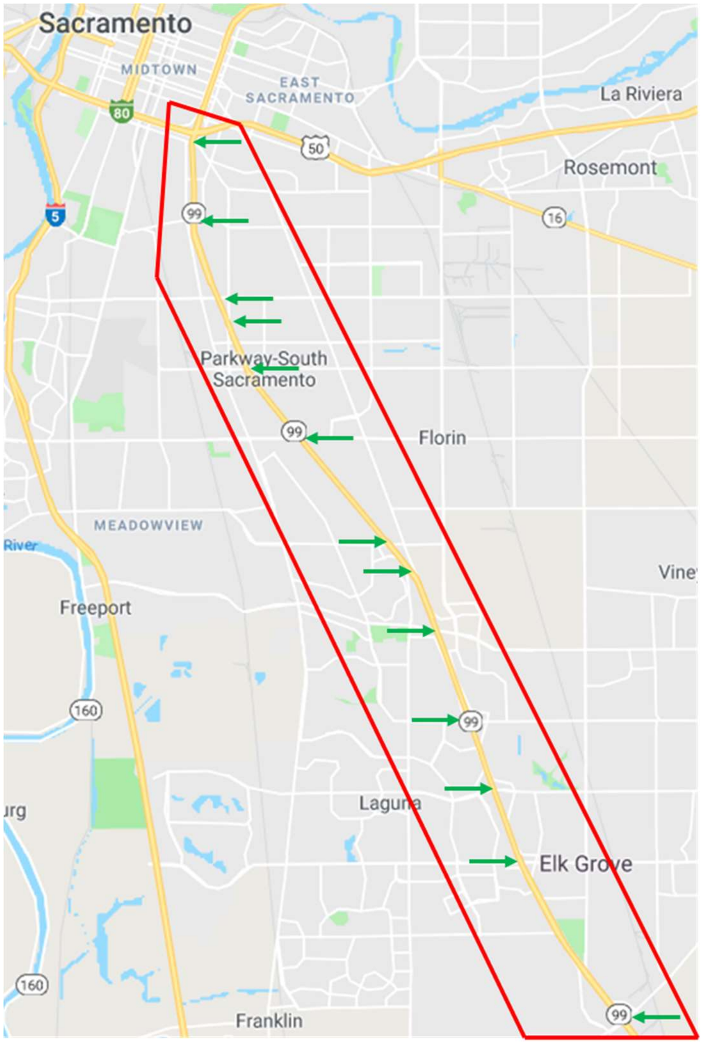


Figure 2.1 SR-99 Study Corridor

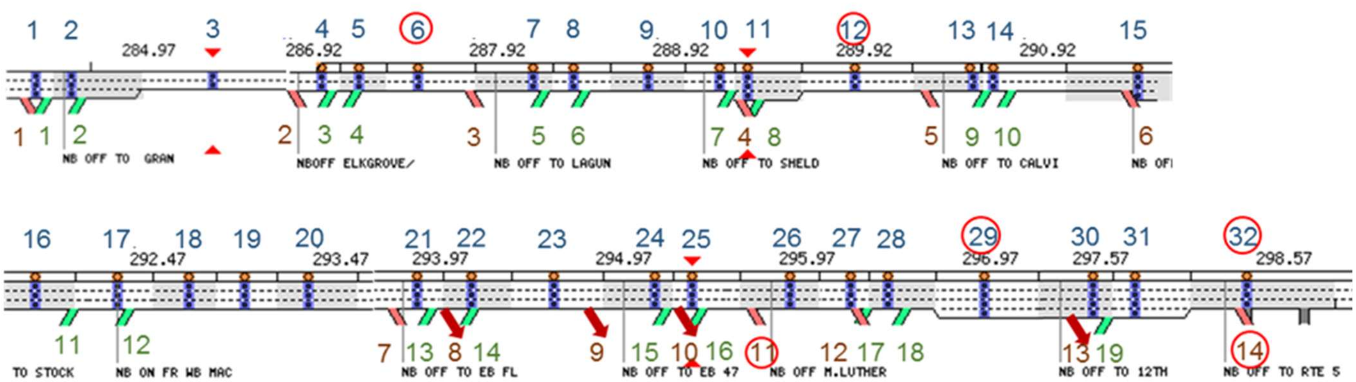


Figure 2.2 Northbound SR-99 Lane Configurations and Detector Locations

2.1. 1 Ramp Metering Algorithm

The coordinated ramp metering algorithm uses a simulation model to determine the traffic speed and density on each freeway section at each time step. The simulation model is based on the cell transmission macroscopic model that estimates the number of vehicles in each cell (segment of freeway (cell) using density in each time step [15]. Appendix A.1 provides additional details on the cell transmission model.

The algorithm determines the ramp metering rates to minimize the total travel time spent (TTS) and maximizes the total distance travelled (TTD) subject to appropriate constraints. These measures are directly related to vehicle hours travelled (VHT), and TTD is related to vehicle miles traveled (VMT). Also, the freeway average speed is defined as VMT/VHT, so the selected objectives lead to higher freeway speeds.

The TTS is the total travel time on the freeway plus and the delay on the on-ramp, where α_w is the on-ramp weighting parameter:

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

The total distance travelled (TTD) is defined as

$$TTD(k) = T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N} L_i \lambda_i f_i(k+j) + T \sum_{j=0}^{N_p-1} L_N \lambda_N f_N(k+j) \tag{2}$$

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

$$J = TTS - TTD_\alpha \tag{3}$$

where the subscript α represents positive weighting parameters for each segment. Choosing the weighting parameters $\alpha_{TTD,N} \gg \alpha_{TTD,0} > 0$ emphasizes maximizing the flow on the most downstream segment N and equation (3) can be written as

$$\begin{aligned} J = T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N} L_i \lambda_i \rho_i(k+j) + \alpha_w T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N} w_i(k+j) \\ - \alpha_{TTD,0} T \sum_{j=0}^{N_p-1} \sum_{i=1}^{N} L_i \lambda_i f_i(k+j) - \alpha_{TTD,N} T \sum_{j=0}^{N_p-1} L_N \lambda_N f_N(k+j) \end{aligned} \tag{4}$$

The ramp metering rates obtained from the algorithm are subject to constraints on maximum and minimum mainline density, on-ramp storage, and ramp metering rate. These constraints are formulated as the following inequalities:

$$0 \le w_i(k) \le L_i^O w_i^J \tag{5}$$

$$r_i^m \leq r_i(k) \leq min\left\{d_i(k), r_i^O, \lambda_i\left(F_i - \bar{f}_{i-1}(k)\right), \lambda_i u_i(k)\left(\rho_i^J - \bar{\rho}_i(k)\right)\right\} \quad (6)$$

$$0 \leq \rho_i(k) \leq min\{\rho_i^J, \phi(u_i(k))\} \quad (7)$$

Equation 5 relates to the on-ramp queue storage capacity. Equation 6 ensures the minimum and maximum allowable ramp metering rates are satisfied; the lower bound of on-ramp metering rate r_i^m is maintained at 240 veh/hr to prevent oversaturation. The upper bound of on-ramp metering rate is the minimum of the a) the on-ramp demand, b) the maximum allowable metering rate, c) spare capacity on the mainline under free-flow conditions:$\lambda_i\left(F_i - \bar{f}_{i-1}(k)\right)$, and d) space capacity on the mainline under congested conditions: $\lambda_i u_i(k)\left(\rho_i^J - \bar{\rho}_i(k)\right)$. Equation 7 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.

2.1. 2 Implementation

Figure 2.3 shows the structure of the CRM system (*1, 2*). The CRM algorithm software resides on a dedicated computer (PATH computer) in Caltrans District 3 TMC. The PATH computer receives loop detector data (flow, speed, occupancy) every 30-seconds. The software performs data processing, traffic state estimation, and calculation of the optimal metering rate. The metering rates are sent to the corresponding on-ramp 2070 controllers for implementation using field used fixed IP addresses.

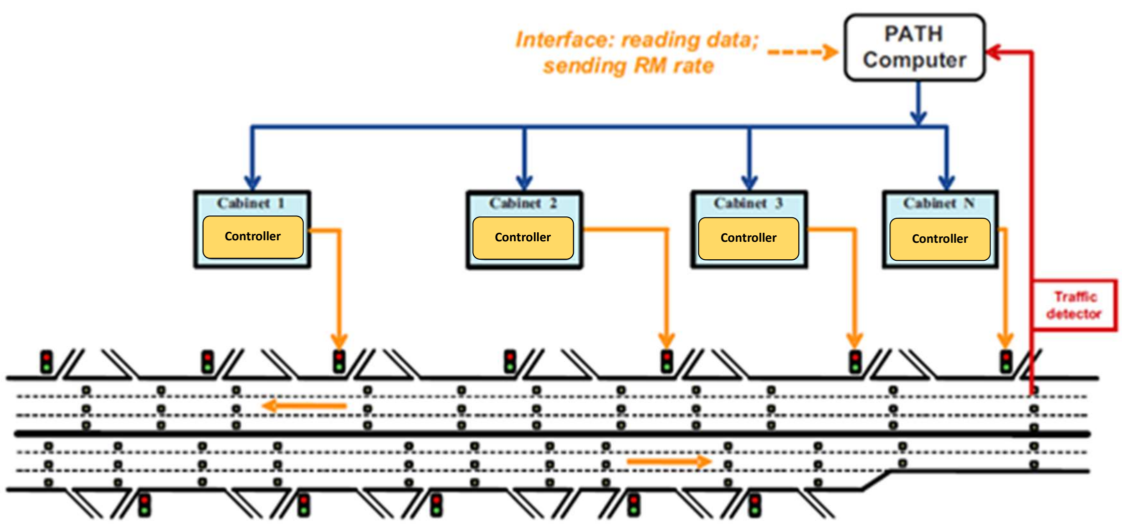


Figure 2.3 Interface between ramp metering computer and controllers (*1*)

This coordinated ramp metering algorithm is currently not implemented on all the freeway on-ramps on the SR-99 study corridor. Five of the on-ramps (Elk Grove Boulevard, Eastbound Laguna Boulevard, Westbound Laguna Boulevard, Eastbound Sheldon Road, and Westbound Sheldon Road) currently operate under the local responsive ramp metering strategy (*1*). The on-ramp demand at these upstream on-ramps are relatively low (less than 500 veh/hr). PATH has found that the coordinated ramp metering algorithm does not generate different ramp metering rates at these five on-ramps, as compared to those generated by local responsive ramp metering [15].

Lastly, the analysis should take into account the downstream freeway-to-freeway interchange at US-50, which could cause queue spillback on SR-99 when US-50 (which does not employ coordinated ramp metering) becomes overly congested.

The CRM hours of operation are from 6:00 to 9:00 AM and from 3:00 to 6:00 PM. The CRM algorithm is centralized and running in the Caltrans Traffic Management Center (TMC). Detector data is collected (every 30 seconds) from the mainline loops and all 11 on-ramps and communicated back to the TMC. The algorithm processes the data to determine state of the entire corridor and calculates an optimal metering rate for each on-ramp. Updates are based on the on-ramp demand essentially checking for any spill over. The metering rates are sent to the field for execution.

The corridor is congested during the morning peak period. This morning peak period typically begins around 6:30 AM and ends around 10:00 AM. The morning congestion pattern exhibits the typical peak period when there is high demand for suburb to downtown trips during the morning hours. The main bottlenecks are the on-ramp merging and weaving sections located near the Calvine Road interchange, the Florin Road interchange, as well as the off-ramp at the US-50 freeway interchange. Figure 2.4(a) shows the speed contour plot of a representative weekday prior to the implementation of CRM.

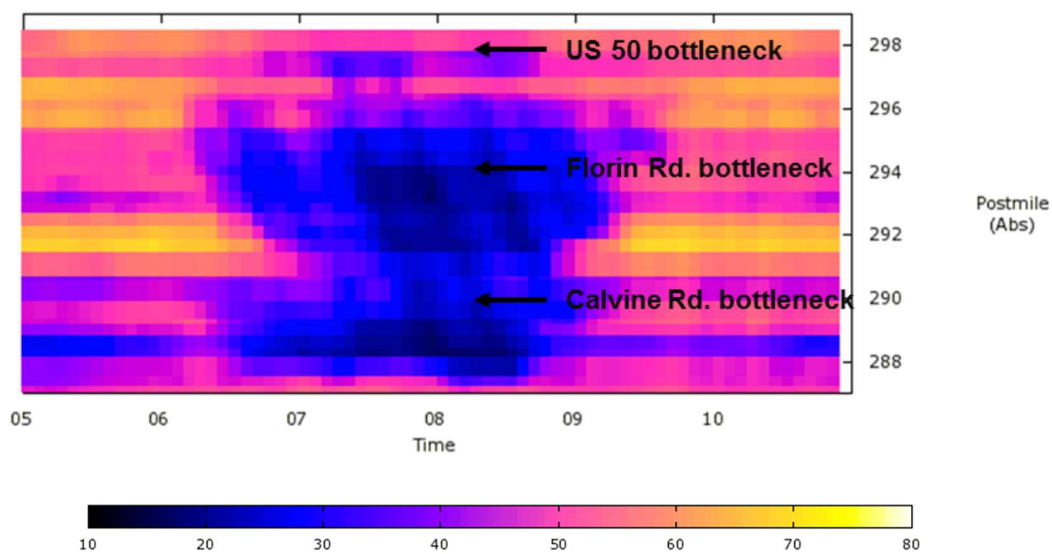


Figure 2.4 SR-99 Weekday Speed Contour Prior to Coordinated Ramp Metering – 10/6/2016

2.2 I-80 Corridor – District 4

The selected CRM site in District 4 is a section of the I-80 Smart Corridor, which extends from the Carquinez Bridge to the MacArthur Maze (I580/80/880 freeway interchange) just before to San Francisco-Oakland Bay Bridge (SFOBB), for a total length of 28 miles with 44 ramp meters (see Figure 2.5). The arterial interchanges consist of mainly diamond interchanges and partial cloverleaf interchanges while the freeway-to-freeway interchanges consist of stacked interchanges.

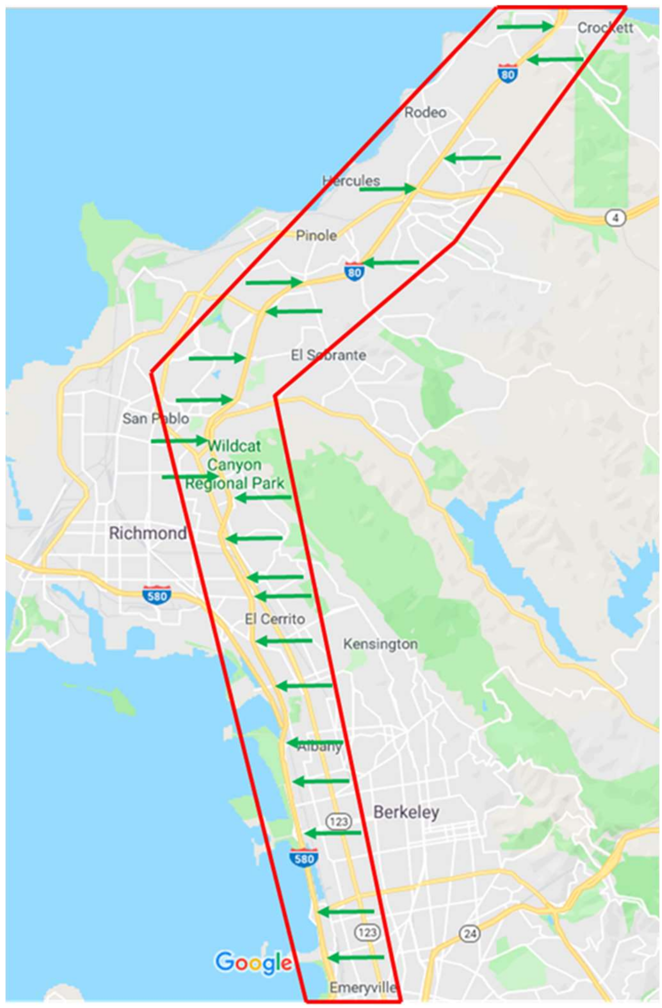


Figure 2.5 I-80 Study Corridor

Detailed lane configurations for both travel directions of the corridor are shown in Figure 2.6. In the eastbound direction, there are four general purpose lanes and one high occupancy vehicle (HOV) lane upstream of the I-580/Buchanan Street interchange, followed by three general purpose lanes and one HOV lane downstream of the I-580/Buchanan Street interchange. In the westbound direction, there are three general purpose lanes and one high occupancy vehicle (HOV) lane upstream of the I-580/Buchanan Street interchange, followed by four general purpose lanes and one high occupancy vehicle (HOV) lane downstream of the I-580/Buchanan Street interchange.

The I-80 freeway study corridor is equipped with dual loop detectors on the freeway's mainline that can accurately measure vehicle speed and single loop detectors on the ramps. The loop detectors are connected to 2070 controllers under the universal ramp metering system (URMS) framework in the District 4 Traffic Management Center (TMC). In the eastbound direction, there are 60 mainline and HOV lane detectors, as indicated by the blue numerical labels (Figure 2.6). There are also detectors placed at the on-ramps and off-ramps, as indicated by the green numerical labels and red numerical labels for on-ramps and off-ramps, respectively. In the westbound direction, there are 59 mainline and HOV lane detectors, as indicated by the blue numerical labels. There are also detectors placed at the on-ramps and off-ramps, as indicated by the green numerical labels and red numerical labels for on-ramps and off-ramps, respectively. Detectors with numerical labels circled in red are currently non-functional, and cannot generate any data. Tables B.2 and B.3 in Appendix B show a list of the on-ramp and off-ramp detectors and their status.

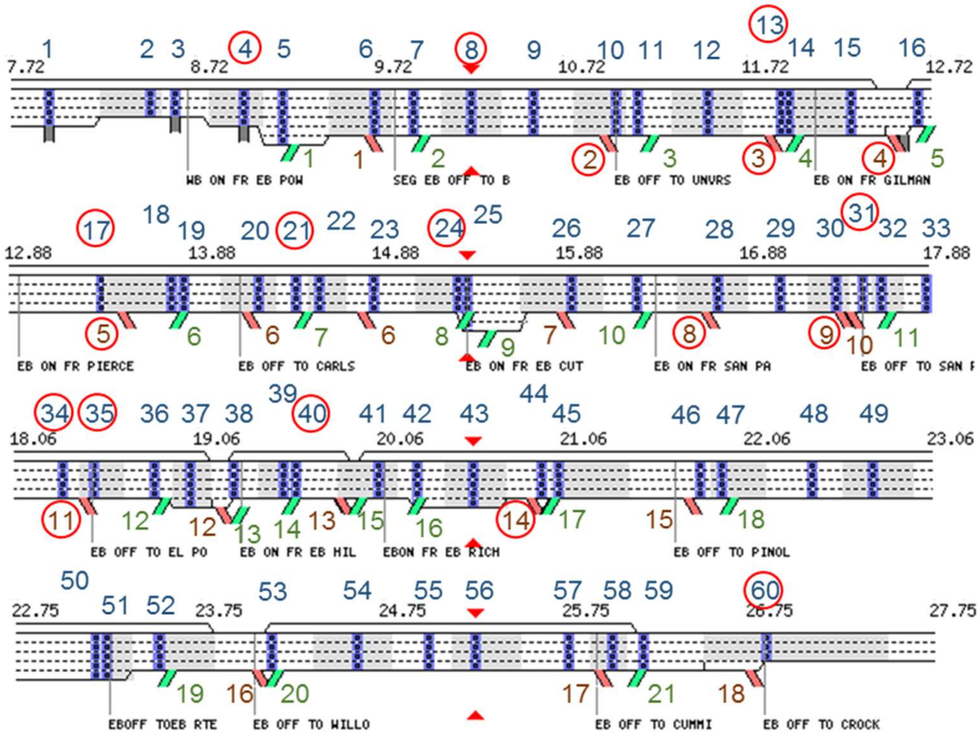


Figure 2.6 (a) Eastbound I-80 Lane Configurations and Detector Locations

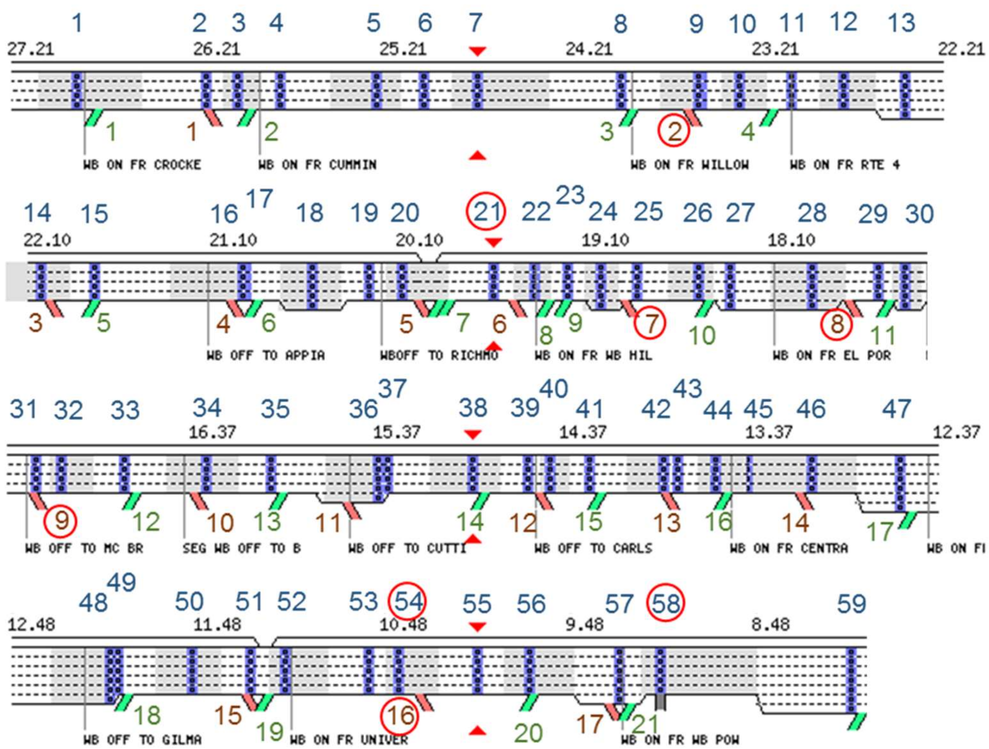


Figure 2.6 (b) Westbound I-80 Lane Configurations and Detector Locations

2.2.1 Ramp Metering Algorithm

The on-ramp metering system is a coordinated ramp metering algorithm based on fuzzy logic control (FLC) [22] and is active from 5:00 AM to 8:00 PM every day. The ramp metering algorithm also combines coordination with its nearby parallel arterial San Pablo Avenue to best optimize corridor level performance in the event of an incident. The algorithm requires minimal data inputs; occupancies obtained from the freeway mainline and on-ramp loop detectors and the arterial loop detectors will be used. In addition, speed data collected from the dual loop freeway mainline detectors are used in the FLC. Lastly, video surveillance of incidents is required for non-recurrent congestion where freeway/arterial diversion is required.

The Fuzzy logic engine uses several variables and weights to the input detector volume and occupancy data which determined the ramp metering rates. There are six input variables in the ramp metering algorithm at each metered on-ramp (Table 2.1). Data for each input variable are collected every 30 seconds. Each metered on-ramp has its own fuzzy logic controller, which determines a new metering rate independently every 1 minute [17].

The mainline and on-ramp inputs use a 5-minute moving average calculated from the previous ten 30-second samples to smooth any sharp oscillations. The local mainline occupancy and local mainline speed inputs are collected from the detector immediately upstream of the on-ramp merge. In the event of missing or faulty data at the mainline detector immediately upstream of the merge, the next available upstream detector is used to provide data as a substitute. The system is capable of checking up to 8 upstream detectors in order to obtain quality data. The downstream occupancy and speed inputs are collected at detector located

1 to 2 miles downstream or immediately upstream of a major recurrent bottleneck. The detectors used in the algorithm are dual loop detectors that allow for direct measurement of speed. Multiple ramp metering controllers may use the same downstream detector to collect data for their input variables. This permits the coordination of multiple ramp meters and response to traffic conditions further downstream. The queue occupancy input relies on data collected at the ramp metering stop bar, which is typically located half way between the on-ramp entrance and the merging area. The advanced queue occupancy is collected from a detector located at the entrance of the on-ramp.

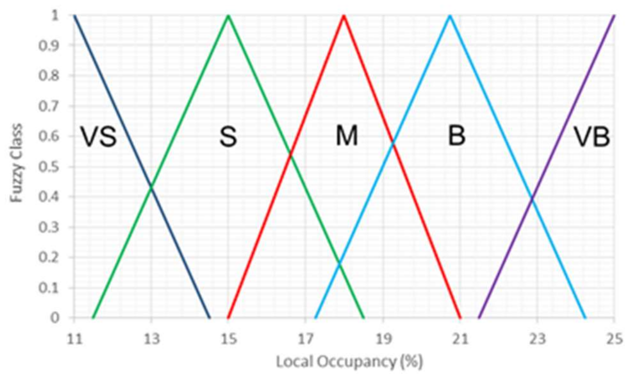
Table 2.1 Fuzzy logic Control - Controller Input Variables [17]

Input	Typical Detector Locations
Local Occupancy	Immediately upstream of merge
Local Speed	Immediately upstream of merge
Downstream Occupancy	1 to 2 miles downstream or immediately upstream of the next bottleneck
Downstream Speed	1 to 2 miles downstream or immediately upstream of the next bottleneck
Queue Occupancy	Ramp metering stop bar
Advanced Queue Occupancy	On-ramp entrance

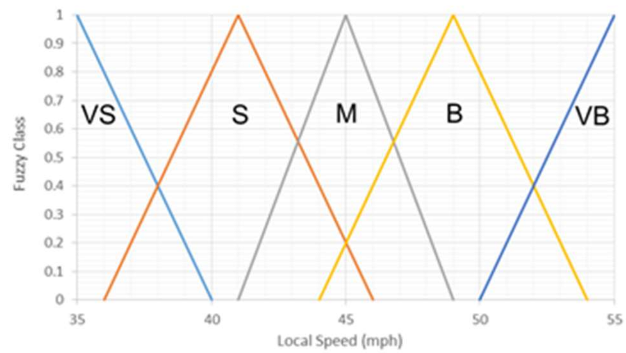
The fuzzy logic control involves three main steps: 1) fuzzification to convert the quantitative inputs into natural language variables, 2) rule evaluation to implement the control heuristics, and 3) defuzzification to map the qualitative rule outcomes to a numerical output [17]. These steps are described below:

Fuzzification

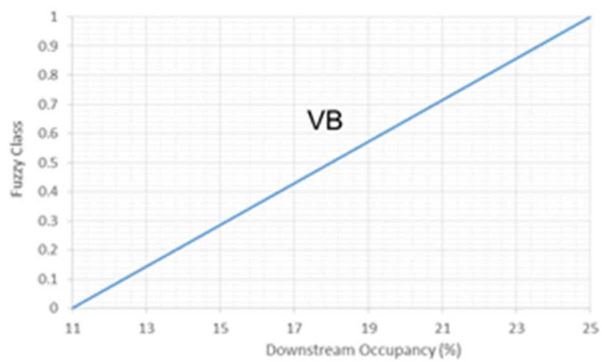
Fuzzification preprocesses the controller inputs by translating each numerical input into a set of fuzzy classes, also known as linguistic variables. For the local and downstream occupancy and speed, the fuzzy classes used are very small (VS), small (S), medium (M), big (B), and very big (VB). The degree of activation indicates how true that class is on a scale of 0 to 1. The trueness of each class can also be thought of as a degree of likelihood or probability, as fuzzy logic is based on Bayesian set theory. Figures2.5 show the fuzzy classes when the system-wide parameter defaults are used.



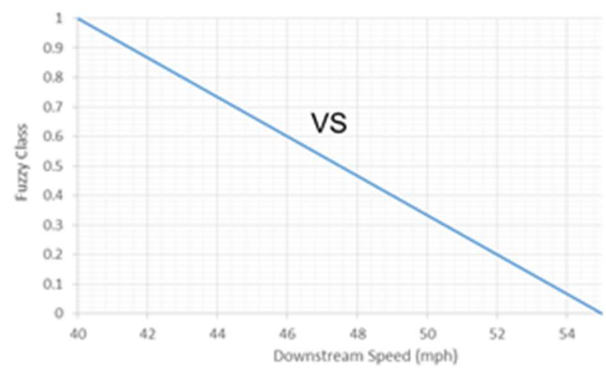
a) Default fuzzy classes for local occupancy



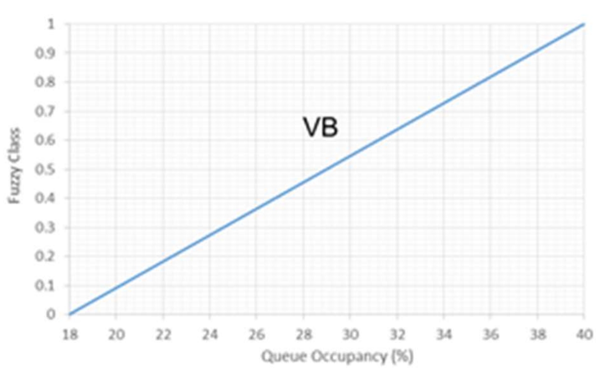
b) Default fuzzy classes for local speed



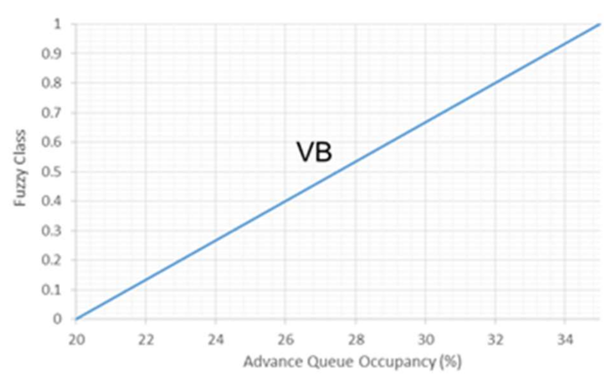
c) Default fuzzy classes for downstream occupancy



d) Default fuzzy classes for downstream speed



e) Default fuzzy class for queue occupancy



f) Default fuzzy class for advance queue occupancy

Figure 2.7 Default Fuzzy Classes

For example, if the local occupancy were 20.0 percent, the M class would be true to a degree of 0.2, and the B class would be true to a degree of 0.7, while the remaining classes would be zero (Figure 2.7a). If the local occupancy input were less than 11 percent, the VS class would be true to a degree of 1.0, and the remaining classes would be zero. If the occupancy input were greater than 25.0 percent, then the VB class would be true to a degree of 1.0, and the remaining classes would be zero. Thus, the local occupancy input is active for at least one class at all times. Between 11 and 25 percent, the controller response is dynamic. Outside of this dynamic range, this input still activates a control response, but behavior is static. The downstream occupancy only uses the VB class, but it begins activating at 11.0 percent and reaches full activation at 25 percent (Figure 2.7c). The local speed uses all five fuzzy classes (Figure 2.7b). The dynamic range of this input is between 40 and 55 mph. The downstream speed (bottom of Figure 2.7d) uses only the VS class, which starts activating at 55 mph and fully activates at 40 mph and below. The queue occupancy and advance queue occupancy inputs use the VB class. For ramps with adequate placement of ramp detectors, the parameter defaults for both of the inputs activate at 12 percent, and fully activate at 30 percent. The fuzzy class for advance queue occupancy looks identical to the one shown for queue occupancy in Figure 2.7e.

Rule Evaluation

The algorithm rules shown in Table 2.2 are a set of if-then statements similar to the heuristics an operator would use to control the system [4]. For a given premise, a fuzzy class of metering rate is specified, either VS, S, M, B, or VB. The rule outcome is equal to the degree of activation of the rule premise. Each rule has a weighting that reflects its relative importance within the rule base. By adjusting these rule weights, the operator can balance the performance objectives.

Table 2.2 Rules for Fuzzy Ramp Metering Algorithm

Rule	Weight	Premise	Outcome
1	0.5	If local occupancy is VB	Metering rate is VS
2	0.2	If local occupancy is B	Metering rate is S
3	0.2	If local occupancy is M	Metering rate is M
4	0.2	If local occupancy is S	Metering rate is B
5	0.2	If local occupancy is VS	Metering rate is VB
6	0.6	If local speed is VS AND local occupancy is VB	Metering rate is VS
7	0.2	If local speed is S	Metering rate is S
8	0.2	If local speed is B	Metering rate is B
9	0.2	If local speed is VB and local occupancy is VS	Metering rate is VB
10	0.8	If downstream speed is VS AND downstream occupancy is VB	Metering rate is VS
11	0.4	If queue occupancy is VB	Metering rate is VB
12	0.8	If advance queue occupancy is VB	Metering rate is VB

Rules 1 through 5 specify a fuzzy metering class given the local mainline occupancy. Rules 6-9 use the relationship between local speed and local occupancy for a more specific congestion index. Rules 6 and 10 use the AND operator between two premises. Rules 1 and 6 have relatively higher weights in order to restrict the metering rate when the vehicles are unable to merge onto the mainline. As the mainline becomes highly congested, there may be a secondary queue of metered vehicles. In this case, ramp metering is no longer beneficial. To maximize system-wide benefit in the event of a highly congested merge, the vehicles are typically better off stored on the ramp than at the merge, to allow the secondary queue dissipate. Rule 10 has a high weight in order to prevent or delay the activation of bottlenecks downstream, which is the intended goal of ramp metering. Rules 11 and 12 are intended to prevent on-ramp queue spillback. High weights are typically used if it is important to prevent inference of arterial operation.

Defuzzification

The last step in the fuzzy logic control is to produce a numerical metering rate given all of the rule outcomes. Just as the inputs to the controller are represented by fuzzy classes to translate from a numerical input to a set of linguistic variables, so is the metering rate represented 16 by a set of fuzzy classes to convert from a set of linguistic variables to a single metering rate (*5*). This reverse process from a fuzzy to a crisp, or quantitative state, is known as defuzzification. The fuzzy classes for a single metered lane are shown in Figure 2.8.

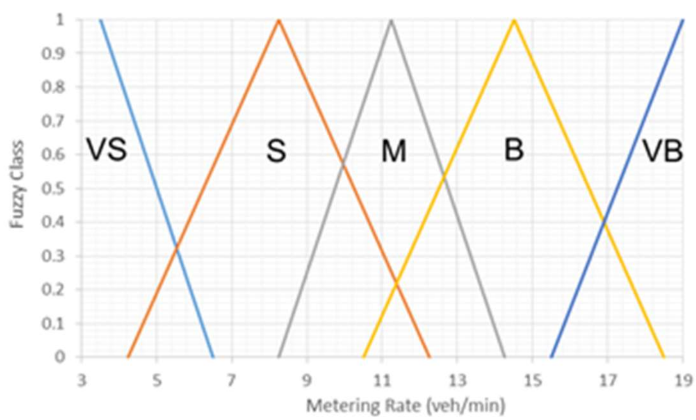


Figure 2.8 Default Fuzzy Class for Metering Rate (*5*)

The implicated area of each rule outcome is found by scaling its fuzzy metering class by its activation degree. The centroid of the rule outcomes is found with the following equation, where each rule's implicated area is multiplied by the rule weighting:

$$Metering\ Rate = \frac{\sum_{i=1}^{N} w_i c_i I_i}{\sum_{i=1}^{N} w_i I_i}$$

Where:
w_i: importance of the ith rule,
c_i: centroid of the output class,

I_i: implicated area of the output class
After defuzzification, the metering rate is adjusted to account for the number of carpool vehicles and illegal entries that bypassed metering during the previous sampling interval (*5*).

2.2.2 Implementation

In recent years, the I-80 had not adopted any ramp metering systems until early 2017.

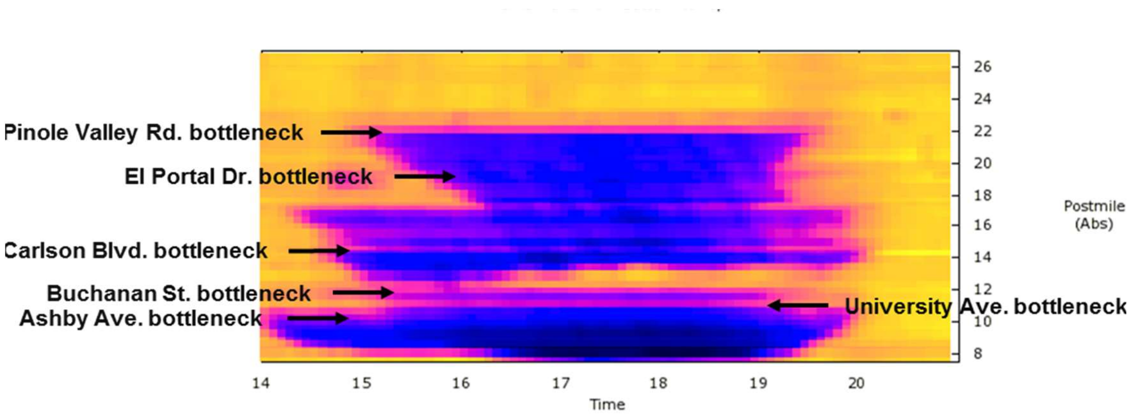
Caltrans District 4 currently maintains a simple communications structure when operating the ramp metering system at the I-80 corridor. At each ramp metering controller cabinet, there is a wireless modem that facilitates the communication with the District Traffic Management Center (TMC). The metering rates are centrally controlled at the TMC computer. Future projects intend to upgrade the communications from wireless modem to fiber. Furthermore, there is currently only one universal set of fuzzy ramp metering rules for each metered on-ramp; future upgrades would consider implementing unique sets of fuzzy ramp metering rules for different metered on-ramps.

Caltrans District 4 has implements queue override at all of the metered on-ramps. The queue override checks for high occupancy at the on-ramp queue detector, located at the entrance of the on-ramp. If the on-ramp queue detector occupancy reaches 40% or above for two consecutive 30 second intervals, queue override would be activated; the fuzzy logic algorithm would be switched off replaced by a fixed ramp metering rate of 900 vehicles/hour. In addition, multiple nearby metered on-ramps belong to the same league, and if fuzzy logic metering is switched off at any metered on-ramp, all of the remaining metered on-ramps in the same league would switch off fuzzy logic metering and revert to a pre-determined time-of-day ramp metering plan that assigns ramp metering rates based on local occupancy thresholds. For fuzzy logic metering to return, the on-ramp queue detector occupancy must reduce to 30% or lower for two consecutive 30 second intervals. Furthermore, the ramp metering system would also switch off fuzzy logic metering and revert to time-of-day ramp metering if the detector data fluctuated rapidly.

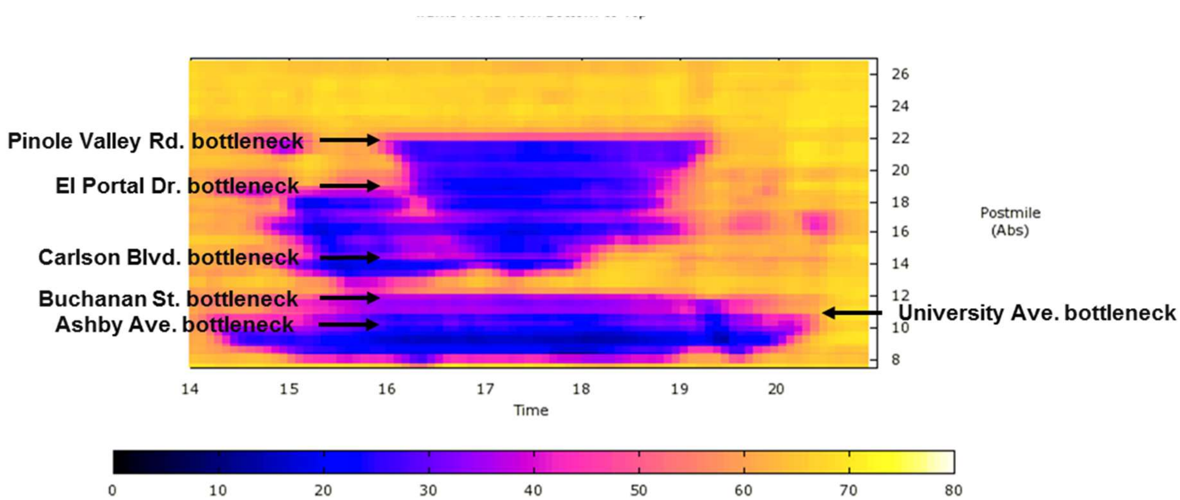
In the eastbound direction, the on-ramp merging sections located at the Ashby Avenue and University Avenue, the short weaving section between the Gilman Street on-ramp and the Buchanan Street/I-580 off-ramp, and the uphill merging sections at the Carlson Boulevard, El Portal Drive, and Pinole Valley Road on-ramps contribute to the evening peak recurrent delay observed in this corridor. This evening peak period typically begins shortly after 2:00 PM and ends around 8:00 PM, and is a result of trips from San Francisco and Oakland to the East Bay suburbs such as Richmond and Vallejo.

In the westbound direction, the uphill weaving section located between the SR-4 on-ramp and the Pinole Valley Road off-ramp, the uphill merging section at the Pinole Valley Road on-ramp, the short weaving section between the San Pablo Dam Road on-ramp and the McBryde Avenue off-ramp, and the short weaving section between the I-580/Buchanan Street and the Gilman Street off-ramp contribute to the morning peak recurrent delay observed in this corridor. This morning peak period typically begins shortly before 6:00 AM and ends shortly before 11:00 AM, and is a result of trips from East Bay suburbs such as Richmond and Vallejo to San Francisco and Oakland. Furthermore, the I-580/I-880/I-80 freeway split at the MacArthur Maze contributes to both the morning and evening peak recurrent delay observed in the westbound direction. The bottleneck at the MacArthur Maze typical lasts from 6:00 AM to 6:00 PM and is a result of the large number of lane change maneuvers at the I-580/I-880/I-80 freeway split.

Details of the congestion pattern are displayed in Figure 2.9 and figure 2.10. Figure 2.9 shows the speed contour plot of a representative weekday prior to and after implementing coordinated ramp metering in the eastbound direction while figure 2.10 shows the speed contour of a typical weekday prior to and after implementing coordinated ramp metering in the westbound direction. Although the bottlenecks are still present, the durations are shorter and the observed speeds are generally higher.

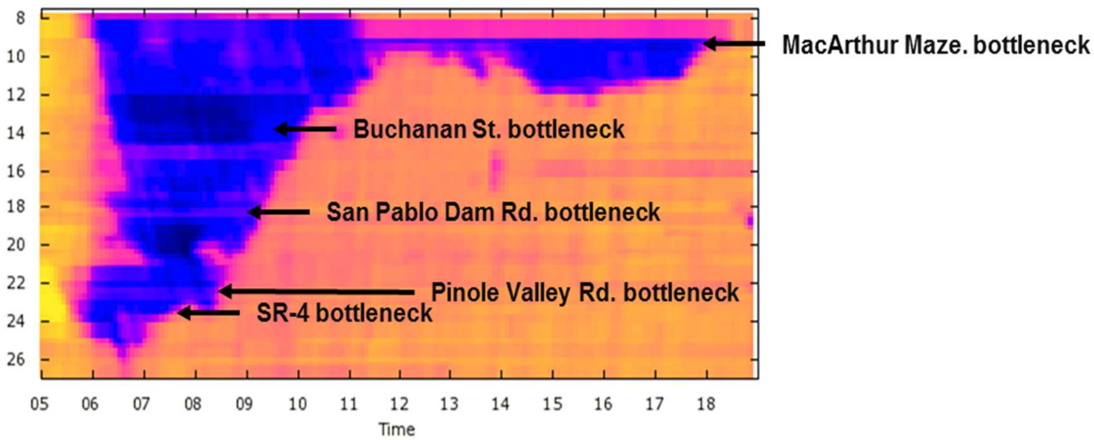


(a) Before coordinated ramp metering.



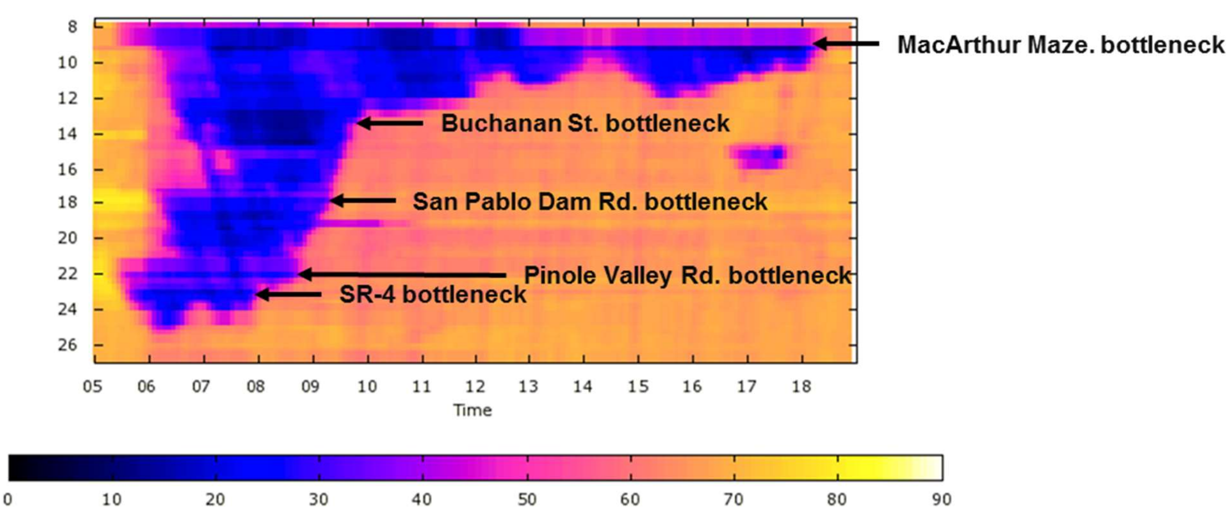
(b) After coordinated ramp metering 10/3/2018

Figure 2.9 Typical Weekday Speed Contour plot of Eastbound I-80.



(a) Before coordinated ramp metering – 10/12/2016

(b)



(c) After coordinated ramp metering – 10/10/2018

Figure 2.10 Typical Weekday Speed Contour Plot of Westbound I-80.

CHAPTER 3
PERFORMANCE MEASURES

3.1 Performance Measures

Several performance measures (MOEs) have been used to assess the freeway performance [3], especially freeway ramp metering algorithms. In this study will initially focus on used MOEs used in Caltrans studies [20,23].

A. Freeway mainline

- Average Travel Time on Freeway mainline (min, min/mile)
- Total Delay on Freeway mainline
- Travel Time Reliability
- Throughput- Vehicles Miles Traveled (VMT)
- Bottleneck discharge rate
- Spatial Distribution of Freeway Mainline Speeds
- Freeway Mainline Average Occupancy
- Spatial Distribution of Freeway Mainline Occupancy

B. On-Ramps

- Average Delay (minute/vehicle, minute/mile/vehicle)
- Queue Length
- Time that the queue detector is active

The final list of MOEs was selected based on the characteristics of test sites, availability of field data and algorithm characteristics.

Freeway Mainline Vehicle-Miles-Traveled (VMT): This is the product of mainline flow and distance at all freeway segments. This is an indication of the freeway throughput and can be determined using vehicle counts from the loop detectors. VMT is provided in the Caltrans Performance Measurement System (PeMS) [2] for each freeway as well as for its specific segments during a particular time of the day. Furthermore, VMT has been widely used by similar ramp metering empirical studies conducted in California [14], Oregon [1], and Wisconsin [6].

Freeway Bottleneck Discharge Rate: The freeway bottleneck discharge rate is defined as the maximum sustained flow over a 15-minute period [12]. Observation of bottleneck discharge flows can be made via the mainline loop detectors located downstream of the freeway bottleneck. This can be done using the flow data provided by PeMS which shows vehicle counts collected every 5 minutes. Detailed raw data also provide 30-second vehicle counts if the analysis demands higher data resolution. In addition, moving average may be used to smooth the fluctuation in the data. Additionally, video data can better facilitate the field observations, as demonstrated in a study conducted on Interstate 5 in Sacramento, California [13]. Supplemental data on queue discharge can be obtained by using video cameras at the bottleneck location if detector data are not available.

Freeway Mainline Average Speed: freeway mainline average speed is a surrogate measure of travel time and delay. This is a performance metric that has been commonly used by many ramp metering field studies [4,10,18,21]. The freeway mainline speeds are provided by PeMS at each loop detector of each mainline lane. Figure 3.1 shows a comparison of "before" and "after" ramp metering at a specific bottleneck.

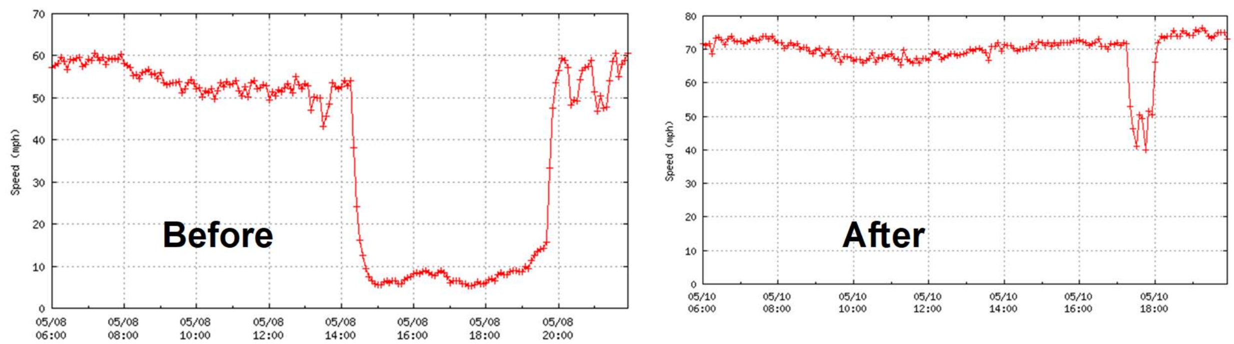


Figure 3.1 Impact of Ramp Metering – Mainline Speed I-580 EB at Hacienda Dr

For the SR-99 corridor in District 3 (Sacramento, California), freeway mainline speeds are directly measured by the dual-loop detectors.

Similarly, for the I-80 corridor in District 4 (Oakland, California), freeway mainline speeds are directly measured by the dual-loop detectors.

For the I-110 corridor in District 7 (Los Angeles, California), freeway mainline speeds are indirectly measured by the single-loop detectors. PeMS uses assumption in vehicle length (G-factor) and the measured flow and occupancy data to interpolate the freeway mainline speeds.

Spatial Distribution of Freeway Mainline Speeds: Variation of freeway mainline speeds from location to location is a surrogate measure of the presence and severity of stop-and-go waves on the freeway mainline. The stop-and-go waves can be observed if the freeway mainline speeds frequently fluctuated between adjacent detectors. Presence of severe speed fluctuations and stop-and-go waves can be a significant safety risk for rear-end collisions at the back-of-queue.

Variation of freeway mainline speeds from across multiple lanes is surrogate measure of potential lane changes as well as safety near a freeway bottleneck. Large variations between adjacent lanes, for example, stopped vehicles in the right lane vs. vehicles travel at 40 mph in the adjacent lane, can induce unsafe lane change maneuvers as vehicles in the slower lane proceed to travel at their higher desired speeds. This can also further reduce the freeway bottleneck discharge rate as vehicles in the adjacent lane must reduce their speeds to allow for such lane changes. PeMS provides lane-by-lane speed data at all of the selected corridors.

Freeway Mainline Average Occupancy: the freeway mainline average occupancy is an indirect measure of density, and an indication of the extent of freeway mainline congestion. This performance metric has been used by the study conducted in Seattle, Washington [22]. The freeway mainline occupancy is directly measured by the mainline loop detectors and the data can be found in PeMS.

Spatial Distribution of Freeway Mainline Occupancy: Variation of freeway mainline occupancies from location to location is a surrogate measure of the presence and severity of stop-and-go waves on the freeway mainline. The stop-and-go waves can be observed if the freeway mainline occupancies frequently fluctuated between adjacent detectors. Presence of stop-and-go waves can be a significant safety risk for rear-end collisions at the back-of-queue.

Variation of freeway mainline occupancies from across multiple lanes is surrogate measure of potential lane changes as well as safety near a freeway bottleneck. High right lane occupancy typically indicates stopped vehicles in the right lane, and when combined with the lower occupancy in the adjacent lane, drivers would perceive that the adjacent lane allows for higher speeds. This can trigger unsafe lane change maneuvers as vehicles in the slower lane proceed to travel at their higher desired speeds. This can also further reduce the freeway bottleneck discharge rate as vehicles in the adjacent lane must reduce their speeds to allow for such lane changes. PeMS provides lane-by-lane occupancy data at all of the selected corridors.

Freeway Mainline Travel Time and Delay: These measures have been widely used in many empirical studies on ramp metering [4, 10, 20]. The freeway mainline delay can also be calculated if given the free-flow speed (subtract free-flow travel time). Figure 3.2 shows an example of ramp metering assessment on a section of Interstate-5 Northbound in District 3 based on travel time (average and travel time reliability) derived from detector data processed from PeMS.

Travel time is typically calculated using the speed data collected at the loop detectors; the speed data collected at each loop detector can be used to calculate the travel time through the segment of the freeway surrounding the corresponding loop detector, and the sum of the travel time at each segment is the total travel time. In addition, travel time can also be determined by direct measurements of the arrival times at the two distinct locations of the same vehicle; this is typically done through tracking toll tags equipped on individual vehicles and time-stamping them at various locations along the freeway mainline, and this requires only a small sample of vehicles on the freeway, however, travel time data collected from time-stamping the toll-tags can have large variations.

PeMS provides travel time data for freeway mainline, and the users can specify a particular segment to collect the travel time data. It also provides travel time data for individual lanes (including High Occupancy hicle lanes). Delay data are calculated based on reference speeds of 35 mph and 65 mph.

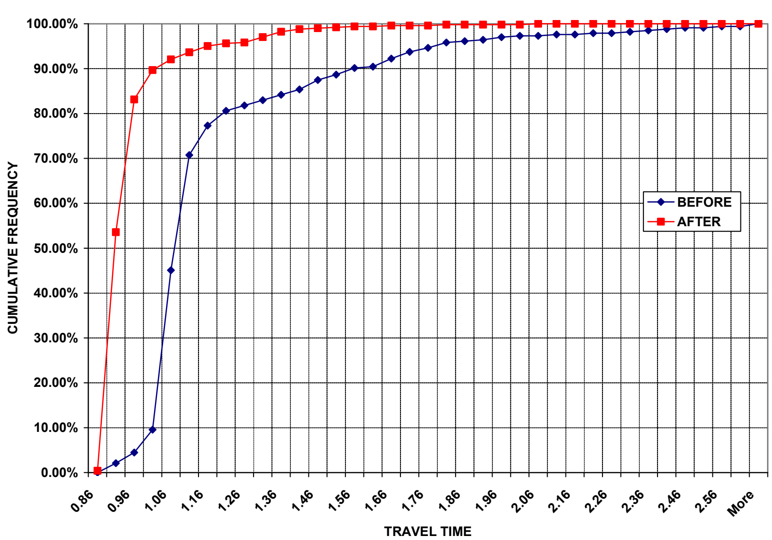


Figure 3.2 Travel Time Distribution—I-5N Before & After Ramp Metering Implementation[3]

Freeway Mainline Travel Time Reliability: Improvement in travel time reliability is more important than the improvement in average travel time because better predictability allows travelers to incur less cost or penalty due to late or early arrivals at their destination. Furthermore, reducing the average travel time may not be beneficial if there would still be regular occurrences of travel times lasting twice or longer than the average travel time. Travel time reliability has been considered in a recent ramp metering study [12].

PeMS provides multiple measures of travel time reliability. For each specified freeway segment, the mean, median, standard deviation, and the 25th and 75th percentiles are provided. Such data also indicate the shape and skewness of the travel time distribution, and the buffer time index (BTI) [9].

$$BTI = \frac{TT_{95th} - TT_{avg}}{TT_{avg}} \cdot 100\%$$

Where:
BTI: buffer time index
TT_{95th}: 95th percentile travel time
TT_{avg}: average travel time

On-Ramp Performance Measures

The selection of the appropriate measures for the metered on-ramps strongly depends on the data availability. Estimation of queue delay and queue length require properly placed loop detectors that may not be available at the test sites. Data may be collected at selected on-ramps using video recordings but the usefulness is limited because "before" data may not be available. The amount of time that the queue detector was activated can be obtained from the TMC and may be a reliable performance measure.

On-ramp Queue Length: Improved freeway mainline performance cannot simply be used to show that the ramp metering system is effective. If the excess on-ramp queues caused spillback, then the significant on-ramp delay may negate the benefits observed on the freeway mainline. Recent ramp metering studies have considered on-ramp queue lengths as criteria for evaluation [12,18]. Although data for on-ramp queue length is not available in PeMS, the on-ramp queue length can be estimated using the on-ramp detector data.

The on-ramp queue length can be estimated using the on-ramp detector data. First, the on-ramp excess accumulation $Q(t)$, or the number of vehicles in queue, at the end of time step t can be determined based on the following iterations:

$$\begin{gathered} Q(0) = 0 \\ Q(1) = Q(0) + A(1) - D(1) \\ Q(2) = Q(1) + A(2) - D(2) \\ \vdots \\ Q(t) = Q(t-1) + A(t) - D(t) \end{gathered}$$

where:

$A(t)$: number of vehicle arrivals during time step t, measured by the on-ramp queue detector
$D(t)$: number of departures during time step t, measured by the detector at the metering light
At the end of each time step t, the length of the on-ramp queue can be estimated by the following:

$$Q(t) \cdot \rho_{jam}$$

where ρ_{jam} is the jam density (typically 25ft/veh) when on-ramp vehicles are in queue.

On-ramp Delay: The effectiveness of the ramp metering system cannot be evaluated only using freeway mainline performance metrics. Excessive on-ramp delay may outweigh and negate the benefit observed on the freeway mainline. Although data for on-ramp delay is not available in PeMS, the on-ramp delay can be calculated using the on-ramp detector data.

The on-ramp delay can be calculated by the following formula:

$$\sum_{t=1}^{T} Q(t) \cdot \tau$$

where:
$Q(t)$: excess accumulation (number of vehicles in queue) at the end of time step t
τ: duration of each time step
T: total number of time steps in the analysis period

On-ramp Queue Detector Occupancy: The occupancy data collected at the queue detector (located at the upstream on-ramp entrance) can be a surrogate measure of the extent of on-ramp queue spillback. For the on-ramp queue detectors used by Caltrans, an occupancy of 30% to 40% indicates that there is significant queue spillback that has likely propagated to the arterial streets, while an occupancy of 10% indicates that the on-ramp queue has not yet propagated to the arterial streets.

Number and Duration of Queue Overrides: Long queues may form at the on-ramps that have limited queue storage. This can interfere with the operation of the adjacent surface street network. This is a common occurrence on California freeways because most of the on-ramps do not provide sufficient queue storage [12]. Most of the operational ramp metering systems employ a "queue override" feature that is intended to prevent the on-ramp queue from obstructing traffic conditions along the adjacent surface streets [12, 18]. The override is triggered whenever a sensor placed at the entrance of the on-ramp detects a potential queue spillover of the on-ramp vehicles on the adjacent surface streets. This clears the on-ramp queue by temporarily turning off ramp metering. Unfortunately, this approach may reduce the effectiveness of the employed ramp metering systems during the time of the highest traffic demand, when the ramp metering is most needed. Therefore, the frequency and duration of queue override activation would provide an indication of how much the freeway mainline has been negatively impacted as a result of limited on-ramp queue storage and the need to reduce ramp metering's impact on arterial streets. This performance metric has been considered in recent study conducted in Nevada [16].

Arterial Flows and Occupancy

As suggested by the ramp metering study conducted by the Minnesota Department of Transportation [4] freeway ramp metering can significantly impact of the operations of its nearby arterials, especially if there is a parallel arterial that may serve the shorter freeway trips and facilitate diversion in the event of a freeway incident. Thus changes in arterial flow and occupancy would indicate potential diversions as a result of freeway ramp metering. Higher than average arterial flow and occupancy could indicate a large volume of freeway traffic diverted to the arterial. Extremely high arterial occupancy (30% or higher) shows that the arterial could be oversaturated and experiencing queue spillback.

For this evaluation, the parallel arterials near I-80 in District 4 will be examined. Data for arterial flows and occupancies can be collected using the loop detectors upstream of the stop bars at signalized intersections.

The I-80 corridor in District 4 relies on its parallel arterial San Pablo Ave. to divert some short freeway trips during recurrent conditions and to divert a portion of freeway traffic in the event of a freeway incident.

The I-110 corridor in District 7 uses its parallel arterial Figueroa St. for diverting freeway traffic in the event of a freeway incident but can also divert the arterial traffic to the freeway in the event of an incident on the parallel arterial.

Accident Frequency, Severity, and Duration

Based on suggestions in the ramp metering study conducted by the Minnesota Department of Transportation [4], accident statistics are also very important for evaluating the effectiveness of a ramp metering system. The number, severity, and duration of accidents in the analysis period are direct measures of safety performance. The coordinated ramp metering systems are expected to reduce the frequency, severity, and duration of accidents if the freeway experienced smoother traffic flow and fewer stop-and-go waves. PeMS currently provides data for the number of accidents and their characteristics (type, location, duration and severity). The data obtained from the original police reports documented by the California Highway Patrol (CHP).

Benefit/Cost (B/C) Ratio

The ramp metering study conducted by the Minnesota Department of Transportation [4] also suggested evaluating the financial viability of ramp metering systems. All of the three corridors evaluated in this project have undertaken significant upgrades to implement their coordinate ramp metering systems. Upgrading ramp metering systems may require significant investments both in term of equipment purchases and labor hours. Approximate cost estimates can be obtained from each of the districts to evaluate the benefit/cost ratio. The benefit would mostly come from the delay reduction or time savings experienced by the freeway users. The monetary value of the time savings can be computed using assumption of value of time for the travelers in the metropolitan area, and the local metropolitan planning organization typically publishes information regarding value of time.

CHAPTER 4
EMPIRICAL EVALUATION OF CRM STRATEGIES

The empirical or real-world evaluation of the Caltrans CRM strategies was conceptually divided into separate work tasks; establishing a set of baseline conditions for each study corridor was the first work task or step in the evaluation process. The next task focused on the collection and processing of the available data to quantify the performance of the study corridors for the "before" CRM implementation and the "after" CRM implementation conditions. The final step of the empirical evaluation process was to compare the "before" CRM implementation performance measures with those obtained from evaluating the "after" CMP implementation conditions and summarize the findings. These steps and the results are discussed in the following sections of this chapter.

4.1 Establishing Baseline Conditions

The study evaluated the performance of two different CRM systems on two different test corridors, the I-80 corridor in District 4 and the SR-99 corridor in District 3 as described in Chapter 2.

Because the CRM is already implemented in the test corridors, the assessment was based on the comparison of the performance under CRM and the existing operating system in each site:

The following key issues will be considered in developing the data collection and analysis plan:

1. Because the selected CRMs are evaluated on two different sites with different existing systems it is not possible to determine that a particular CRM is the best across all sites based on the analysis of the field data.
2. In general, the evaluation of an improved control strategy (CRM) in a corridor should be made against the best operation (fine-tuned) of the existing strategy. For example, on I-80 there was no prior metering. It will be unknown if the implemented Fuzzy logic algorithm is better than a typical local responsive ramp strategy.

Collect detailed data on the geometric and operational characteristics of the selected corridors including:

- Freeway and ramp lane configuration diagrams
- Characteristics of the "before" conditions control system in place
- Spatial and Temporal Congestion patterns in the selected corridor

Establish time period for collecting "before" and "after" performance data:

- Typically AM and PM peak periods during weekdays, and on weekends (subject to the ramp metering operation schedule).
- The number of tome periods to collect data will be based on the baseline patterns to ensure statistically significant samples of performance measures
- Initially we will focus on incident free time periods, but we will assess algorithm assessment

under incidents provided that is an option in the algorithm (e.g., DCRM) and appropriate data are available.

Table 4.1 Data Collection Periods for Collecting "before" and "after" Performance Data

Corridor & Direction	Length (miles)	Days Of Week	Time Of Day	Data Collection Period	
				"Before"	"After"
District 4 Interstate 80 Westbound **District 4 Interstate 80 Eastbound**	18.9	Non-holiday Weekdays (Mon-Fri)	5:00 AM to 11:00 AM 1:00 PM to 8:00 PM	Sept-Oct 2016	Sept-Oct 2018
District 3 State Route 99 Northbound	14.3	Non-holiday Weekdays (Mon-Fri)	6:00 AM to 9:00 AM	Sept-Nov 2018	Sept-Nov 2019

4.2 Data Collection and Processing

The research team collected performance data for the selected sites "before" and "after" for the time periods and conditions that were listed in Table 4.1. Data processing software scripts were developed to facilitate the data processing and additional visualization tools were employed for these data analyses.

Field data collection was not possible because the agreed to and selected "before" CRM implementation periods preceded the contract execution and notice to proceed dates for this work effort. With that, this project's empirical evaluation was based on continuous and automatically collected data, primarily Caltrans PeMS and INRIX Analytics data [11].

The primary source of data was Caltrans PeMS detector data and INRIX Analytics travel time /speed data to establish performance along the freeways' mainline. INRIX is a private firm that provides speed and travel time data on highway facilities based on data provided by private vehicles and vehicle fleets. Existing agreements between state agencies like Metropolitan Transportation Commission (MTC) and Los Angeles Metro (LA Metro) and INRIX make possible the availability of the INRIX data at no cost.

The estimation of discharge rate (capacity) at freeway bottlenecks, requires measurement of flow rates upstream and downstream of the bottleneck location. The initial intent of the study was that if loop detector data were not available, then the research team would collect these data using video cameras and software (e.g., Miovision systems routinely used by Caltrans) provided that suitable video camera locations could be found at the selected corridor locations. However, the study corridor's selected "before" periods was incompatible with field data collection (the "before" periods preceded the contract's execution and notice to proceed). As such, Caltrans PeMS hourly traffic volumes were used to monitor traffic volumes at key locations.

4.3 Findings from Empirical Before/After Evaluation

Upon downloading, cleaning and processing the Caltrans PeMS and INRIX Analytics data that were just described, the research team created summary tables and graphics for the selected performance measures. The resulting freeway performance for the "before" and "after" CRM implementation for the I-80 and SR-99 corridors are presented next.

Table 4.2 lists the selected performance measures and shows the I-80 Eastbound observed values for the AM Peak Period, PM Peak Period, and for the 24-hour day for an average non-holiday weekday, contrasting the freeway's performance for the "before" and "after" CRM implementation periods. Table 4.3 shows the same for the I-80 Westbound study corridor; as does Table 4.4 for the SR-99 Northbound study corridor. The data source for the results shown in Table 4.2, Table 4.3 and Table 4.4 were Caltrans PeMS 5-minute summary downloaded data files.

In tables 4.2, 4.3 and 4.4, the peak period's performance measures that are associated with the dominant direction of travel is shown in a bold font. For the I-80 corridor, traffic is heaviest in the AM peak period in the westbound direction (traffic headed toward downtown San Francisco). As such, the AM Peak Period is bolded on table 4.3. Likewise, traffic is the heaviest in the PM peak period in the eastbound direction, and the PM Peak Period's performance measures are highlighted in Table 4.2. For the northbound SR-99, the traffic is heaviest during the AM peak period, with traffic headed toward downtown Sacramento – and the AM peak period's performance measures have been bolded in Table 4.4.

Appendix D contains a set of graphics (line charts) showing the observed performance measures by time of day on an average non-holiday weekday for the selected "before" and "after" period. These line charts also allow visual verification of the reported differences between the "before" CRM implementation and the "after" CRM implementation for an average non-holiday weekday.

Freeway incident and/or collision rates were not analyzed for this before/after evaluation because performance periods in the range of two months is too short to obtain credible collision rate estimates. The number of collisions per month and the nature of collisions vary too much to obtain stable estimators for periods less than 12 months or so (12 months of "before" data and another 12 months of "after" data).

Eastbound I-80 Corridor: Corridor utilization as measured by corridor-wide VMT for the eastbound I-80 study corridor decreased when comparing the "before" to "after" conditions. This held true for the AM peak period, PM peak period and the overall daily trends. Likewise, the average on-ramp occupancies and volumes decreased for both peak periods and daily trends. The PM peak and daily Vehicle Hours of Delay (VHD-35) decreased as well, while the AM peak period's held constant with no changes observed. It should be noted that the percentage point declines in VHD-35 were only about half (or less) of the values of the observed declines in VMT.

The average PM peak vehicular travel-time increased nominally (from 28.35 minutes to 28.44 minutes), a 0.32% increase, while the overall corridor's travel time decreased modestly for the AM peak period and for the overall daily trends. One would expect vehicular delays to decrease with declining utilization (i.e., VMT).

The travel-time reliability got a bit better for all time periods analyzed (AM peak, PM peak and daily), as seen by the reduction in both the Planning Time Index (PTI) and the Travel Time Index (TTI). This is consistent with the declines in VMT.

It would be difficult to attribute the changes in the traffic utilization (as measured by VMT and ramp volumes) or the observed changes in the corridor's performance to the updates in the ramp metering strategy because these utilization and performance changes are relatively consistent throughout the day, not exaggerated or isolated to the times of the day when ramp metering was implemented. This can be seen in the time-of-day plots provided in Appendix D of this report.

Westbound I-80 Corridor: The findings from the evaluation of the westbound I-80 corridor were similar to those observed for the eastbound I-80 corridor. VMT and travel-times decreased for the AM peak period, PM peak period and when tallied for the entire non-holiday weekday. While vehicular utilization decreased, the vehicular delays, measured using the VHD-35 metric, increased for all three periods (AM peak, PM peak and daily).

The motorist's average travel times decreased for all three time periods (AM peak, PM peak and daily), as one would expect with decreasing vehicular utilization (i.e., VMT).

The travel-time reliability got a bit better for all time periods analyzed (AM peak, PM peak and daily), as seen by the reduction in both the Planning Time Index (PTI) and the Travel Time Index (TTI). This is consistent with the declines in VMT.

Consistent with the findings from the eastbound I-80 corridor, it would be difficult to attribute the changes in the traffic utilization (as measured by VMT and ramp volumes) or the observed changes in the corridor's performance to the updates in the ramp metering strategy because these utilization and performance changes are relatively consistent throughout the day, not exaggerated or isolated to the times of the day when ramp metering was implemented. Again, this can be seen in the time-of-day plots provided in Appendix D.

Northbound SR-99 Corridor: The findings or the observed changes in the corridor's performance measures for the northbound SR-99 corridor are similar to the findings from the I-80 corridor. Vehicle utilization (VMT and on-ramp volumes), vehicular delays (VHD-35) and corridor travel times all decreased between the "before" and "after" periods studied. The percentage point reductions in VHD-35 were substantial compared to the declines in VMT and corridor travel times.

Overall, the corridor's travel time reliability got better, as can be seen by the decreases in the corridor's PTI and TTI metrics. The one exception is that the PTI increased nominally during the AM peak period. These trends are generally consistent with the observed decreases in vehicular utilization (VMT and on-ramp volumes).

And like the I-80 corridor and with the observed decreases in VMT and the consistent trends across the entire 24-hour day (for an average non-holiday weekday), it would be difficult to attribute the changes in the corridor's performance to changes in ramp metering policies or implemented strategies.

Table 4.2 District 4 Eastbound I-80 Average Weekday Freeway Performance

Corridor Performance Measure	(a) Before Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	358,781	**679,827**	1,175,602
VHT (vehicle-hours)	5,680	**19,593**	24,721
VHD-35 (vehicle-hours)	19	**5,034**	3,523
Travel Time (minutes)	17.71	**32.01**	18.04
PTI (no units)	1.17	**2.60**	1.75
TTI (no units)	1.10	**1.96**	1.39
On-Ramp Volumes (vph)	262	**507**	299

Corridor Performance Measure	(b) With Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	338,255	**602,637**	1,062,067
VHT (vehicle-hours)	5,176	**17,437**	21,409
VHD-35 (vehicle-hours)	0	**4,404**	2,728
Travel Time (minutes)	17.10	**31.56**	17.28
PTI (no units)	1.13	**2.50**	1.60
TTI (no units)	1.06	**1.93**	1.34
On-Ramp Volumes (vph)	223	**411**	247

Corridor Performance Measure	(c) Change – Before Vs. After (percent)		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	-5.72%	**-11.35%**	-9.66%
VHT (vehicle-hours)	-8.88%	**-11.00%**	-13.40%
VHD-35 (vehicle-hours)	-97.93%	**-12.51%**	-22.57%
Travel Time (minutes)	-3.44%	**-1.41%**	-4.17%
PTI (no units)	-3.67%	**-4.04%**	-8.51%
TTI (no units)	-3.38%	**-1.43%**	-3.89%
On-Ramp Volumes (vph)	-15.03%	**-18.98%**	-17.63%

Table 4.3 District 4 Westbound I-80 Average Weekday Freeway Performance

Corridor Performance Measure	(a) Before Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**589,780**	557,417	1,360,684
VHT (vehicle-hours)	**16,862**	11,298	28,587
VHD-35 (vehicle-hours)	**4,181**	1,485	4,181
Travel Time (minutes)	**32.89**	22.06	19.89
PTI (no units)	**2.60**	1.65	1.77
TTI (no units)	**1.94**	1.31	1.40
On-Ramp Volumes (vph)	**453**	501	358

Corridor Performance Measure	(b) With Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**573,752**	517,241	1,269,174
VHT (vehicle-hours)	**16,323**	9,956	26,014
VHD-35 (vehicle-hours)	**4,018**	990	3,730
Travel Time (minutes)	**32.18**	20.09	19.24
PTI (no units)	**2.57**	1.43	1.69
TTI (no units)	**1.89**	1.19	1.35
On-Ramp Volumes (vph)	**383**	412	303

Corridor Performance Measure	(c) Change – Before Vs. After (percent)		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**-2.72%**	-7.21%	-6.73%
VHT (vehicle-hours)	**-3.20%**	-11.88%	-9.00%
VHD-35 (vehicle-hours)	**-3.89%**	-33.34%	-10.79%
Travel Time (minutes)	**-2.15%**	-8.94%	-3.29%
PTI (no units)	**-1.19%**	-13.42%	-4.74%
TTI (no units)	**-2.17%**	-8.79%	-4.20%
On-Ramp Volumes (vph)	**-15.47%**	-17.78%	-15.39%

Table 4.4 District 3 Northbound SR-99 Average Weekday Freeway Performance

Corridor Performance Measure	(a) Before Updated Ramp Metering Strategy	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**190,652**	1,069,630
VHT (vehicle-hours)	**5,298**	19,907
VHD-35 (vehicle-hours)	**1,100**	1,437
Travel Time (minutes)	**22.99**	15.17
PTI (no units)	**1.93**	1.25
TTI (no units)	**1.44**	1.22
On-Ramp Volumes (vph)	**497**	359

Corridor Performance Measure	(b) With Updated Ramp Metering Strategy	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**177,888**	1,017,313
VHT (vehicle-hours)	**4,670**	18,102
VHD-35 (vehicle-hours)	**894**	1,114
Travel Time (minutes)	**21.83**	14.40
PTI (no units)	**1.25**	1.34
TTI (no units)	**1.22**	1.14
On-Ramp Volumes (vph)	**463**	338

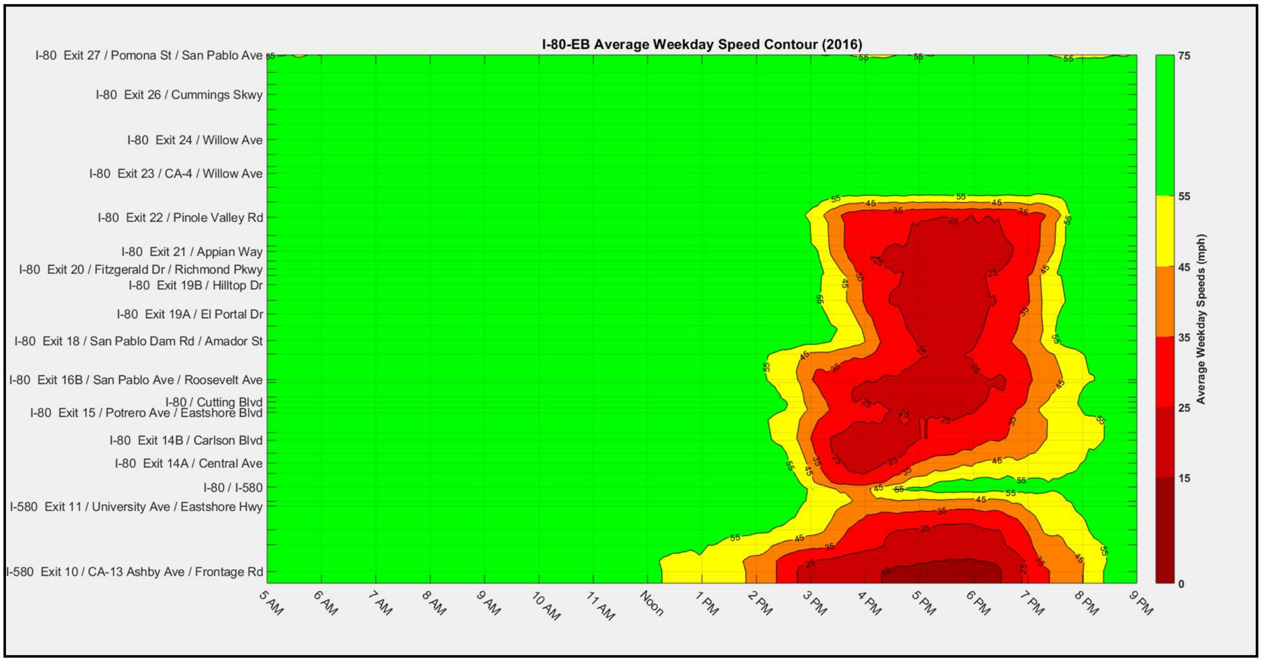
Corridor Performance Measure	(c) Change – Before Vs. After (percent)	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**-6.70%**	-4.89%
VHT (vehicle-hours)	**-11.84%**	-9.06%
VHD-35 (vehicle-hours)	**-18.76%**	-22.44%
Travel Time (minutes)	**-5.06%**	-5.09%
PTI (no units)	**0.52%**	7.20%
TTI (no units)	**-0.69%**	-6.56%
On-Ramp Volumes (vph)	**-6.74%**	-5.98%

Figure 4.1 shows the observed traffic speeds for an average non-holiday weekday for the District 4 Eastbound I-80 study corridor. Likewise, Figure 4.2 shows the observed traffic speeds for an average non-holiday weekday for the Westbound I-80 study corridor. In like fashion, Figure 4.3 shows the observed traffic speeds for an average non-holiday weekday for the District 3 Northbound SR-99 study corridor. The "before" conditions are shown in the top pane and the "after" conditions are shown in the bottom pane in Figure 4.1, Figure 4.2, and Figure 4.3.

The congestion patterns in Figures 4.1, 4.2 and 4.3 were generally consistent with the previously displayed corridor performance measures and the travel-time line plots in Appendix D. These congestion plots clearly show that the eastbound I-80 corridor is heavily congested in the PM peak period, while the westbound I-80 and northbound SR-99 corridors' congestion is predominately concentrated in the AM peak period.

From visual inspection of Figures 4.1, 4.2 and 4.3, the overall congestion patterns appear very similar when comparing the "before" CRM and the "after" CRM implementation scenarios for each of the study corridors. There are no consistent or identifiable changes to these speed contour plots that can be directly attributable to implementation of updated CRM strategies.

With the results or findings being mixed or obscured by the changes in corridor utilization as measured by VMT between the "before" and "after" periods, it was difficult to draw meaningful conclusions about the effectiveness of implementing the updated CRM strategies on the study corridors. A different approach was taken to try to remove the effects of these VMT changes on the corridor's performance, which is described in the following subsection of this report along with the associated results.



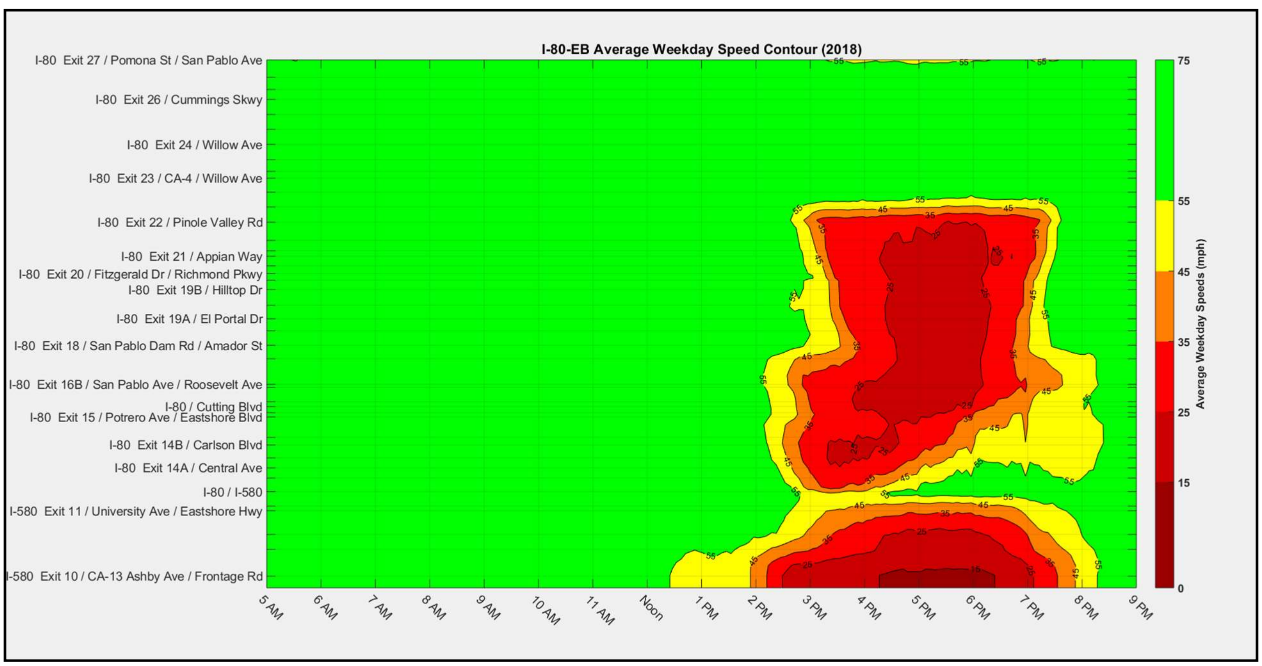


Figure 4.1 I-80 EB Average Weekday Speed Contours: 2016-before (top) & 2018-after (bottom)
(Source: INRIX Roadways 5-minute averaged speed data)

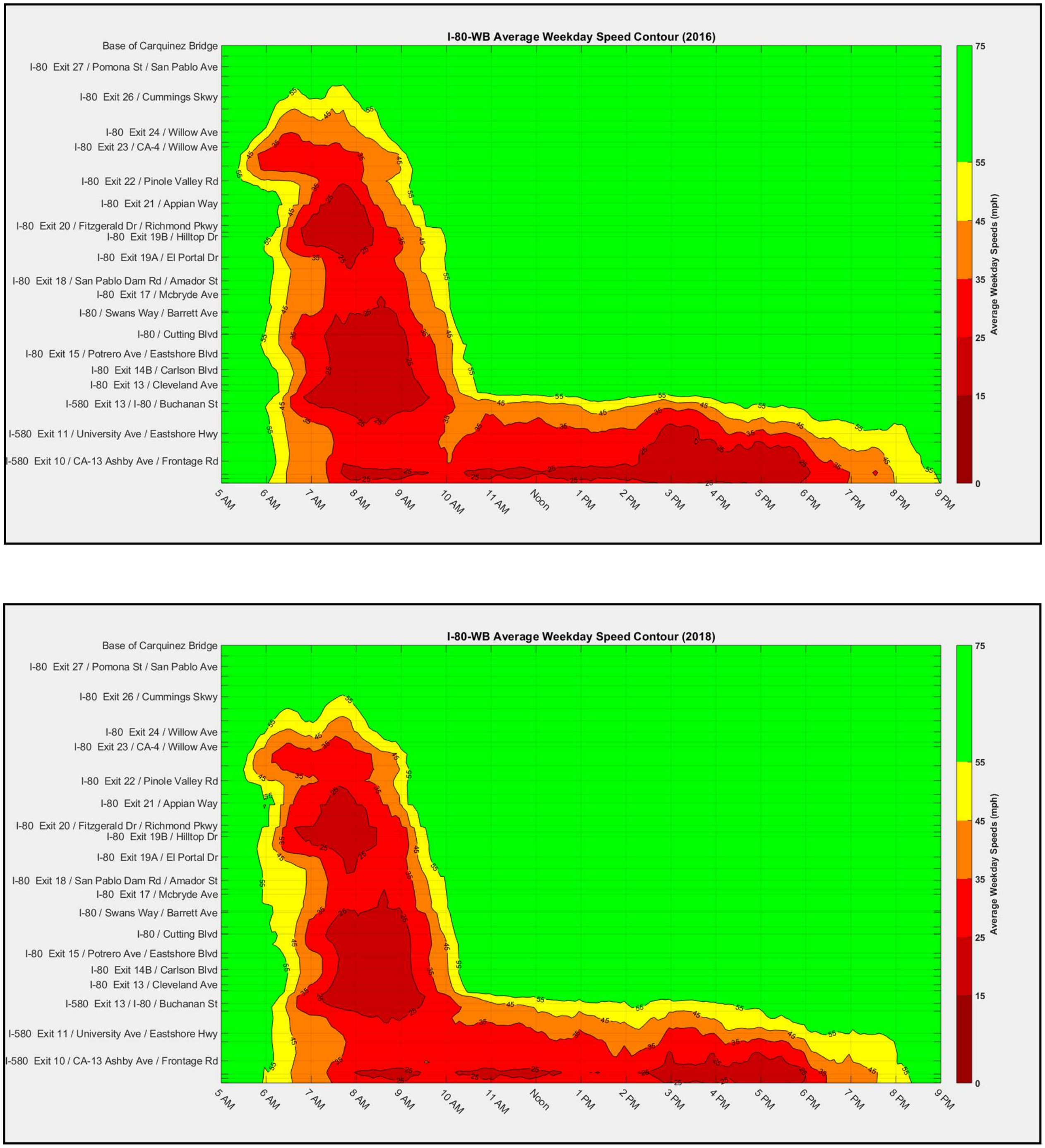
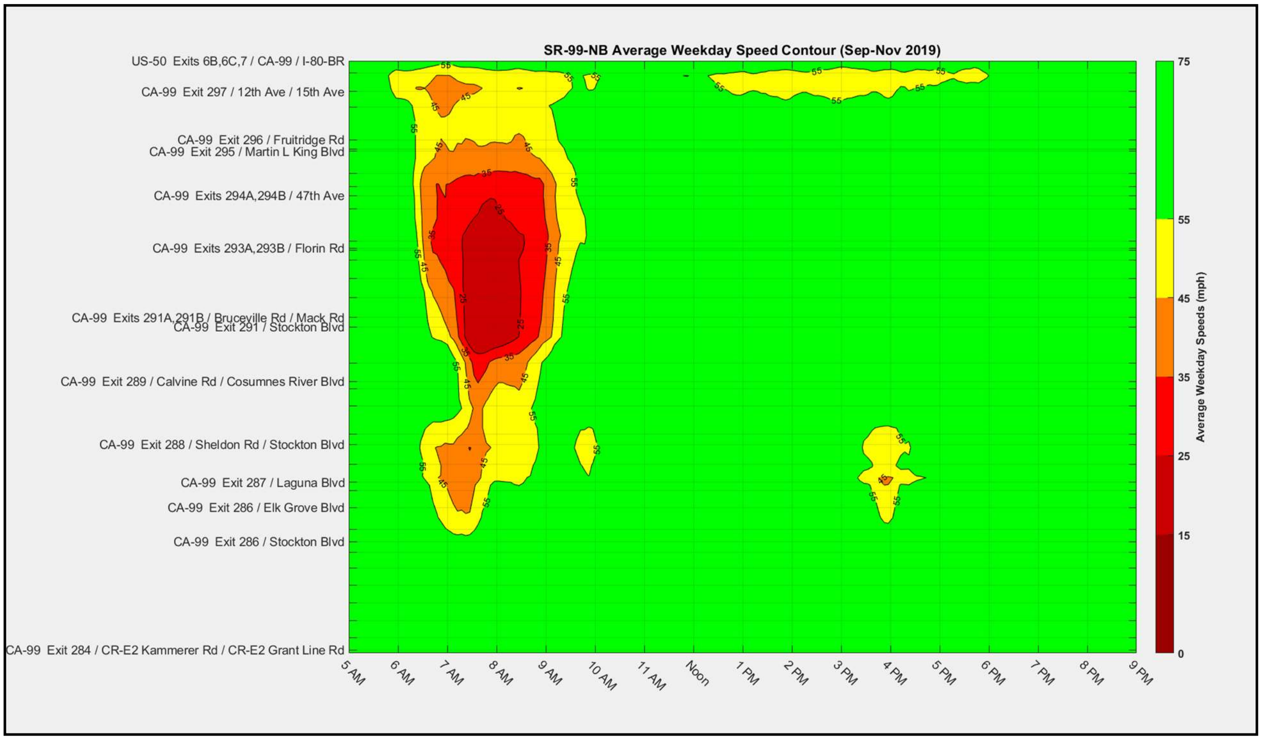


Figure 4.2 I-80 WB Average Weekday Speed Contours: 2016-before (top) & 2018-after (bottom)
(Source: INRIX Roadways 5-minute averaged speed data)



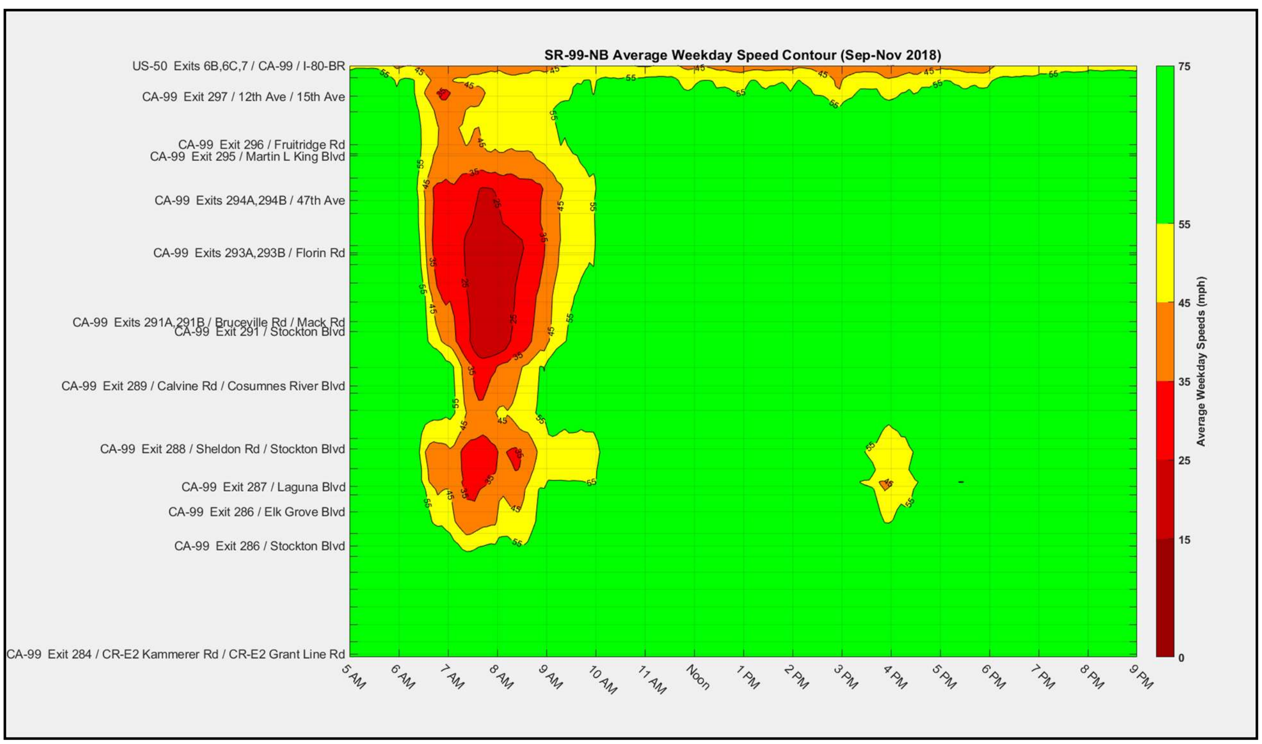


Figure 4.3 SR-99 NB Average Weekday Speed Contours: 2018-before (top) & 2019-after (bottom)
(Source: INRIX Roadways 5-minute averaged speed data)

4.4 Findings From Empirical Before/After Evaluation -- Balanced VMT Analysis

With the I-80 and SR-99 corridor utilization (VMT) decreasing between the before and after evaluation periods, it was not possible to directly measure the delay savings from implementing the updated CRM strategies. We developed and implemented an analysis methodology to quantify the changes in VHT and delays independent of these VMT reductions. The methodology addresses the question "What would the changes in VHT and delays been had there been no changes in corridor utilization (i.e., VMT)?"

To accomplish this, a subset of the days in the before dataset and a subset of the days from the after dataset were selected such that the average corridor VMT in the before dataset matched or equaled the average corridor VMT in the after dataset. With this, we had the ability to perform a "before" and " after" comparison where there was no growth or reduction in VMT when we compared the before CRM implementation's corridor performance with the after CRM implementation's corridor performance. There were multiple before and after datasets that could be created which met this criterion, some with very few days and some with many more days. We used as many days of data from the before datasets and as many days from the after datasets as possible (to avoid small sample instabilities in the results) and still balance the corridor average VMT in the before and after datasets.

Table 4.5 lists the selected performance measures and shows the I-80 Eastbound observed values for the AM Peak Period, PM Peak Period, and for the 24-hour day for an average non-holiday weekday, contrasting the freeway's performance for the "before" and "after" CRM implementation periods (using the balanced VMT analysis procedures). Table 4.6 shows the same for the I-80 Westbound study corridor; as does Table 4.7 for the SR-99 Northbound study corridor.

It is clear there is very little differences in the corridor's average VMT estimates when comparing the "before" and the "after" periods. This was by design of the balanced VMT analysis – to select a set of "before" days and "after" days where the average VMT matched or was balanced.

The balanced-VMT analysis showed a 3-4% reduction in AM and PM Peak Period VHT for Eastbound I-80, with a 2-9% reduction in Westbound VHT for the Peak Periods. Overall, the I-80 study corridor showed about a 4-5% reduction in VHT (combined for Eastbound and Westbound direction of travel, and the AM and PM peak periods). In District 3, the Northbound SR-99 study corridor showed about an 8% decline in VHT during the AM peak period.

The VHD-35 reduction levels are less consistent than the VHT reductions. This is mainly due to the choice of the 35-mph speed threshold for estimating the VHD-35 performance metric and the non-linear relationship between traffic volumes (or VMT) and delays (i.e., VHD-35). In a few instances, small VHD-35 values resulted in large relative changes (i.e., % changes) in the reported VHD-35 performance measure. The reported relative VHD-35 reductions (% changes) shown in the bottom portion of Tables 4.5, 4.6 and 4.7 should be used with caution and not taken out of context.

The corridor travel time savings were consistent with the observed VHT reductions, with travel time savings being in the 3-9% range for the study corridors' peak direction of travel. The reductions in corridor travel time reliability (as measured by PTI and TTI) were in the 18-28% for the PTI and in the 2-15% range for the TTI. On-ramp volumes were not estimated and compared, because in these analyses the corridor's "before' VMT and "after" VMT (or corridor level volumes) were balanced.

For the I-80 study corridor in District 4 and the northbound SR-99 corridor in District 3, the corridors performance was monitored and compared for the "before" and "after" CRM implementation periods. However, it would be difficult if not impossible to draw a conclusion that one strategy outperformed the other based on these observed performance measures for a few key reasons. First, the I-80 corridor was operating with no metering during the "before" period and operating a CRM Fuzzy logic strategy during the "after" period. While the SR-99 corridor was operating a local adaptive ramp metering during the "before" period and a CRM strategy that was developed by UC Berkeley PATH during the "after" period.

Furthermore, we must remember the old statistical adage that "correlation does not imply causation". Just because the corridors' performance improved between the "before" and "after" periods does not necessitate that 100% of these observed improvements can be directly attributed to the upgraded ramp metering strategies. The I-80 CRM implementation was one component of a much larger I-80 ICM implantation, which included other strategies (like changeable message signs and variable speed control) which may have affected driver behavior and the corridor's performance.

Finally, other factors that could not be measured and accounted for may have been partially responsible. For example, changes in origin-destination patterns (e.g., more long trips and less short trips on a freeway corridor), or reduced weaving and merging activities could have been partially responsible. Likewise, vehicle intelligence is increasing over time, with in-vehicle navigational support, driver warning, and driver assist features; these advanced in-vehicle capabilities could be influencing and changing driver behavior and/or collision rates.

Table 4.5 District 4 Eastbound I-80 Average Weekday Freeway Performance (Balanced VMT)

Corridor Performance Measure	(d) Before Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	347,839	**626,338**	1,115,041
VHT (vehicle-hours)	5,481	**19,395**	24,096
VHD-35 (vehicle-hours)	7	**5,625**	3,844
Travel Time (minutes)	17.64	**35.12**	18.33
PTI (no units)	1.20	**3.34**	1.83
TTI (no units)	1.09	**2.13**	1.35

Corridor Performance Measure	(e) With Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	347,796	**626,092**	1,114,721
VHT (vehicle-hours)	5,303	**18,700**	21,878
VHD-35 (vehicle-hours)	0*	**5,205**	2,608
Travel Time (minutes)	17.03	**32.52**	16.99
PTI (no units)	1.12	**2.68**	1.72
TTI (no units)	1.05	**1.99**	1.38

* Estimated value: 0.401 vehicle-hours – rounds down to “0”.

Corridor Performance Measure	(f) Change – Before Vs. After (percent)		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	-0.01%	**-0.04%**	-0.03%
VHT (vehicle-hours)	-3.25%	**-3.59%**	-9.21%
VHD-35 (vehicle-hours)	-99.05%	**-7.47%**	-32.14%
Travel Time (minutes)	-3.46%	**-7.41%**	-7.30%
PTI (no units)	-7.15%	**-19.67%**	-5.93%
TTI (no units)	-3.8%	**-6.37%**	+2.04%

Table 4.6 District 4 Westbound I-80 Average Weekday Freeway Performance (Balanced VMT)

Corridor Performance Measure	(d) Before Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**587,687**	537,925	1,320,002
VHT (vehicle-hours)	**16,881**	11,165	27,928
VHD-35 (vehicle-hours)	**4,252**	1,602	4,256
Travel Time (minutes)	**32.94**	22.39	19.98
PTI (no units)	**2.76**	1.75	1.82
TTI (no units)	**1.94**	1.31	1.40

Corridor Performance Measure	(e) With Updated Ramp Metering Strategy		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**587,842**	538,035	1,319,168
VHT (vehicle-hours)	**16,577**	10,209	26,836
VHD-35 (vehicle-hours)	**4,040**	963	3,904
Travel Time (minutes)	**31.87**	19.86	19.06
PTI (no units)	**2.25**	1.58	1.68
TTI (no units)	**1.89**	1.19	1.35

Corridor Performance Measure	(f) Change – Before Vs. After (percent)		
	AM PP 5:00-11:00 am	PM PP 1:00-8:00 pm	Daily
VMT (vehicle-miles)	**0.03%**	0.02%	-0.06%
VHT (vehicle-hours)	**-1.80%**	-8.57%	-3.91%
VHD-35 (vehicle-hours)	**-4.97%**	-39.87%	-8.28%
Travel Time (minutes)	**-3.27%**	-11.30%	-4.59%
PTI (no units)	**-18.31%**	-9.68%	-8.14%
TTI (no units)	**-2.16%**	-8.78%	-4.23%

Table 4.7 District 3 Northbound SR-99 Average Weekday Freeway Performance (Balanced VMT)

Corridor Performance Measure	(d) Before Updated Ramp Metering Strategy	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**186,018**	1,038,097
VHT (vehicle-hours)	**5,391**	19,463
VHD-35 (vehicle-hours)	**1,284**	1,466
Travel Time (minutes)	**24.15**	15.24
PTI (no units)	**2.82**	1.49
TTI (no units)	**1.97**	1.25

Corridor Performance Measure	(e) With Updated Ramp Metering Strategy	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**185,568**	1,038,489
VHT (vehicle-hours)	**4,942**	18,375
VHD-35 (vehicle-hours)	**1,123**	965
Travel Time (minutes)	**22.09**	14.25
PTI (no units)	**2.03**	1.33
TTI (no units)	**1.68**	1.16

Corridor Performance Measure	(f) Change – Before Vs. After (percent)	
	AM PP 6:00-9:00 am	Daily
VMT (vehicle-miles)	**-0.24%**	0.04%
VHT (vehicle-hours)	**-8.32%**	-5.59%
VHD-35 (vehicle-hours)	**-12.54%**	-34.18%
Travel Time (minutes)	**-8.51%**	-6.50%
PTI (no units)	**-27.96%**	-10.92%
TTI (no units)	**-14.72%**	-6.80%

CHAPTER 5
FINDINGS, LESSONS LEARNED, AND RECOMMONDATIONS

This chapter summarizes the findings of the operational performance evaluation of the selected corridors, sessions learned and recommendations. Several noteworthy lessons have been learned from the SR-99 and I-80 ICM evaluation, and other recent freeway corridor evaluations. Most of these became clear during interviews or discussions with Caltrans managers and engineers, algorithm developers and academic researchers.

Findings

The evaluation of the implementation of CRM on the selected corridors was based on "before" and "after" days where the average VMT was balanced. The results showed a 3-4% reduction in AM and PM Peak Period VHT for Eastbound I-80, with a 2-9% reduction in Westbound VHT for the peak periods. Overall, the I-80 study corridor showed about a 4-5% reduction in VHT. In District 3, the Northbound SR-99 study corridor showed about an 8% decline in VHT during the AM peak period. The reductions in corridor travel time reliability were 18-28% for the PTI and in the 2-15% range for the TTI.

Both CRM strategies improved the corridor traffic performance and can be implemented in the existing Caltrans traffic management centers. However, it is difficult to determine which strategy outperformed the other based on these observed performance measures, because of the differences in operating characteristics in each corridor. The I-80 corridor was operating with no metering in the "before" period and operating a CRM Fuzzy logic strategy during the "after" period. Furthermore CRM implementation was a component of a larger I-80 ICM implantation, which included other strategies (changeable message signs and variable speed control). The SR-99 corridor was operating a local adaptive ramp metering in the "before" period and a CRM strategy developed by UC Berkeley PATH in the "after" period.

Advancing a small number of CRM strategies might work better than a "one size fits all" approach

Midway through this evaluation, we came to the realization that the "one size fits all" mentality might not lead us to the best recommendations for statewide ramp metering policy. Rather, the optimal CRM strategy might depend on the corridor's characteristics, the levels of congestion, and the existing ITS hardware already installed and operating on that corridor.

Before selecting a ramp metering strategy for a freeway corridor, the corridor's characteristics should be taken into account. For example, ramp metering may not produce the expected benefits during heavily congested period. When the vehicle detectors near the upstream end of the on-ramp (sometimes called queue detectors) register high vehicle occupancy rates, then the Caltrans ramp metering strategies are generally set to the maximum rates to keep the queues on the freeway's on-ramps from extending onto and blocking traffic on adjacent arterial streets. There are no gains in freeway performance from any of the advanced CRM strategies during these times when the on-ramp metering rates are controlled by the on-ramp queue detectors instead of being controlled by the freeway's performance. Benefits can still be realized at the fringes of the peaks and/or during off-peak times (when traffic queues can be contained on the freeway's on-ramps).

Along this same line, metering freeway-to-freeway connectors is tricky; managing queues and causing delays on freeway-to-freeway connectors is not a simple feat. Not metering or controlling traffic on and upstream of major freeway-to-freeway connectors can likewise limit the effectiveness of CRM strategies on selected freeway corridors. In other situations, bottlenecks on the freeway system that are upstream of a selected freeway study corridor can meter or restrict traffic flows and render ramp metering strategies ineffective; and bottlenecks downstream of the selected freeway corridor can significantly reduce CRM benefits performance if measured over the larger freeway system. These factors not only impact CRM benefits, they impact the ability to produce credible results in a CRM Before/After evaluation, or at least they complicate the CRM performance evaluation process and increase costs of performing credible CRM performance evaluations.

One lesson learned from conducting the empirical Before/After evaluation of the District 4 I-80 and District 3 SR-99 corridors was this – It is not plausible to determine which CRM strategy would produce the most overall or statewide benefit from simply comparing the CRM results from one corridor with a CRM strategy to one corridor with a Fuzzy logic CRM implementation. A one corridor sample used to estimate the gains is way too small of a sample for developing detailed conclusions and recommendations for statewide implementation.

Along this same line of thought, the viability of the comparison is decreased as differences between the two corridors increase. For example, different levels of congestion on the two corridors along with the nonlinear nature of the volume-delay relations can confound direct comparisons. Likewise, different "Before" ramp metering conditions (no ramp metering on one corridor and local ramp metering on the other) can bias direct comparisons of the resulting benefits. If a CRM strategy is highly effective on a freeway corridor, one could expect similar results on other corridors with similar geometric characteristics and similar levels of congestion. To conduct a fair and meaningful empirical Before/After style evaluation, one would basically need to install CRM strategy A on a corridor, then install strategy B on the same corridor, and have in place the ability to monitor the freeway's performance during the evaluation periods. Even then, other factors could complicate or at least partially negate the validity of the comparison. Adverse weather events (an unusually wet rainy season), changes/growth and/or seasonal traffic trends, or upstream or downstream freeway enhancements could come into play and impact the resulting freeway's performance. And, even if a very careful Before/After CRM performance evaluation like this were conducted on a California freeway corridor, there is little evidence to suggest that the outcome would be the same on other freeway corridors. In the same vain, the results from a very detailed simulation model used to evaluate the performance of competing CRM strategies for a pre-selected freeway corridor would not necessarily be transferable to other freeway corridors.

The good news is that there is sufficient evidence to generally conclude that well-designed CRM strategies improve mainline freeway performance. Which one works best? We believe (but cannot prove) that the one that performs best might vary from corridor to corridor. It's even possible that the best performing CRM strategy under moderate congestion might not outperform competing CRM strategies under heavier levels of traffic congestion (on the same corridor).

Developing a structured, well-defined process for selecting CRM strategies

Currently Caltrans does not have a structured, well-defined process for choosing or matching CRM strategies to freeway corridors. We recommend that Caltrans develop guidelines for the CRM selection process. These guidelines should include checklists or decision support flowcharts (decision process support), highlight potential implementation issues, and provide resources for technical support. These guidelines should also be kept current and informed by future lessons learned as academic white papers, experiences from FHWA other state DOTs become available, and as Caltrans gain additional experience with CRM deployments.

Furthermore, we recommend that Caltrans select two, at most three, CRM strategies to be included in the CRM selection guidelines. Both the CRM Fuzzy logic strategy deployed on the I-80 ICM corridor, and the CMR strategy used on the SR-99 corridor warrant consideration in the decision processes for future CRM deployment.

The CRM Fuzzy logic strategy works with Caltrans architecture, is easy to understand, easy to implement (on modified Intelight firmware), and can ingest 30 second data, and is scalable. The CRM Fuzzy logic is based on open source software, which is a benefit. However, it might be more of a challenge to integrate into the Caltrans system and technical support might be an issue. Additionally, Caltrans should consider whether it has the skillset to maintain and/or update the CRM Fuzzy logic software as needed or how these issues would be handled.

The District 3 CRM system installed on the SR-99 corridor has undergone minor adjustments since its initial implementation. There is an ongoing project which intends to develop a GUI (Graphical User Interface) which will make the implementation more convenient for trained Caltrans engineers. All of the complexity of the underlying code and algorithms (not necessary for implementation and system maintenance) will be behind the scenes – not visible to the users in the GUI. From the data acquisition/control side of the system, CRM implementations is straight forward. The user only needs to input or adjust the freeway corridor configuration parameters, the CRM and the GUI will be adapted to the road geometry etc. For the SR-99 CRM implementation, it was helpful that Caltrans already had a functional intranet system, this enabled the University researchers to directly communicate with all the controllers.

From discussions with District 4 management, we recommend that a feasibility study be conducted, looking into whether the Alinea-HERO strategy might be a good CRM candidate for Caltrans. Currently, Caltrans has only limited experience with the Alinea-HERO system. According to District 4 management, the Caltrans firmware will not support the Alinea-HERO software; with that, the Alinea-HERO firmware would be required. One benefit of the Alinea-HERO system is that it can balance queues across the corridor, while the CRM Fuzzy logic system cannot. Additionally, the Alinea-HERO system [7] has better look ahead capabilities and more equitable distribution of queues upstream of bottlenecks than the CRM Fuzzy logic system. HERO is a proprietary and consultant owned, so technical support is available; however, consultant provided products and services come with a cost while the CRM Fuzzy logic is basically a no-cost option.

Monitoring CRM performance gains and empirical Before/After evaluations

Next, we recommend that the CRM selection guidelines also include guidelines for evaluating and monitoring the performance of the CRM strategy selected – for conducting the Before/After performance evaluation and documenting lessons learned. During a phone discussion with David Man (District 4 Chief Office of Electrical Systems), we learned that over time the benefits of the I-80 CRM improved in the off-peak direction as Caltrans adjusted parameters and learned more about how the system responded. CRM monitoring plans could help assure that CRM gains and lessons learned like these are documented and made available for decision making at Headquarters and/or other Caltrans Districts. Between now and the time when a sufficient number of Before/After performance evaluations have been completed to clearly document trends in CRM gains, maybe the results from the empirical Before/After evaluations simply be used to document the performance gains and justify the continued investments in CRM implementation.

Additional lessons learned deal with data sources and the role of big-data in these CRM performance evaluations. Caltrans PeMS and other big-data sources (like INRIX, HERE, or StreetLight Data) cannot provide all the information required for a comprehensive Before/After performance evaluation. Some field data collection may be necessary depending on the performance measures chosen for the evaluation. A few of the potential data needs that may not well served by today's big-data providers are:

- Freeway on-ramp queue monitoring (measuring on-ramp queue lengths)
- Monitoring freeway speeds or corridor travel-times for managed lanes
- Monitoring average vehicle occupancies
- Collecting vehicle classification counts

Monitoring freeway performance on a lane-by-lane basis may not be necessary for an empirical evaluation of CRM performance. Likewise, for vehicle occupancy and/or vehicle classification data. However, it is difficult (at best) to determine the overall time savings of CRM strategies without a reliable method of quantifying the delays at the on-ramps. Freeway on-ramp queue monitoring (measuring on-ramp queue lengths) is a critical data need for evaluating overall benefits of CRM strategies; otherwise how does one know if the mainline delays are completely or only partially offset by the on-ramp (metering) delays.

We recommend that Caltrans develop a standardized set of performance measures, recommended data sources, and timeline for data collection, and that these be determined well in advance of the CRM implementation schedule. If collecting local or manual data are part of the data collection plan, then these tasks need to be finished (with the collected data reviewed for reliability and accuracy) in advance of any implementation changes to the corridor for the Before half of a Before/After evaluation.

Other factors that could plausibly impact findings of Before/After freeway performance evaluations are the consistency or accuracy of the underlying data used for the freeway corridor performance evaluation. Caltrans PeMS data are regularly used for urban freeway performance evaluations. Regularly occurring events like detector maintenance (e.g., new loops, or loop replacement), controller hardware or firmware replacement/ updates, PeMS software (algorithm) updates could result in changes in the PeMS reported traffic volumes and/or speeds and the resulting freeway performance measures in freeway performance measures. During a previous freeway corridor performance evaluation, Caltrans uncovered inconsistencies in PeMS reported mainline freeway VMT that needed to be adjusted to produce credible performance measures. Similarly, Oregon DOT recently uncovered inconsistencies in INRIX Analytics reported freeway mainline speeds when comparing annual average weekday congestion trends for Portland area freeways. Further inquiries showed that these inconsistencies at least in part resulted from large influxes of connected vehicle data being added to the INRIX probe data which altered the proportion of trucks in the INRIX (sampled) vehicle sets. Generally, factors like these are not within Caltrans control and hopefully these biases would be relatively small. However, for a Before/After freeway performance to be credible and produce reliable results, they must be considered and accounted for.

Closing Remarks

Overall, we found sufficient evidence that CRM implementations deliver sufficient gains to warrant continued study and deployment by Caltrans. Currently, there is not enough information to make a global recommendation for any single CRM strategy above the other competing strategies. Further, the CRM technologies, their underlying algorithms, and the state-of-the-art practices are constantly under development and continuously evolving, as are other relevant technologies such as artificial intelligence software and general computing capabilities. What works best today might not retain this title in years to come.

Finding freeway corridors with CRM implementations that were suitable for an empirical Before/After performance evaluation proved quite challenging. Even with that, this work did show that mainline freeway performance improved with the implementation of the tested CRM strategies. However, we could not definitively attribute 100% of these gains to CRM implantation.

There is substantial work yet to be done, developing statewide guidelines for selecting the most suitable CRM strategy for candidate freeway corridors and the associated CRM implementation plans. We commend Caltrans for their insights and efforts in advancing the concepts and practices of data driven decision processes.

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APPENDIX A. CELL TRANSMISION MODEL

The freeway is divided into N segments (cells). Each segment i has at most one on-ramp and one off-ramp. The following variables are defined for each segment i at each time step k:

$\rho_i(k)$: Mainline density of segment i at time step k (veh/segment)

ρ_i^J: Jam density of segment i (veh/segment)

$f_i(k)$: Mainline flow of vehicles leaving the upstream segment i, moving to the downstream segment $i+1$, at time step k (veh/time step)

$\bar{f}_i(k)$: Measured mainline flow (veh/time step)

F_i: Mainline capacity of segment i (veh/time step)

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

w_i^J: Jam density of the on-ramp corresponding to segment i (veh/segment)

$r_i(k)$: Metering rate; number of vehicles entering segment i through its corresponding on-ramp at time step k, determined by the controller (veh/time step)

r_i^m: Minimum allowable metering rate for the on-ramp i (veh/period)

r_i^o: Maximum allowable metering rate for the on-ramp i (veh/period)

$d_i(k)$: Estimated/measured demand at the on-ramp corresponding to segment i at time step k (veh/time step)

$s_i(k)$: Flow at the off-ramp corresponding to segment i at time step k (veh/time step)

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

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

T: Time step

λ_i: Number of lanes in segment i (dimensionless)

L_i: Length of mainline segment i

L_i^o: Queue storage capacity of on-ramp i (number of vehicles)

The model calculates the mainline density $\rho_i(k)$ over time based on the conservation of vehicles. The density at the next time step is equal to the current density $\rho_i(k)$ plus the additional density because of the vehicles arriving on the freeway and on-ramp, minus the vehicles departing on the freeway mainline and the off-ramp.

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

Because density is related to space mean speed $u_i(k)$, the traffic flow of each time step can be expressed as:

$$f_i(k) = \lambda_i \rho_i(k) u_i(k) \tag{2}$$

Where space mean speed $u_i(k)$ is given, because the selected corridor is equipped with dual loop detectors that can accurately measure vehicle speed.

Substituting equation 2 into equation 1 gives a linearized equation:

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

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

$$w_i(k+1) = w_i(k) + T\big(d_i(k) - r_i(k)\big) \tag{4}$$

Suppose 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:

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

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

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

APPENDIX B. LOOP DETECTORS ON THE SELECTED CORRIDORS

Table 1.1 Ramp Detectors at SR-99 Corridor

On-ramp	**Detector ID***	**Detector Data Status**
1. Eastbound Grant Line Rd.	VDS 317144	Available
2. Westbound Grant Line Rd.	VDS 317142	Available
3. East Stockton Blvd.	VDS 319482	Available
4. Elk Grove Blvd.	VDS 314107	Available
5. Eastbound Laguna Blvd.	VDS 314114	Available
6. Westbound Laguna Blvd.	VDS 314098	Available
7. Eastbound Sheldon Rd.	VDS 317959	Available
8. Westbound Sheldon Rd.	VDS 317949	Available
9. Eastbound Calvine Rd.	VDS 312649	Available
10. Westbound Calvine Rd.	VDS 312652	Available
11. Eastbound Mack Rd.	VDS 312383	Available
12. Westbound Mack Rd.	VDS 312387	Available
13. Eastbound Florin Rd.	VDS 312423	Available
14. Westbound Florin Rd.	VDS 312426	Available
15. Eastbound 47th Ave.	VDS 312515	Available
16. Westbound 47th Ave.	VDS 312521	Available
17. Eastbound Fruitridge Rd.	VDS 312526	Available
18. Westbound Fruitridge Rd.	VDS 312528	Available
19. 12th Ave.	VDS 312563	Available
Off-ramp		
1. Grant Line Rd.	VDS 317145	Available
2. East Stockton Blvd.	VDS 319483	Available
3. Laguna Blvd.	VDS 314115	Available
4. Sheldon Rd.	VDS 317961	Available
5. Calvine Rd.	VDS 312650	Available
6. Stockton Blvd.	VDS 314615	Available
7. Eastbound Florin Rd.	VDS 312424	Available
8. Westbound Florin Rd.	Unavailable	Unavailable
9. Eastbound 47th Ave.	Unavailable	Unavailable
10. Westbound 47th Ave.	Unavailable	Unavailable
11. Martin Luther King Dr.	VDS 312524	Unavailable
12. Westbound Fruitridge Rd.	VDS 312529	Available
13. 12th Ave.	Unavailable	Unavailable
14. US-50	VDS 318577	Unavailable

Table B.2 Ramp Detectors--I-80 Eastbound Corridor

On-ramp	Detector ID*	Detector Data Status
1. Powell St.	VDS 407259	Available
2. Ashby Ave.	VDS 408783	Available
3. University Ave.	VDS 407265	Available
4. Gilman St.	VDS 408466	Available
5. Buchanan St.	VDS 408467	Available
6. Central Ave.	VDS 407260	Available
7. Carlson Blvd.	VDS 407246	Available
8. Cutting Blvd. (loop)	VDS 400182	Available
9. Cutting Blvd. (diagonal)	VDS 407862	Available
10. San Pablo Ave.	VDS 407247	Available
11. San Pablo Dam Rd.	VDS 407251	Available
12. El Portal Dr.	VDS 407274	Available
13. Hilltop Dr. (loop)	VDS 411102	Available
14. Hilltop Dr. (diagonal)	VDS 404392	Available
15. Richmond Pkwy. (loop)	VDS 407254	Available
16. Richmond Pkwy	VDS 407255	Available
17. Appian Way	VDS 407262	Available
18. Pinole Valley Rd.	VDS 407268	Available
19. SR-4	VDS 403273	Available
20. Willow Ave.	VDS 404402	Available
21. Cummings Skyway	VDS 403278	Available
Off-ramp		
1. Ashby Ave.	VDS 407857	Available
2. University Ave.	VDS 407257	Unavailable
3. Gilman St.	VDS 408633	Unavailable
4. Buchanan St.	VDS 407244	Unavailable
5. Central Ave.	VDS 409569	Unavailable
6. Carlson Blvd.	VDS 407245	Available
7. Potrero Ave.	VDS 407271	Available
8. San Pablo Ave.	VDS 407270	Unavailable
9. San Pablo Dam Rd.	VDS 407242	Unavailable
10. Solano Ave.	VDS 408013	Available
11. El Portal Dr.	VDS 416970	Unavailable
12. Hilltop Dr.	VDS 407275	Available
13. Richmond Pkwy.	VDS 407253	Available
14. Appian Way	VDS 407263	Unavailable
15. Pinole Valley Rd.	VDS 407261	Available
16. Willow Ave.	VDS 404403	Available
17. Cummings Skyway	VDS 403305	Available
18. Pomona St.	VDS 407243	Available

**PeMS system*

Table B.3 Ramp Detectors--I-80 Westbound Corridor

On-ramp	Detector ID*	Detector Data Status
1. Powell St.	VDS 406658	Available
2. Ashby Ave.	VDS 406657	Available
3. University Ave.	VDS 406659	Available
4. Gilman St.	VDS 407291	Available
5. Buchanan St.	VDS 408339	Available
6. Central Ave.	VDS 409582	Available
7. Carlson Blvd.	VDS 407282	Available
8. Potrero Ave.	VDS 407307	Available
9. Barrett Ave.	VDS 407306	Available
10. Solano Ave.	VDS 407279	Available
11. San Pablo Dam Rd.	VDS 407250	Available
12. El Portal Dr.	VDS 409785	Available
13. Hilltop Dr. (loop)	VDS 407310	Available
14. Hilltop Dr. (diagonal)	VDS 411126	Available
15. Richmond Pkwy.	VDS 407288	Available
16. Appian Way	VDS 407298	Available
17. Pinole Valley Rd.	VDS 407295	Available
18. SR-4	VDS 407749	Available
19. Willow Ave.	VDS 407293	Available
20. Cummings Skyway	VDS 403306	Available
21. Pomona St.	VDS 407280	Available
Off-ramp		
1. Powell St.	VDS 407290	Available
2. Ashby Ave.	VDS 407874	Unavailable
3. University Ave.	VDS 407281	Unavailable
4. Cleveland Ave.	VDS 407278	Unavailable
5. Central Ave.	VDS 407294	Unavailable
6. Carlson Blvd.	VDS 407283	Available
7. Cutting Blvd.	VDS 407881	Available
8. San Pablo Ave.	VDS 407284	Unavailable
9. McBryde Ave.	VDS 408019	Unavailable
10. San Pablo Dam Rd.	VDS 407285	Available
11. El Portal Dr.	VDS 407308	Unavailable
12. Hilltop Dr.	VDS 404405	Available
13. Richmond Pkwy.	VDS 407287	Available
14. Appian Way	VDS 407296	Unavailable
15. Pinole Valley Rd.	VDS 407305	Available
16. SR-4	VDS 403272	Available
17. Cummings Skyway	VDS 403277	Available

**PeMS system*

APPENDIX C. DISTRICT 7 CRM SYSTEMS

C.1 I-110 Corridor

The Dynamic Corridor Ramp Metering System (DCRMS) in District 7 is implemented along a section of I-110 extending from the State Route-47 (SR-47) interchange to Interstate-405 (I-405) near Los Angeles and includes 28 ramp meters (Figure C.1) for a total length of 14.543 miles. As indicated by the arrows in Figure 2.9, there are 13 interchanges with local arterial streets and 4 interchanges with freeways (SR-47, I-405, SR-91, and I-105). The arterial interchanges consist of diamond interchanges and partial cloverleaf interchanges while the freeway interchanges consist of partially cloverleaf and partially stacked interchanges.

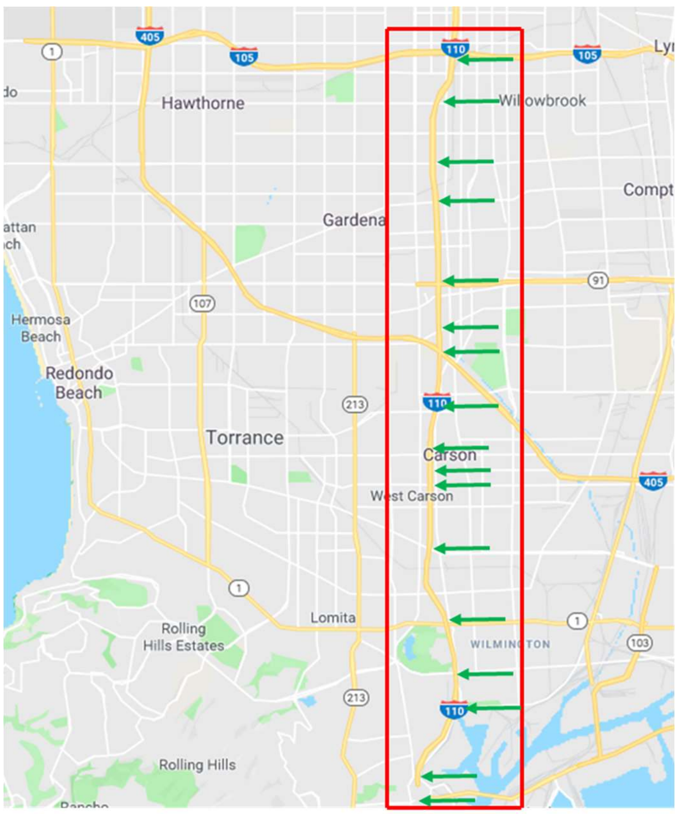
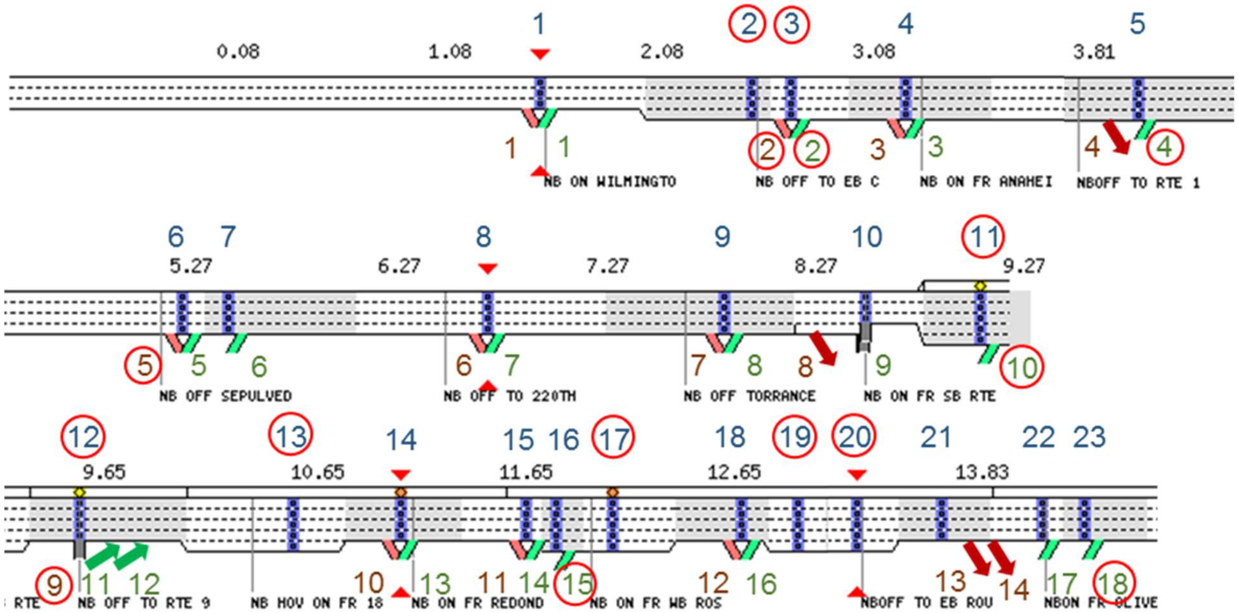


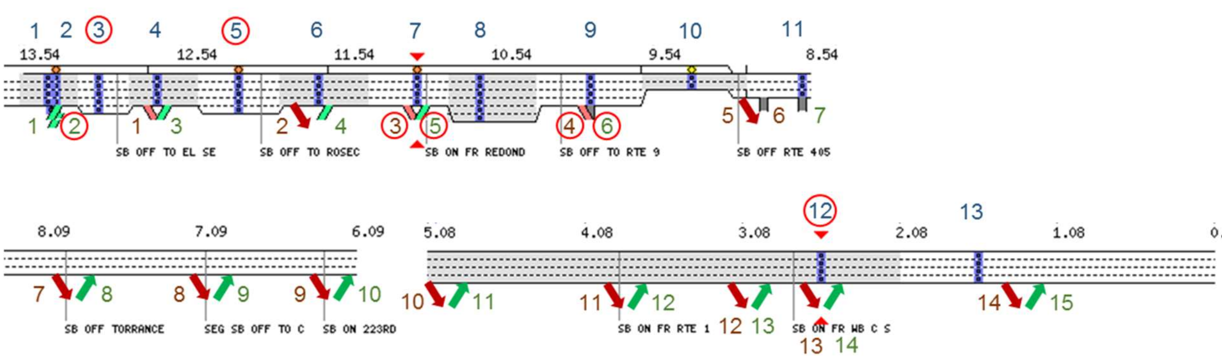
Figure C.1 I-110 Freeway Corridor

Figure C.2 shows detailed lane configurations for both traffic directions of the corridor. In the northbound direction, there are four general purpose lanes (the first two miles are misrepresented in PeMS as a segment with only three lanes). A high occupancy vehicle (HOV) lane is added to the freeway for the portion downstream of the I-405 interchange. In the southbound direction, there are four general purpose lanes and one HOV lane upstream of the I-405 interchange and only four general purpose lanes downstream of the I-405 interchange (the portion shown with only three general purpose lanes is misrepresented in PeMS as a segment with only three lanes).

Figure C.2 also shows the detector coverage. There is a wide coverage of detectors throughout the northbound direction corridor. There are 23 mainline detectors and 4 HOV lane detectors, as indicated by the blue numerical labels. There are also detectors placed at the on-ramps and off-ramps, as indicated by the green numerical labels and red numerical labels for on-ramps and off-ramps, respectively. However, not all off-ramps are equipped with detectors; the green arrows indicate that the Eastbound SR-91 to I-110 and Westbound SR-91 to I-110 on-ramps do not have detectors, the red arrows indicate the Pacific Coast Highway (PCH), I-110 to I-405, I-110 to Eastbound I-105, and I-110 to Westbound I-105 off-ramps that do not have detectors. In addition, detectors with numerical labels circled in red are currently non-functional, as they cannot generate any data. Details regarding the on-ramp and off-ramp detectors (detector ID and data quality) are shown in Table C.1.



(a) Northbound I-110



(b) Southbound I-110

Figure C.2. I-110 Lane Configurations and Detector Locations

Table C.1 Ramp Detectors _I-110

On-ramp	Detector ID*	Detector Data Status
1. John S. Gibson Blvd.	VDS 716473	Available
2. Harry S. Bridges	VDS 716474	Unavailable
3. Anaheim St.	VDS 716475	Available
4. Pacific Coast Highway (PCH)	VDS 716476	Unavailable
5. Eastbound Sepulveda Blvd.	VDS 716477	Available
6. Westbound Sepulveda Blvd.	VDS 718467	Available
7. 220th St.	VDS 716478	Available
8. Torrance Blvd.	VDS 716479	Available
9. I-405 to I-110	VDS 766338	Available
10. 190th St.	VDS 716480	Unavailable
11. Eastbound SR-91 to I-110	Unavailable	Unavailable
12. Westbound SR-91 to I-110	Unavailable	Unavailable
13. Redondo Beach Blvd.	VDS 716486	Available
14. Eastbound Rosecrans Ave.	VDS 775827	Available
15. Westbound Rosecrans Ave.	VDS 716489	Unavailable
16. El Segundo Blvd.	VDS 716493	Available
17. Imperial Hwy.	VDS 716496	Available
18. I-105 to I-110	VDS 766281	Unavailable
Off-ramp		
1. John S. Gibson Blvd.	VDS 763836	Available
2. Harry S. Bridges	VDS 763838	Unavailable
3. Anaheim St.	VDS 763842	Available
4. Pacific Coast Highway (PCH)	Unavailable	Unavailable
5. Sepulveda Blvd.	VDS 763845	Unavailable
6. 220th St.	VDS 763847	Available
7. Torrance Blvd.	VDS 763849	Available
8. I-110 to I-405	Unavailable	Unavailable
9. I-110 to SR-91	VDS 716482	Unavailable
10. Redondo Beach Blvd.	VDS 763886	Available
11. Rosecrans Ave.	VDS 775826	Available
12. El Segundo Blvd.	VDS 763793	Available
13. I-110 to Eastbound I-105	Unavailable	Unavailable
14. I-110 to Westbound I-105	Unavailable	Unavailable

**PeMS system*

C.2 Ramp Metering

The on-ramp metering system initially adopted System-wide Adaptive Ramp Metering (SWARM) and began switching to coordinated ramp metering after October 2017. The coordinated ramp metering algorithm is known as the Dynamic Corridor Ramp Metering (DCRM). The ramp metering algorithm is a variation of the fuzzy logic control that is enhanced to incorporate detector data from downstream freeway segments to coordinate with the adjacent downstream on-ramps, and upstream freeway incident detection and downstream parallel arterial incident detection to coordinate diversion with the parallel arterial Figueroa St. Currently, DCRM system is active 24 hours every day.

The algorithm is similar to the Caltrans District 4 Fuzzy logic, with two distinct extensions: 1) to account for diversion of freeway traffic to local arterials due to incidents, and 2) diversion of arterial traffic on to the freeway due to high demands on local arterials. The DCRMS system allows freeway ramp metering systems to coordinate operations with arterial traffic signal systems within the corridor. There are several input variables that require real-time data collection. Figure C.3 illustrates of the locations in which the data need to be collected. There are three mainline stations:

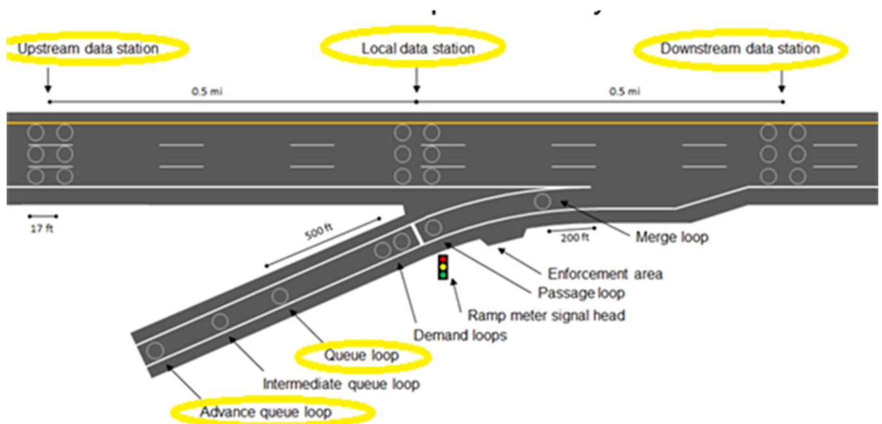


Figure C.3 Detector Locations for Input Variables (*7*)

- Local: station adjacent to the on-ramp merge.
- Upstream data station: upstream of the on-ramp merge, and data can be used in case the local data station is not functioning.
- Downstream: one or more stations downstream of the on-ramp merge. Usually, all stations up to 2 miles downstream of the current on-ramp, to account for downstream bottlenecks.

In addition, there are two on-ramp detectors:

- Queue detector: placed midway between the ramp metering stop bar and the on-ramp entrance.
- Advance queue detector: placed at the entrance of the on-ramp.

The generic DCRM controller also requires the following external system inputs for coordination of operations with the arterial signal system:

- Arterial signal system: provides a real-time measure of ramp demand based on local turning movement counts collected at the adjacent intersection.
- Event management system: based on the real-time incident information entered by the ATMS operator, provides the severity and location of upstream incidents on the freeway and downstream incidents on parallel arterials.

Similar to the fuzzy logic control described in Section 2.2, each numerical input is translated into a set of fuzzy classes, also known as linguistic variables. Details are shown in Table C.2 (*7*).

Table C.3 shows the rules and their corresponding weights of the DCRM control (*7*). The local rules provide the typical local responsive ramp metering algorithm. The downstream rules allows for coordination with the downstream metered on-ramps. The ramp rules are intended to prevent on-ramp queue spillback. The incident rules are intended to facilitate diversion; relaxing the metering rate downstream of a freeway incident can help diverted traffic return from the arterial to the freeway and relaxing the metering upstream of an arterial incident can help divert some arterial traffic to the freeway.

Similar to the fuzzy logic control, the metering rate is determined by the following equation:

$$Metering\ Rate = \frac{\sum_{i=1}^{N} w_i c_i I_i}{\sum_{i=1}^{N} w_i I_i}$$

Where:

w_i: importance of the ith rule,

c_i: centroid of the output class,

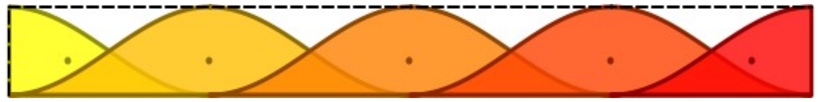
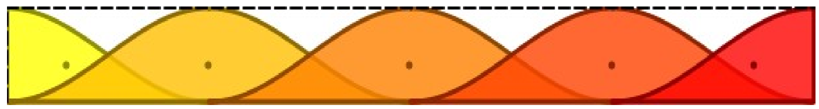
I_i: implicated area of the output class

The fuzzy class of the metering rates is shown in Table C.4.

2.3.2 Operating Conditions

The on-ramp merging sections located at the 220th St. and Torrance Blvd. interchanges, as well as the weaving section between the Redondo Beach Blvd. on-ramp and the Rosecrans Ave. off-ramp, contribute to the morning peak recurrent delay observed in this corridor. This morning peak period typically begins at 6:30 AM and ends around 9:30 AM, and the morning congestion pattern exhibits the typical peak period when there is high demand for suburb to downtown trips during the morning hours.

Table C.2 DCRM Input Variables and Fuzzy Classes (*5*).

Input	Range	Classes
Local Occupancy (%) from local or upstream mainline detector station	**11-25**	 **very Low, low, med, high, very High**
Local Speed (mph) from local mainline detector station	**35-55**	 **very Low, low, med, high, very High**
Downstream Occupancy (%) from downstream mainline detector station with the highest occupancy	**11-25**	 **high**
Downstream Speed (mph) from downstream mainline detector station with the highest occupancy	**40-55**	 **low**
Queue Occupancy (%) from queue detector	**18-40**	 **high**
Advance Queue Occupancy (%) from advance queue detector	**20-35**	 **high**
Ramp Demand (vph) (from arterial signal system)	**0-3200**	 **high**
Upstream Freeway Incident Severity (from event management system)	**0-10**	 **high**

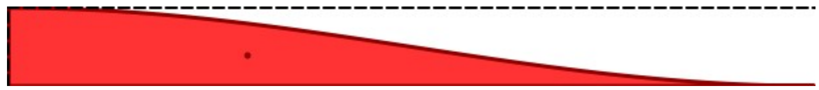
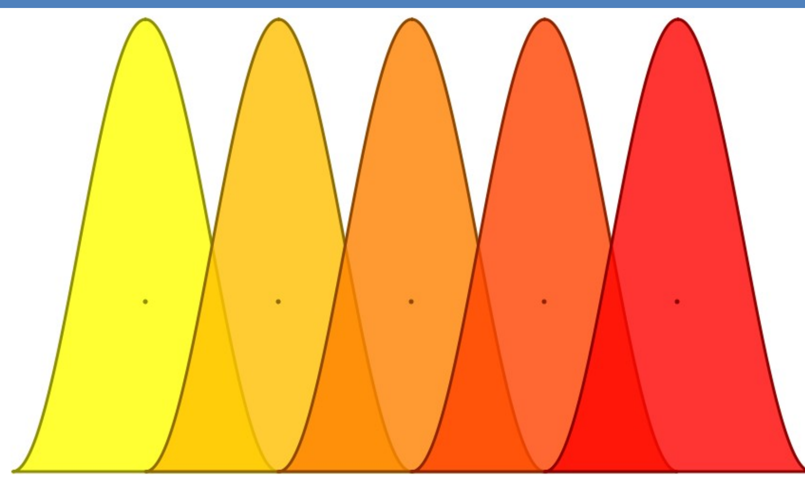
Input	Range	Classes
Upstream Freeway Incident Distance (tenth miles) (from event management system)	**0-20**	 **near**
Downstream Arterial Incident Severity (from event management system)	**0-10**	 **high**
Downstream Arterial Incident Distance (tenth miles) (from event management system)	**0-20**	 **near**

Table C.3 Rules for fuzzy ramp metering algorithm (*7*)

Rule Block	Activation	Rules
Local	Product	RULE 1: if local Occupancy is very High then metering Rate is very Low with 0.5 RULE 2: if local Occupancy is high then metering Rate is low with 0.2 RULE 3: if local Occupancy is med then metering Rate is med with 0.2 RULE 4: if local Occupancy is low then metering Rate is high with 0.2 RULE 5: if local Occupancy is very Low then metering Rate is very High with 0.2 RULE 6: if local Speed is very Low then metering Rate is very Low with 0.6 RULE 7: if local Speed is low then metering Rate is low with 0.2 RULE 8: if local Speed is med then metering Rate is med with 0.2 RULE 9: if local Speed is high then metering Rate is high with 0.2 RULE 10: if local Speed is very High then metering Rate is very High with 0.2
Downstream	Product	RULE 1: if downstream Speed is low and downstream Occupancy is high then metering Rate is very Low with 0.8
Ramp	Product	RULE 1: if queue Occupancy is high then metering Rate is very High with 0.4 RULE 2: if advance Queue Occupancy is high then metering Rate is very High with 0.8 RULE 3: if ramp Demand is high then metering Rate is very High with 1.0
Incident	Product	RULE 1: if upstream Freeway Incident Severity is high and upstream Freeway Incident Distance is near then metering Rate is very High with 1.0 RULE 2: if downstream Arterial Incident Severity is high and downstream Arterial Incident Distance is near then metering Rate is very High with 1.0

Table C.4 DCRM Fuzzy Class for Metering Rates (*7*).

Output	Range	Classes
Metering Rate (veh/min) ***(to the local ramp meter controller)***	***1.125 – 21.375***	 **veryLow, low, med, high, veryHigh**

A.2 System-wide Adaptive Ramp Metering (SWARM)

The SWARM system was first developed by the National Engineering Technology (NET) Corporation under a contract with Caltrans [6]. The algorithm was first implemented in District 12 (Orange County) and then on Interstate 210 in District 7 (Los Angeles and Ventura counties) in the late 1990s. In the SWARM algorithm, the freeway network is divided into contiguous freeway systems, whereby each freeway system is bounded by the location of two bottlenecks, which can be identified by loop detectors, and contains multiple on-ramps and off-ramps in between. There are two "competing" modes of SWARM operation, global and local modes. The local mode contains three sub-modes: headway, storage, and regional traffic responsive. Two metering rates are computed from the global and local modes, and the more restrictive metering rate is implemented in the field.

The global mode operates on an entire system based on forecast densities at the system's bottleneck location. The densities around the bottleneck are forecast by performing a linear regression on a set of data collected from the immediate past time periods and applying a Kalman filtering process to capture nonlinearity (*6*). A tunable parameter, T_{crit} is the forecasting time span into the future (shown in Figure 3.5), and this typically spans several minutes. The excess density (shown in Figure 3.5) is then the difference between the forecast density and the pre-determined threshold density that represents the saturation level at the bottleneck. This excess density is converted to the current required density to avoid congestion in T_{crit}. The required density is defined as:

$$Required\ density = current\ density - \left(\frac{excess\ density}{T_{crit}}\right)$$

The corresponding volume reduction at each detector is computed as:

$$Volume\ reduction = (local\ density - required\ density) * (number\ of\ lanes) * (distance\ to\ next\ detector)$$

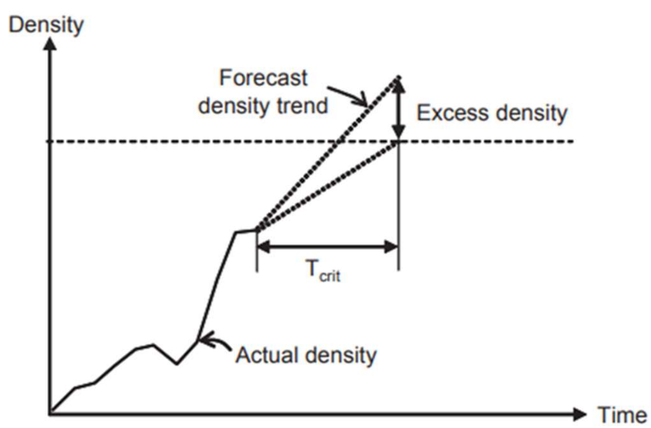


Figure 3.5 Forecasting Theory of SWARM Global Mode (*6*)

The volume reduction (or excess if local density is smaller than the required density) is distributed to upstream on-ramps in the system according to weighting factors predetermined based on demand, queue storage, and other relevant features of each on-ramp (*6*).

The local mode operates with respect to local traffic conditions near each ramp. The local metering system can implement an existing local responsive ramp metering algorithm (*6*). For this application, the local mode is divided into three sub-modes.

The headway sub-mode uses occupancy data collected from the loop detector located upstream of the on-ramp merging area (VDS_i shown in Figure 3.6), and predicts the density immediately downstream of the same on-ramp merging area (measured at VDS_{i+1} shown in Figure 3.6). The algorithm maintains the desired density by restricting the number of vehicles entering the freeway mainline from the on-ramp E_k.

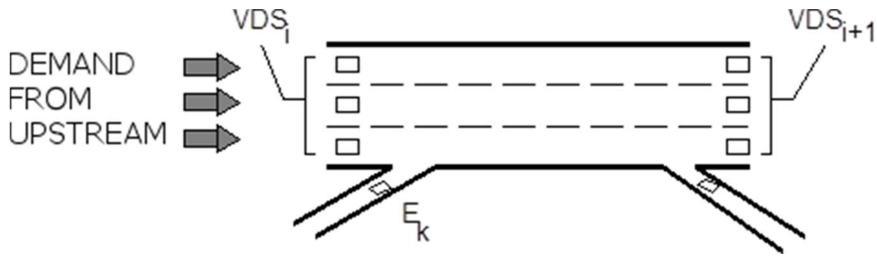


Figure 3.6 Detection Requirements for Headway Sub-Mode (*6*)

The storage sub-mode computes the maximum number of vehicles that can be stored between VDS_i and VDS_{i+1} (shown in Figure 3.7) before the freeway experiences any reduction in bottleneck capacity. The algorithm attempts to prevent the number of vehicles in segment L_z from exceeding the maximum allowable number of vehicles by limiting the number of vehicles entering the freeway mainline from the on-ramp E_k, after accounting for the number of vehicles leaving the freeway at off-ramp X_j.

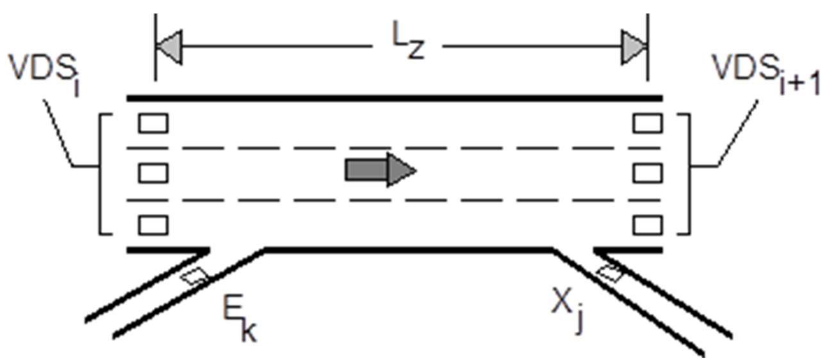
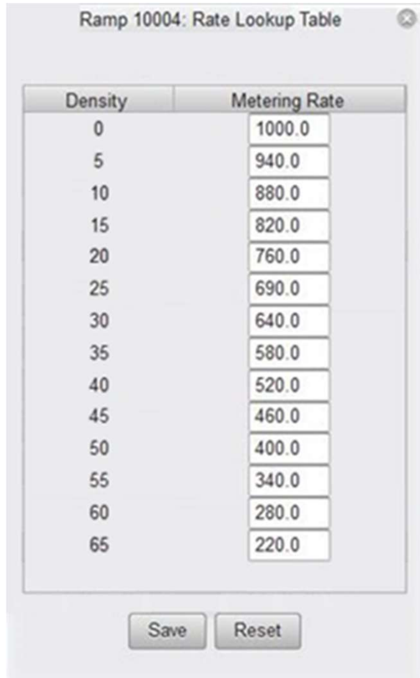


Figure 3.7 Detection Requirements for Headway Sub-Mode (*6*)

The regional traffic responsive sub-mode computes the ramp metering rate based on occupancies at the local and downstream mainline loop detectors. The densities derived from the occupancy data are then used to determine the ramp metering rate in the table shown in Figure 3.8.

SWARM has a built-in capability to clean the defective data in case of loop detector failures, which improves the robustness of the algorithm (*6*). With this feature and accurate prediction models. SWARM is able to accurately detect and avoid potential congestion in advance. However, if prediction models are poor or if supporting loop detector data are not accurate, it cannot generate the intended benefits.

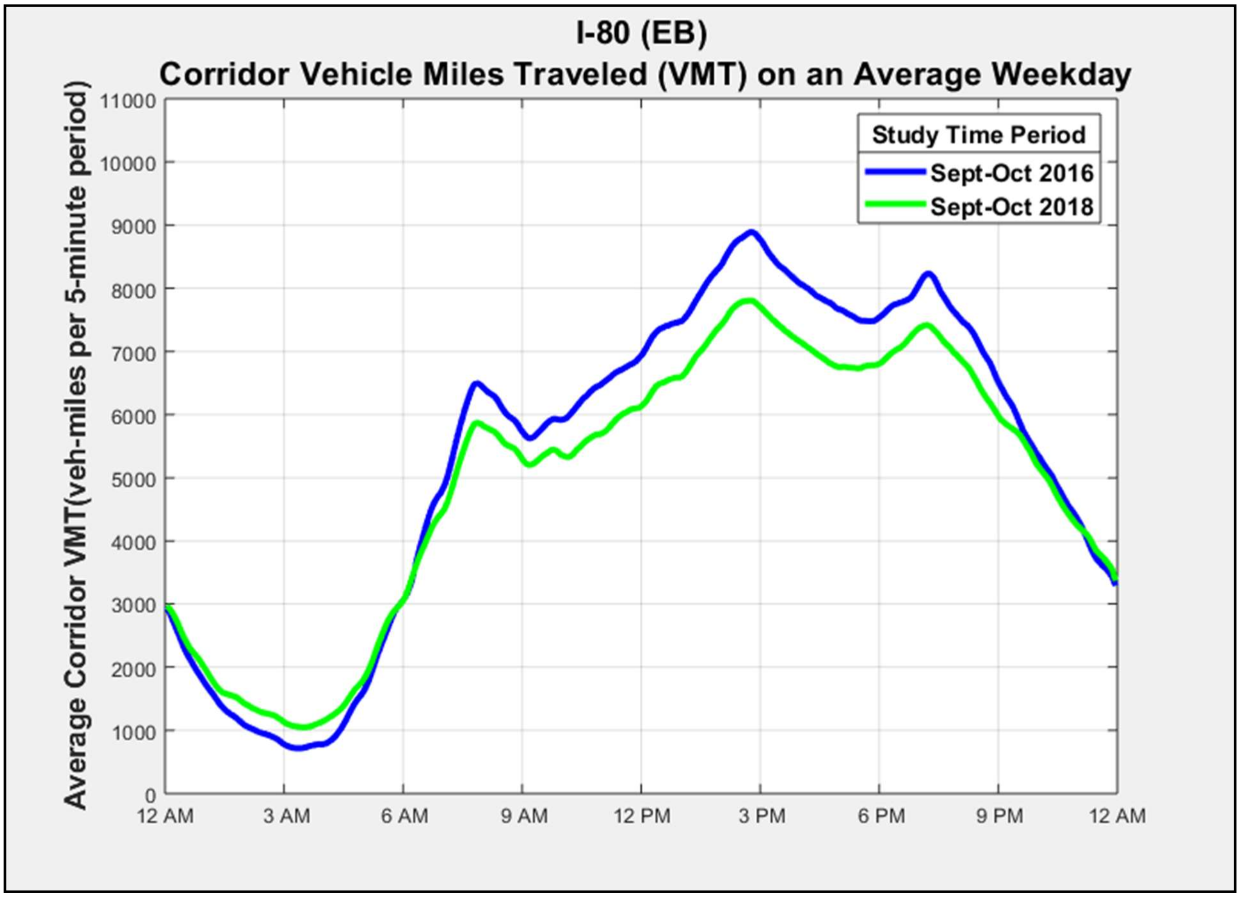

Ramp 10004: Rate Lookup Table

Density	Metering Rate
0	1000.0
5	940.0
10	880.0
15	820.0
20	760.0
25	690.0
30	640.0
35	580.0
40	520.0
45	460.0
50	400.0
55	340.0
60	280.0
65	220.0

Save Reset

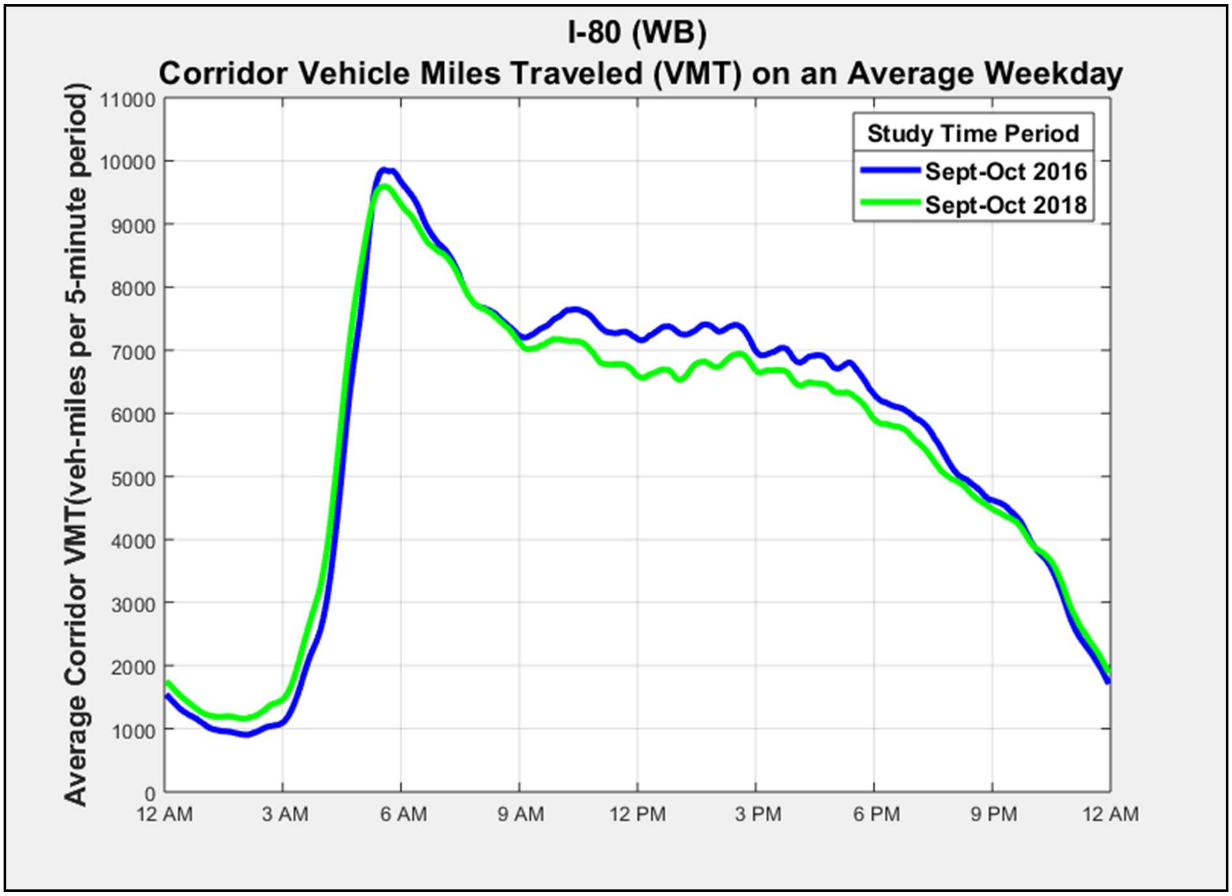
Figure 3.8 Sample Ramp Metering Rate Table (*6*)

APPENDIX D PERFORMANCE MEASURES – WEEKDAY TREND PLOTS



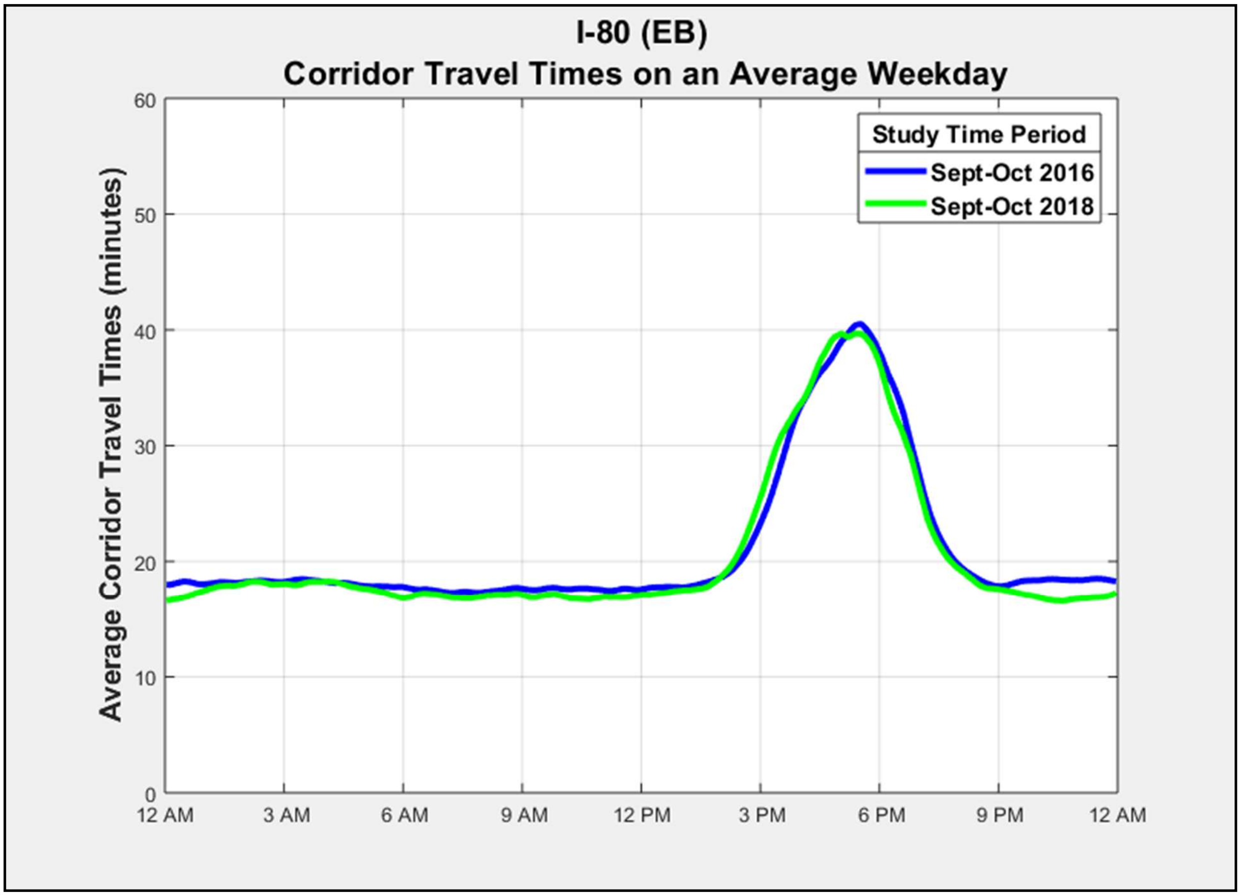
I-80 EB	2016	2018	Change (%)
AM PP VMT:	359,374	333,131	-7.30%
PM PP VMT:	**673,714**	**600,902**	**-10.81%**
Daily VMT:	1,544,095	1,429,965	-7.39%

Figure D.1 I-80 EB Freeway Utilization (VMT)
(Source: Caltans PeMS 5-minute averaged traffic data)



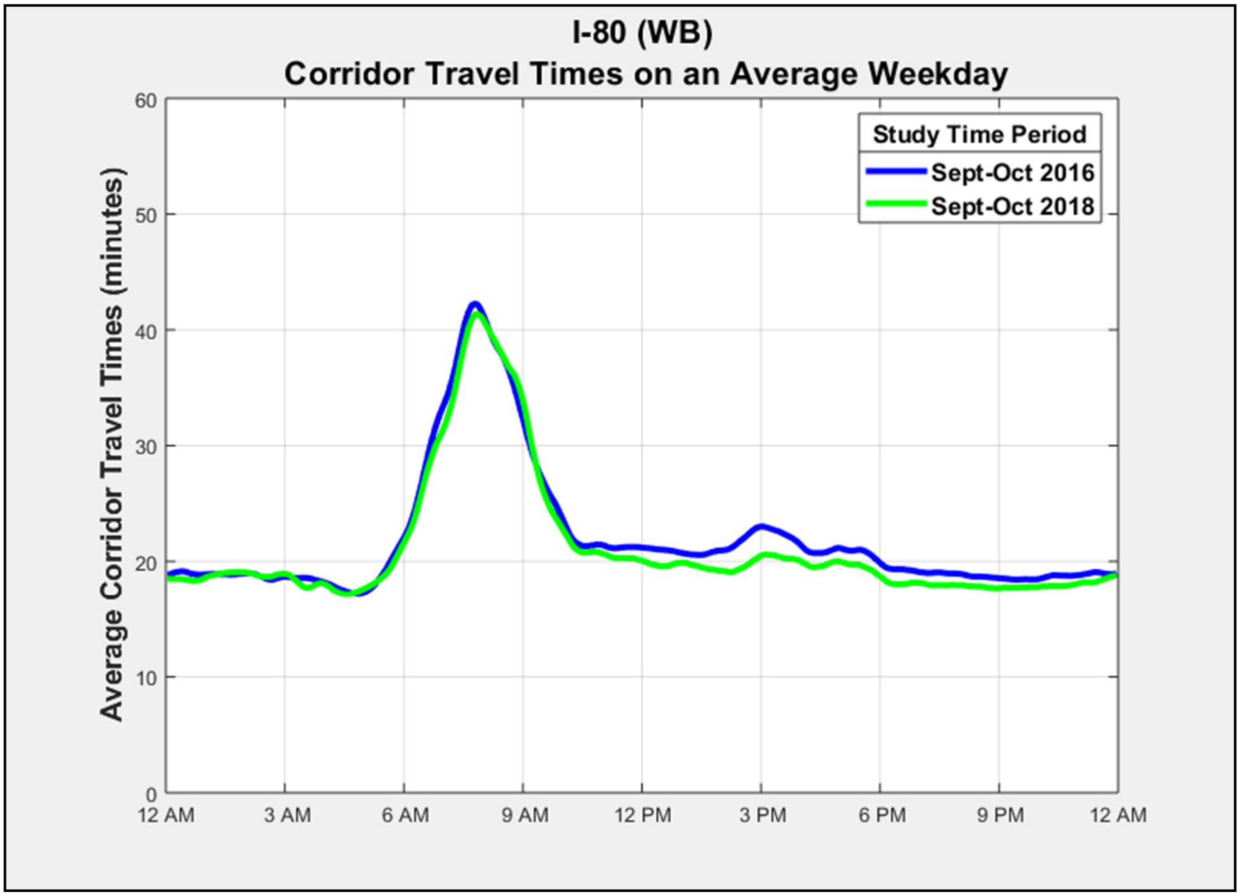
I-80 WB	2016	2018	Change (%)
AM PP VMT:	**590,218**	**577,335**	**-2.18%**
PM PP VMT:	563,895	528,659	-6.25%
Daily VMT:	1,626,740	1,588,709	-2.34%

Figure D.2 I-80 WB Freeway Utilization (VMT)
(Source: Caltans PeMS 5-minute averaged traffic data)



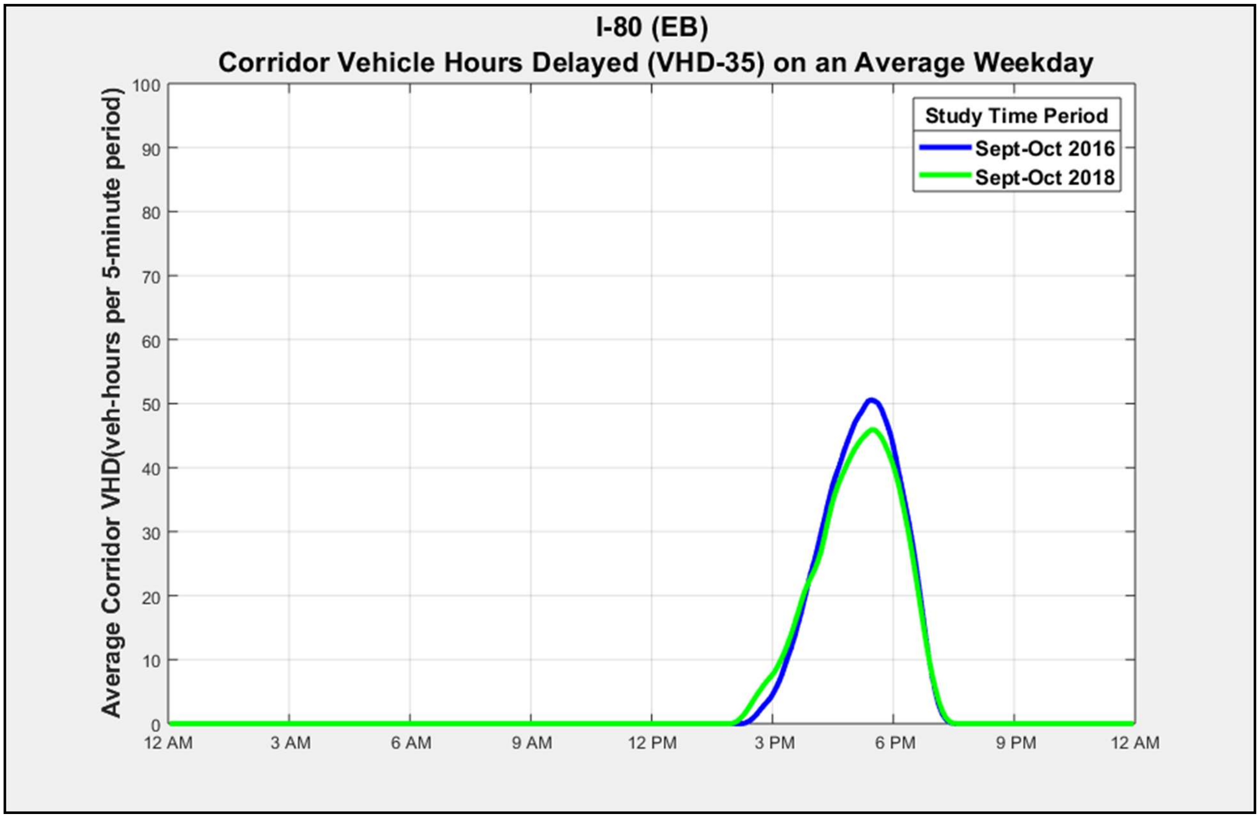
I-80 EB	2016	2018	Change (%)
AM PP Tr Time:	17.579	17.03	-3.12%
PM PP Tr Time:	**28.347**	**28.437**	**0.32%**
Daily Tr Time:	20.994	20.565	-2.04%

Figure D.3 I-80 EB Freeway Travel Times
(Source: Caltans PeMS 5-minute averaged traffic data)



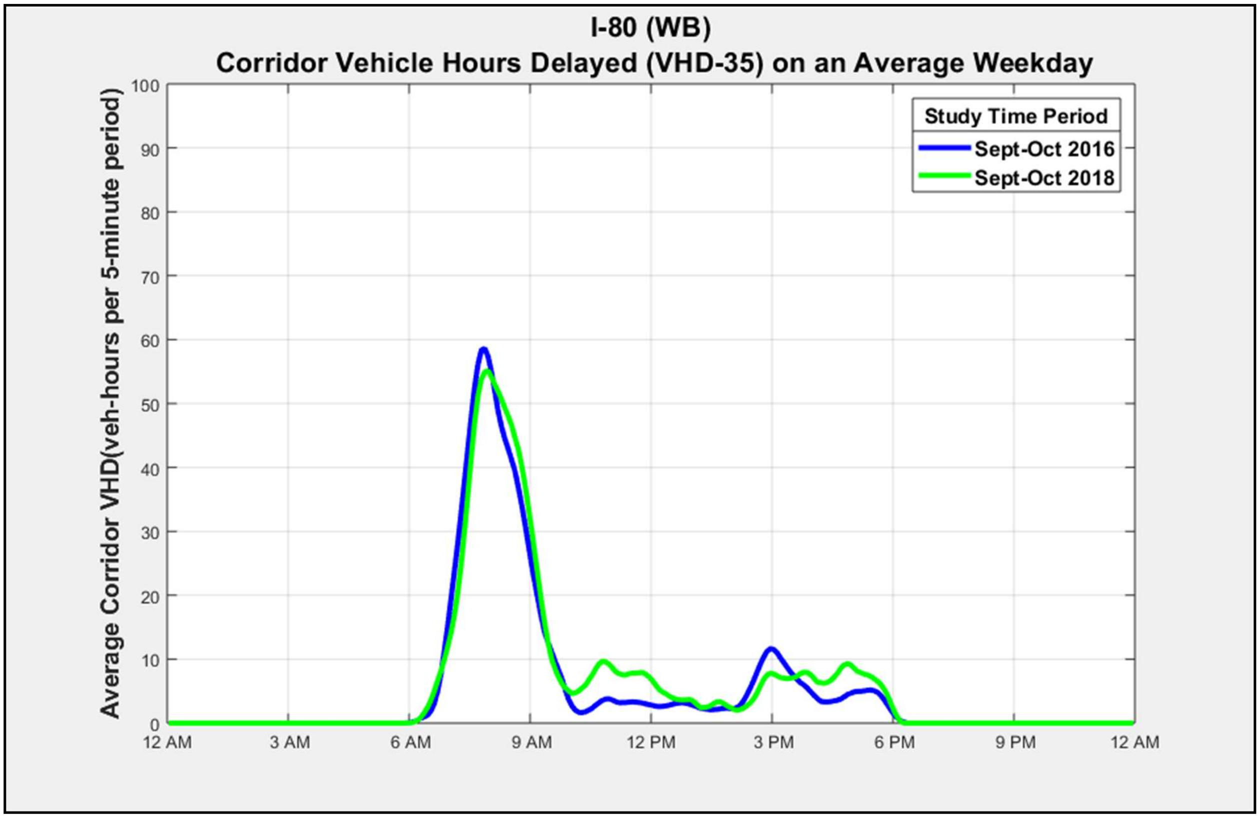
I-80 WB	2016	2018	Change (%)
AM PP Tr Time:	**28.663**	**28.142**	**-1.82%**
PM PP Tr Time:	20.737	19.285	-7.00%
Daily Tr Time:	21.959	21.15	-3.68%

Figure D.4 I-80 WB Freeway Travel Times
(Source: Caltans PeMS 5-minute averaged traffic data)



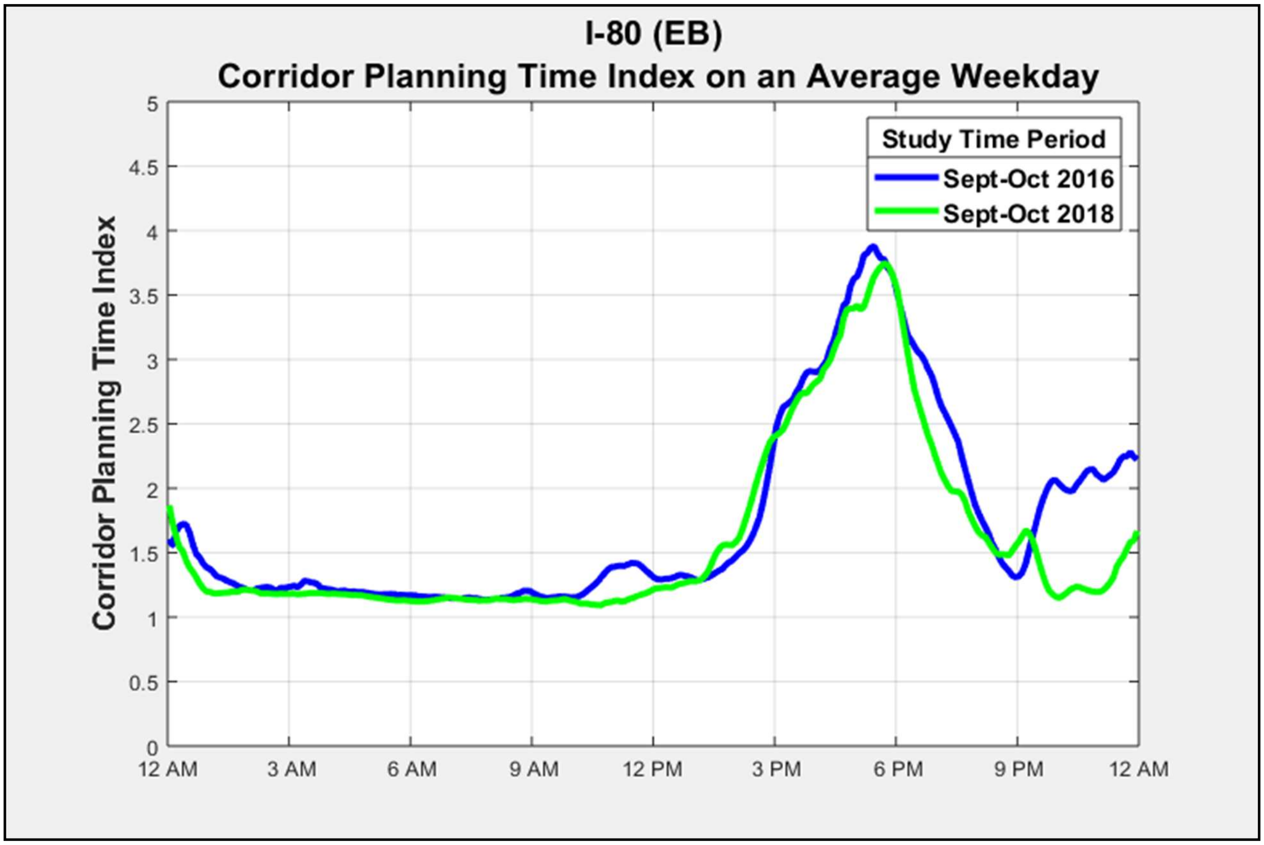
I-80 EB	2016	2018	Change (%)
AM PP VHD-35	0	0	0.00%
PM PP VHD-35	**1,517**	**1,465**	**-3.45%**
Daily VHD-35	1,517	1,465	-3.45%

Figure D.5 I-80 EB Freeway Vehicle Hours Delayed (VHD-35)
(Source: Caltans PeMS 5-minute averaged traffic data)



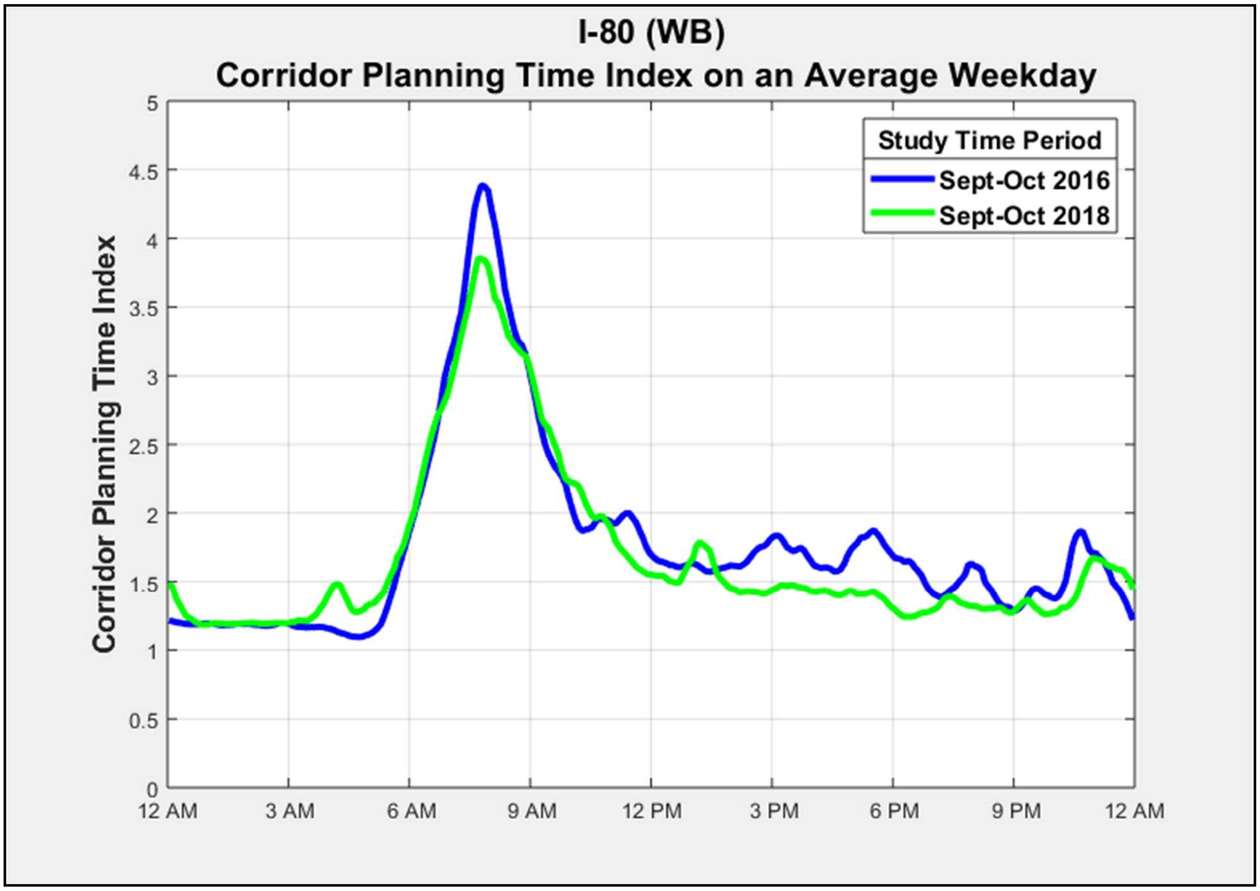
I-80 EB	2016	2018	Change (%)
AM PP VHD-35	**1,245**	**1,294**	**+3.94%**
PM PP VHD-35	304	349	+14.72%
Daily VHD-35	1,623	1,795	+10.57%

Figure D.6 I-80 WB Freeway Vehicle Hours Delayed (VHD-35)
(Source: Caltans PeMS 5-minute averaged traffic data)



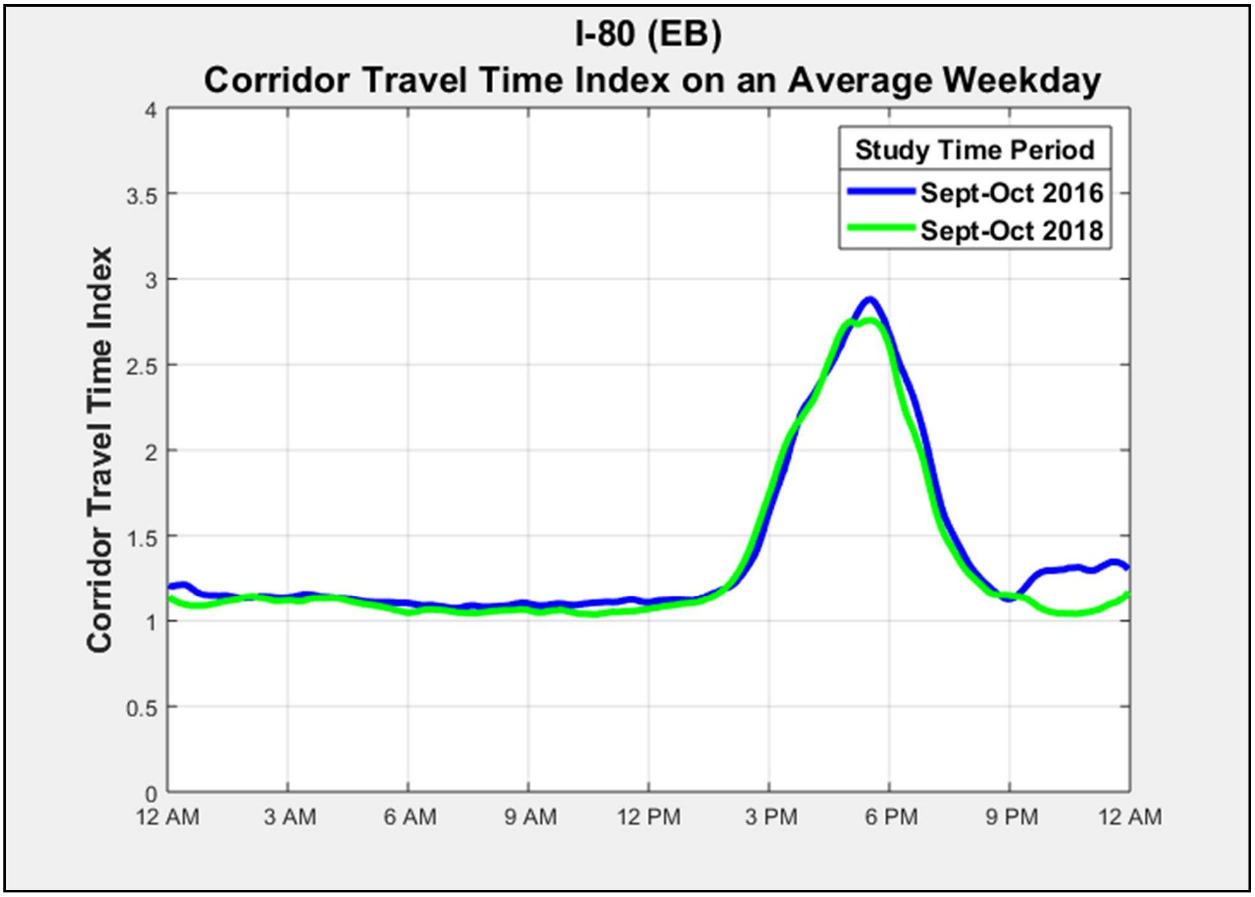
I-80 EB	2016	2018	Change (%)
AM PP PTI	1.173	1.13	-3.64%
PM PP PTI	**2.602**	**2.497**	**-4.02%**
Daily PTI	1.751	1.602	-8.50%

Figure D.7 I-80 EB Freeway Reliability – Planning Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



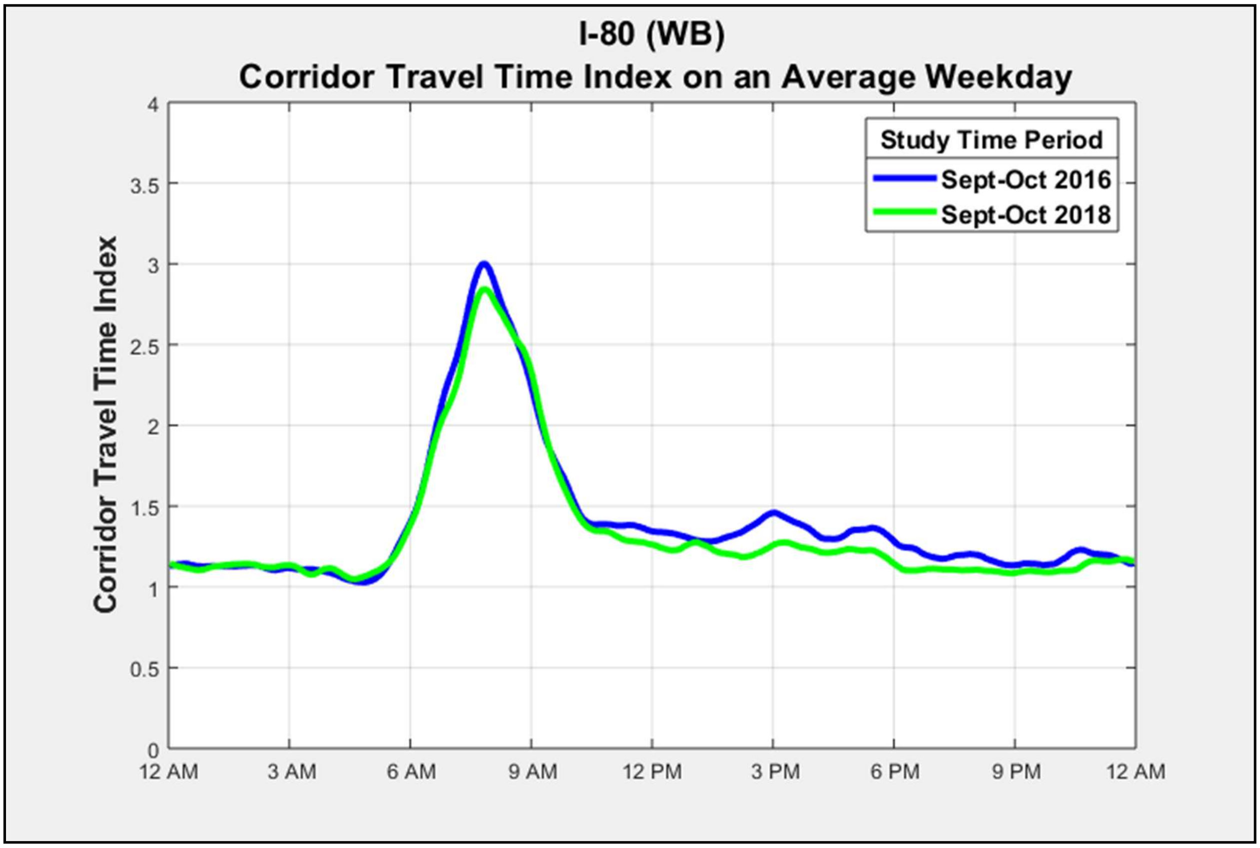
I-80 WB	2016	2018	Change (%)
AM PP PTI	**2.602**	**2.571**	**-1.18%**
PM PP PTI	1.647	1.426	-13.40%
Daily PTI	1.773	1.689	-4.75%

Figure D.8 I-80 WB Freeway Reliability – Planning Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



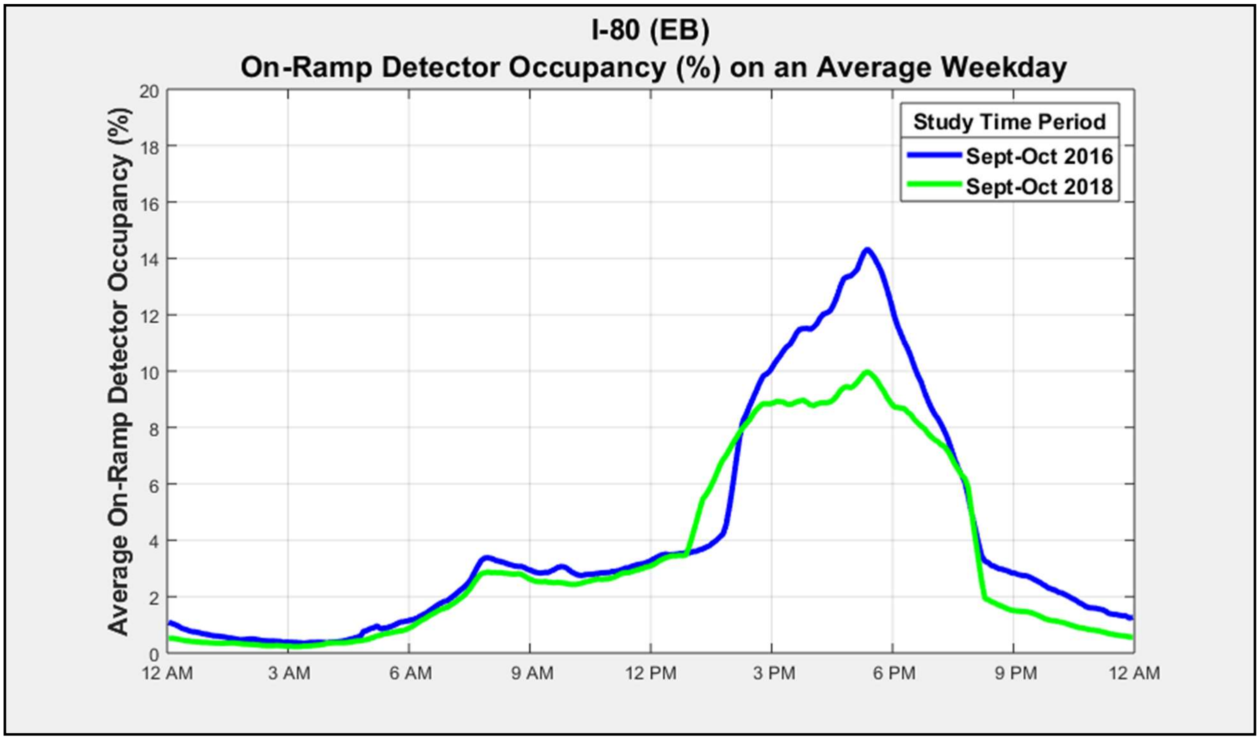
I-80 EB	2016	2018	Change (%)
AM PP PTI	1.095	1.058	-3.41%
PM PP PTI	**1.959**	**1.931**	**-1.44%**
Daily PTI	1.389	1.335	-3.90%

Figure D.9 I-80 EB Freeway Reliability – Travel Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



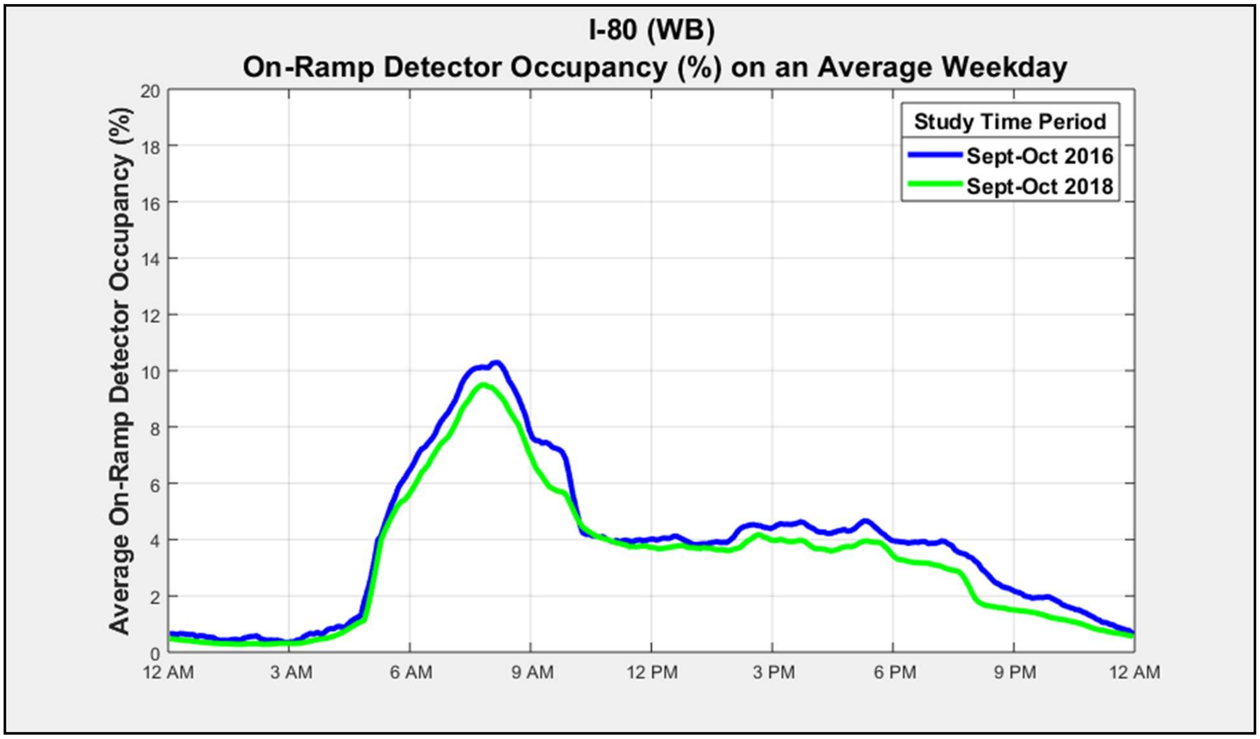
I-80 WB	2016	2018	Change (%)
AM PP TTI	**1.935**	**1.893**	**-2.16%**
PM PP TTI	1.309	1.194	-8.78%
Daily TTI	1.404	1.345	-4.23%

Figure D.10 I-80 WB Freeway Reliability – Travel Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



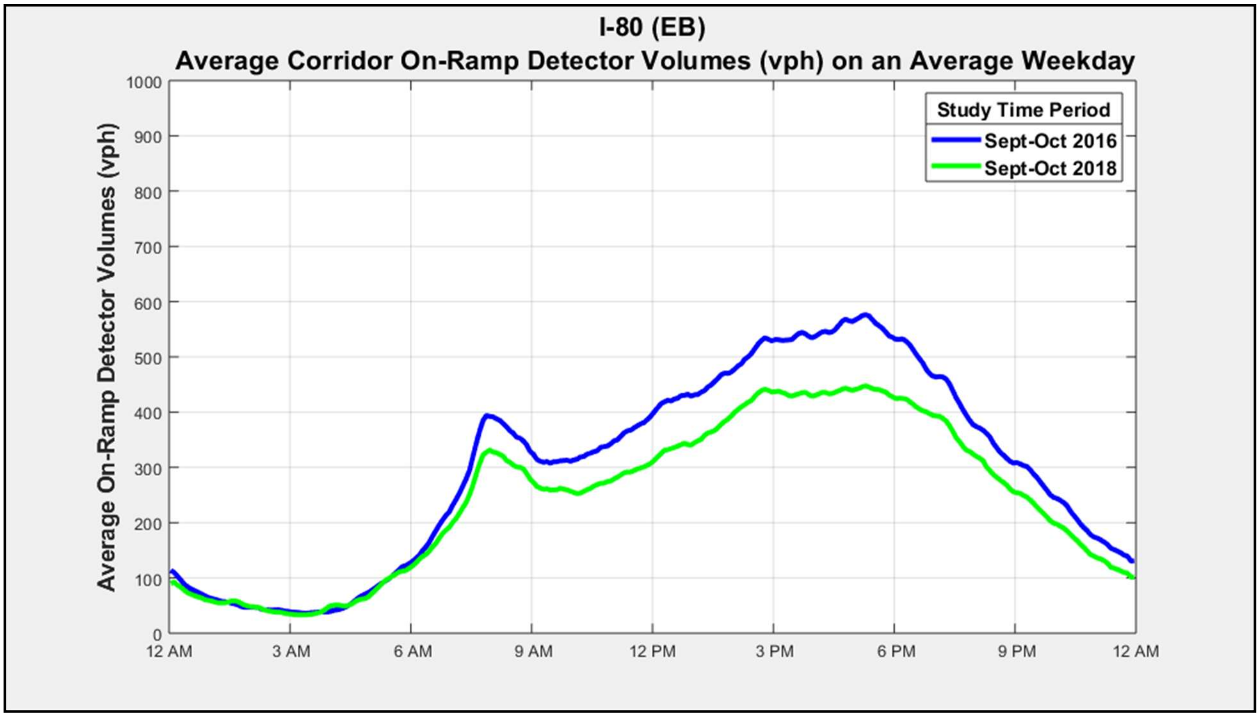
I-80 EB	2016	2018	Change (%)
AM PP Occupancy (%)	2.31	2.00	-13.67%
PM PP Occupancy (%)	**9.57**	**8.10**	**-15.42%**
Daily Occupancy (%)	4.15	3.42	-17.57%

Figure D.11 I-80 EB Freeway On Ramp Detector Occupancy
(Source: Caltans PeMS 5-minute averaged traffic data)



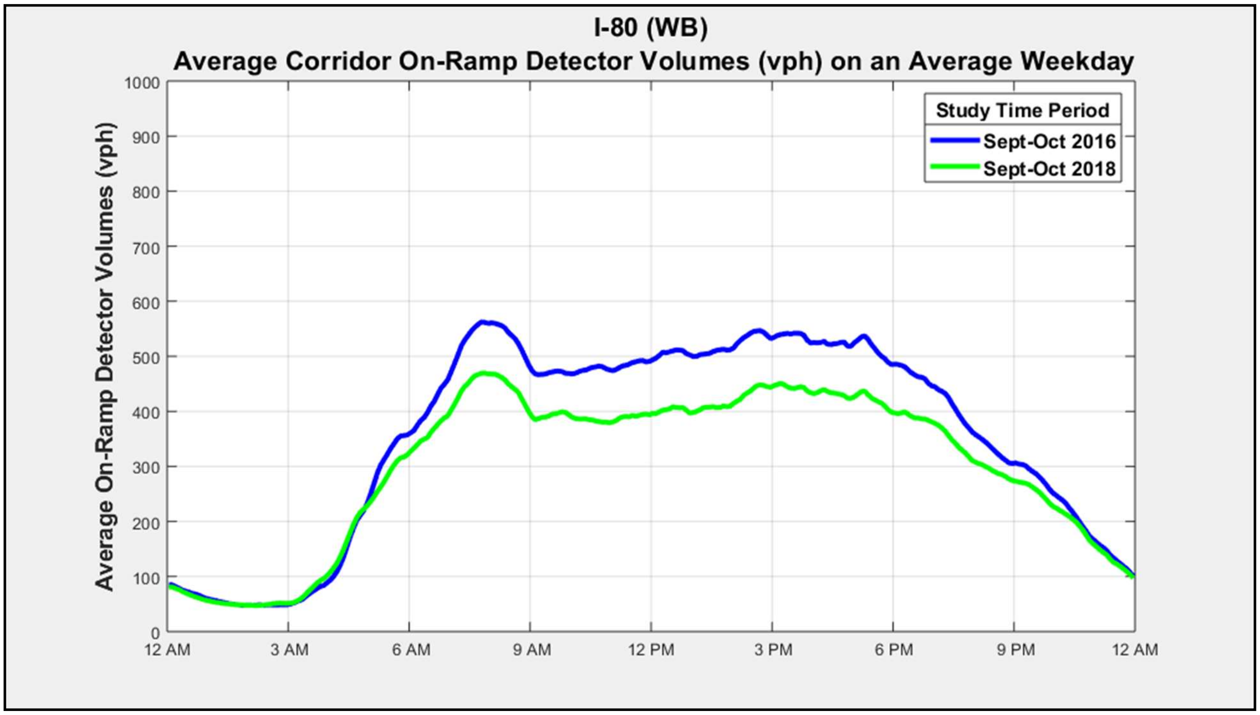
I-80 WB	2016	2018	Change (%)
AM PP Occupancy (%)	**7.19**	**6.44**	**-10.43%**
PM PP Occupancy (%)	4.16	3.61	-13.39%
Daily Occupancy (%)	3.78	3.27	-13.47%

Figure D.12 I-80 WB Freeway On Ramp Detector Occupancy
(Source: Caltans PeMS 5-minute averaged traffic data)



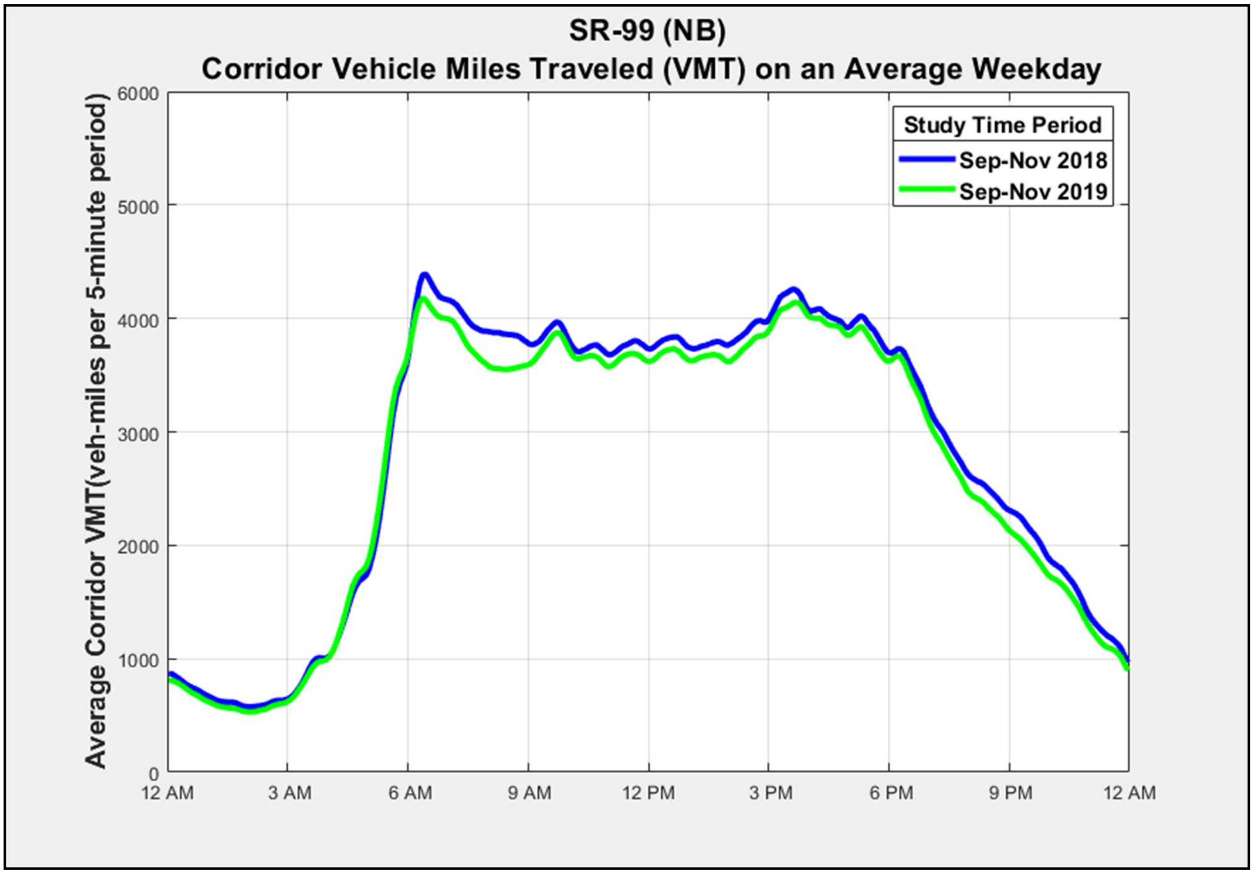
I-80 EB	2016	2018	Change (%)
AM PP Volumes (vph)	261.86	222.50	-15.03%
PM PP Volumes (vph)	**506.85**	**410.64**	**-18.98%**
Daily Volumes (vph)	299.42	246.62	-17.63%

Figure D.13 I-80 EB Average Freeway On Ramp Volumes
(Source: Caltans PeMS 5-minute averaged traffic data)



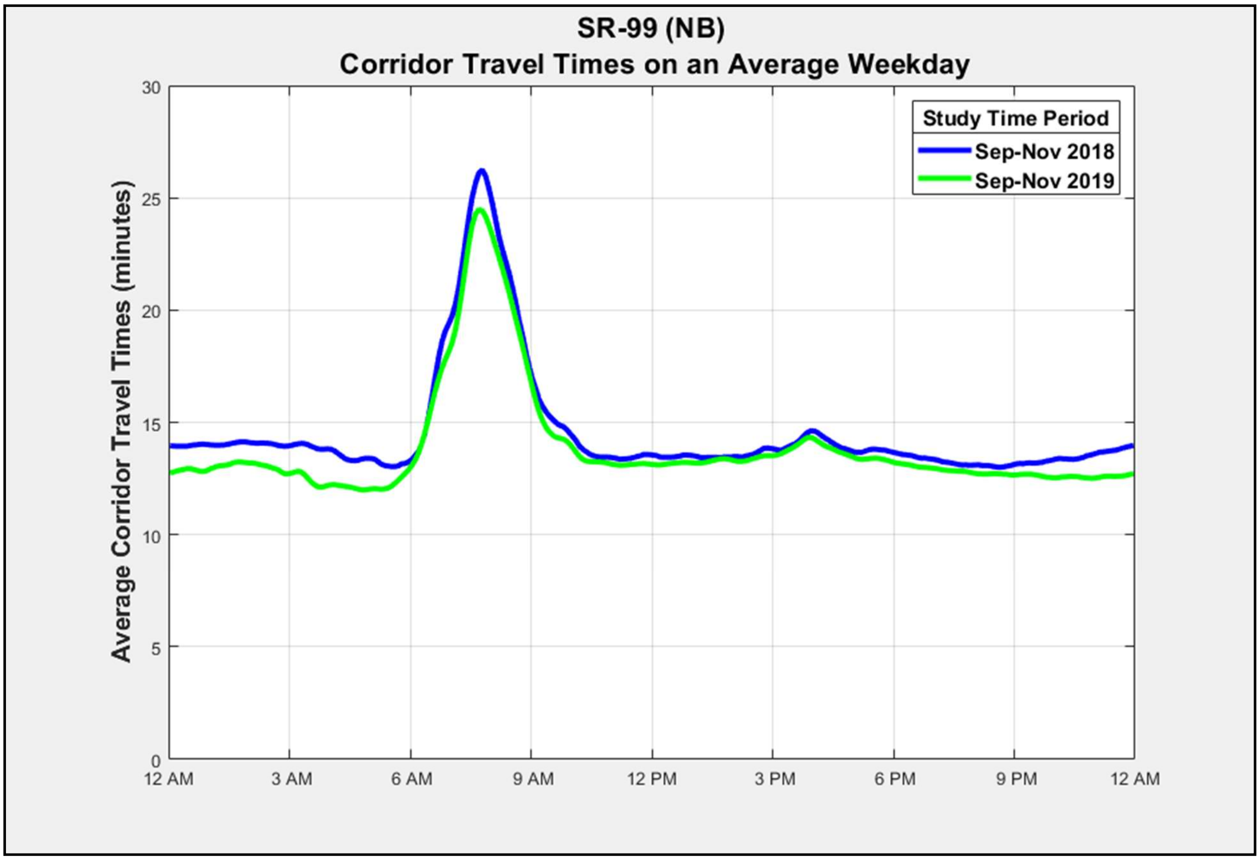
I-80 WB	2016	2018	Change (%)
AM PP Volumes (vph)	**453.40**	**383.27**	**-15.47%**
PM PP Volumes (vph)	500.78	411.75	-17.78%
Daily Volumes (vph)	357.73	302.67	-15.39%

Figure D.14 I-80 WB Average Freeway On Ramp Volumes
(Source: Caltans PeMS 5-minute averaged traffic data)



I-80 EB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP VHD-35	**144,382**	**136,617**	**-5.38%**
PM PP VHD-35	188,570	184,254	-2.29%
Daily VHD-35	814,713	785,892	-3.54%

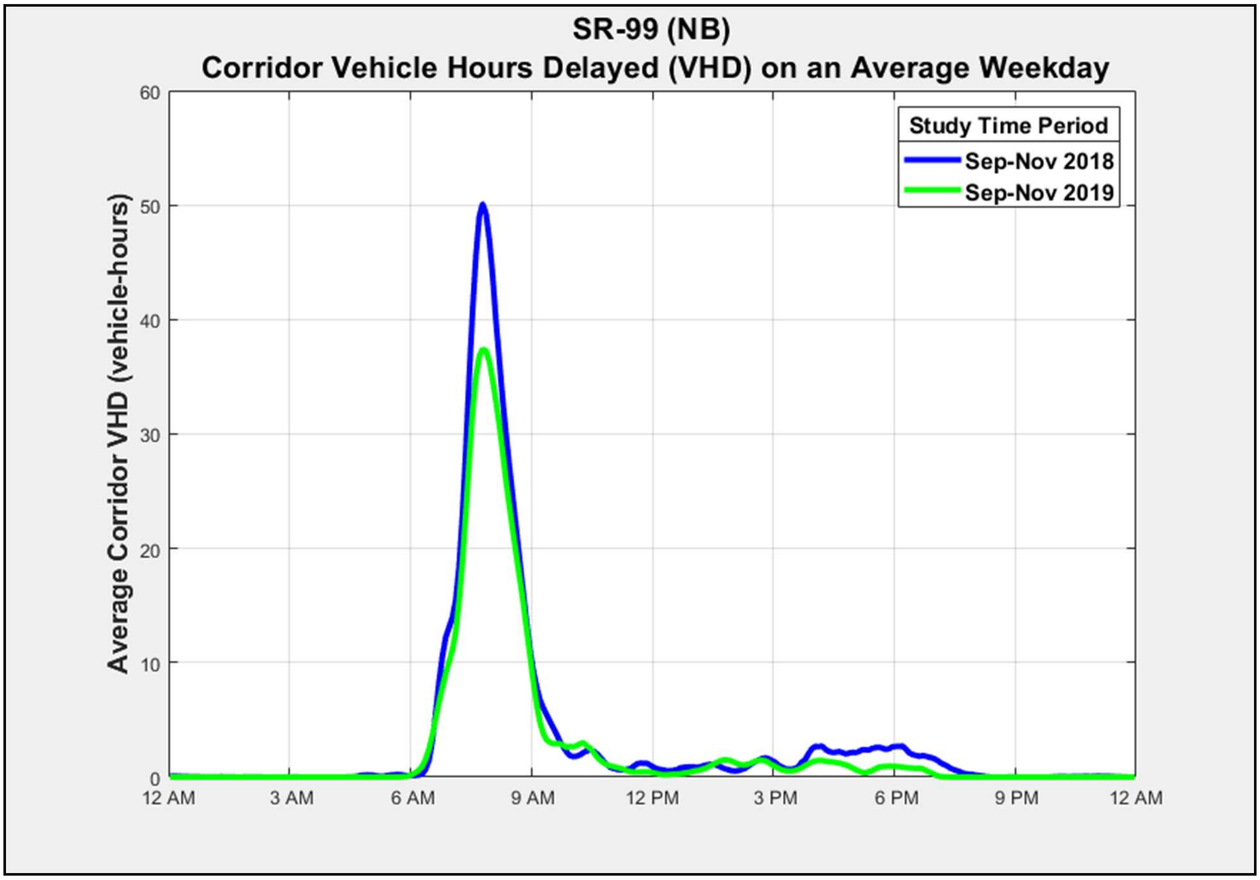
Figure D.15 SR-99 NB Freeway Utilization (VMT)
(Source: Caltans PeMS 5-minute averaged traffic data)



SR-99 NB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP Tr Time:	**20.21**	**19.33**	**-4.32%**
PM PP Tr Time:	13.66	13.39	-2.10%
Daily Tr Time:	14.53	13.86	-4.59%

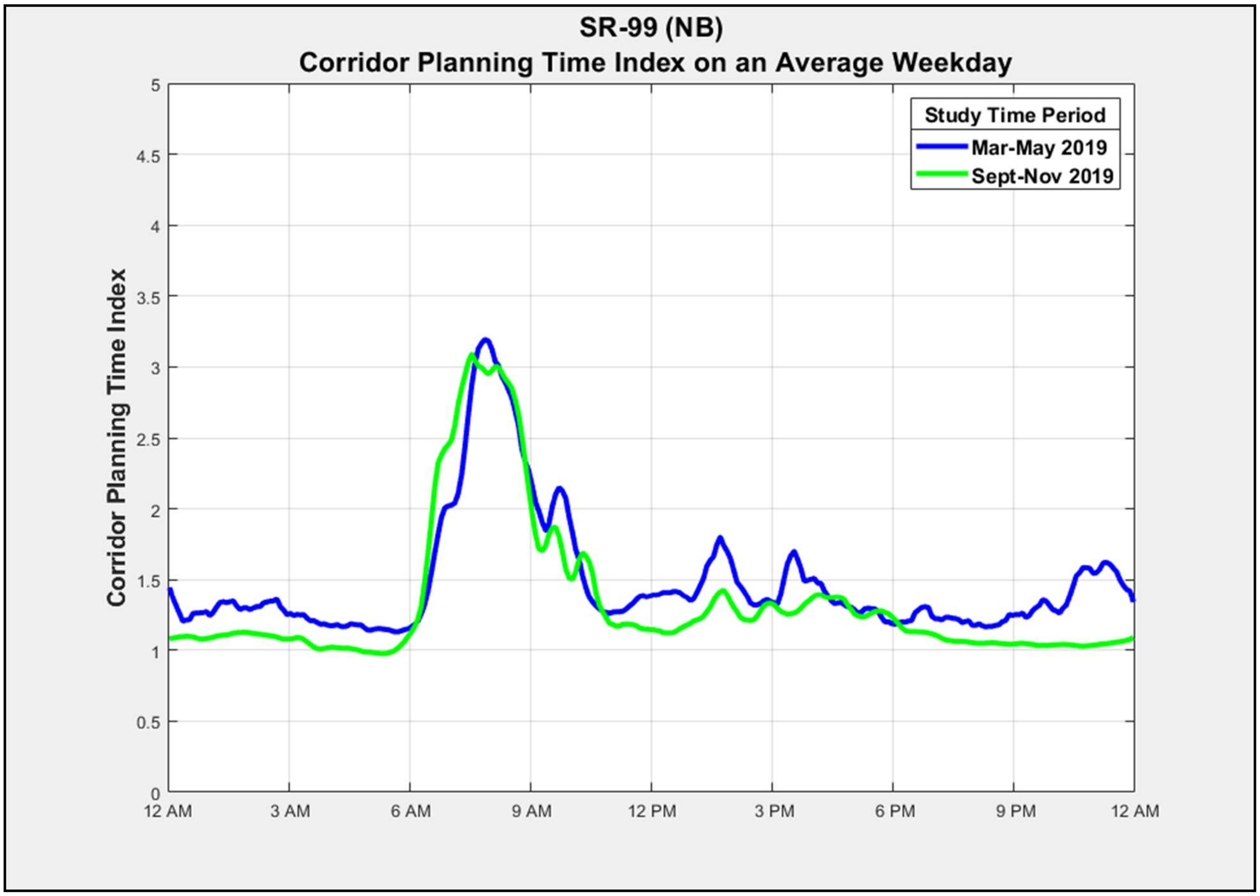
Figure D.16 SR-99 NB Freeway Travel Times

(Source: Caltans PeMS 5-minute averaged traffic data)



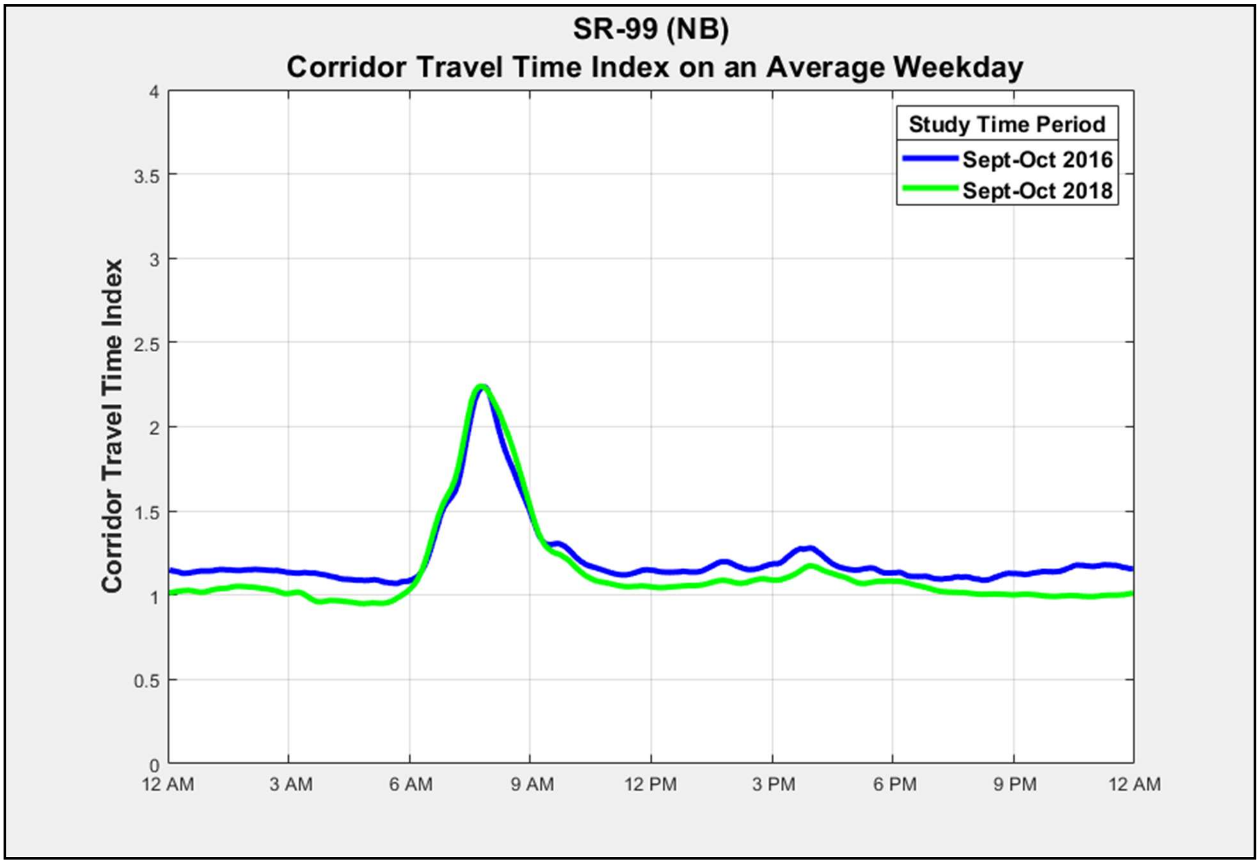
SR-99 NB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP VHD-35	**779.1**	**637.9**	**-18.13%**
PM PP VHD-35	96.5	42.3	-56.20%
Daily VHD-35	1,021.9	797.8	-21.93%

Figure D.17 SR-99 NB Freeway Vehicle Hours Delayed (VHD-35)
(Source: Caltans PeMS 5-minute averaged traffic data)



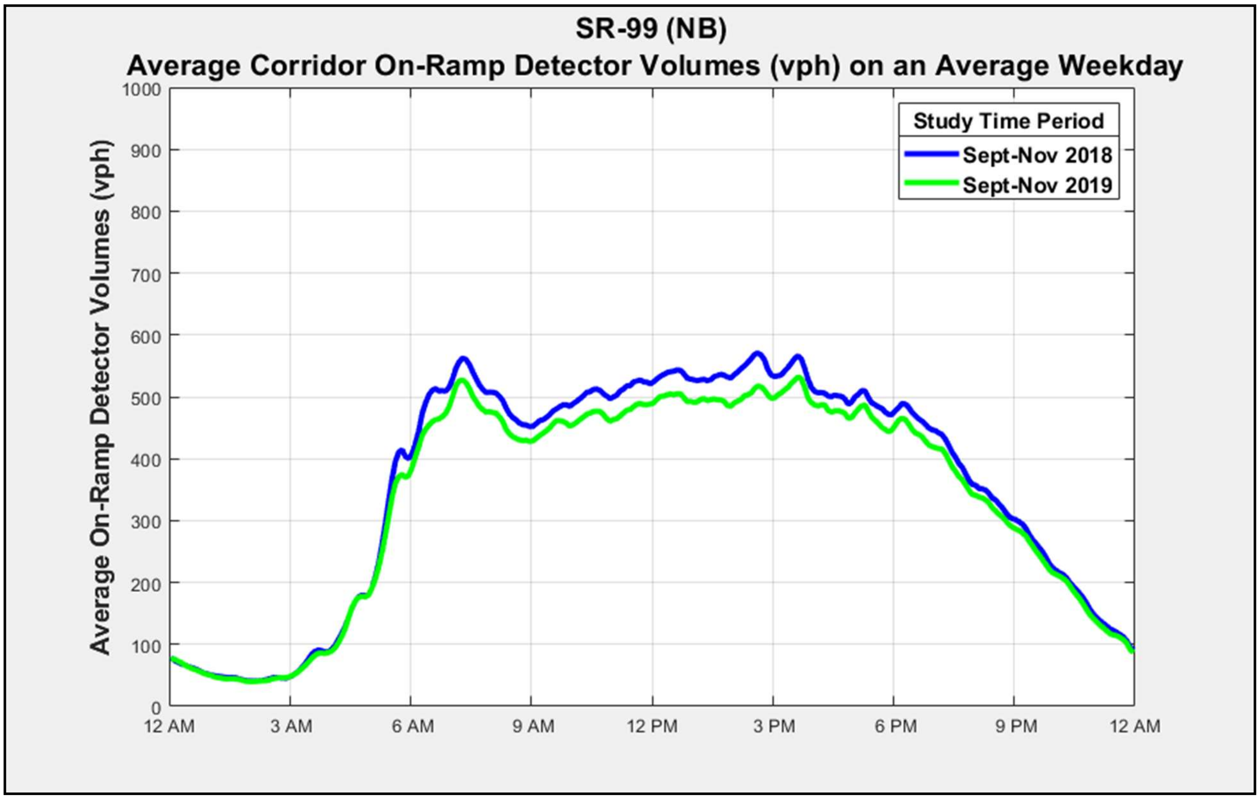
SR-99 NB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP PTI	**1.93**	**1.94**	**+0.89%**
PM PP PTI	1.37	1.25	-9.31%
Daily PTI	1.48	1.34	-9.56%

Figure D.18 SR-99 NB Freeway Reliability – Planning Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



SR-99 NB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP PTI	**1.44**	**1.43**	**-0.63%**
PM PP PTI	1.16	1.08	-6.98%
Daily PTI	1.22	1.14	-6.74%

Figure D.19 SR-99 NB Freeway Reliability – Travel Time Index
(Source: Caltans PeMS 5-minute averaged traffic data)



SR-99 NB	Sep-Nov 2018	Sep-Nov 2019	Change (%)
AM PP Volumes (vph)	**496.8**	**463.3**	**-6.74%**
PM PP Volumes (vph)	503.0	476.6	-5.27%
Daily Volumes (vph)	359.3	337.8	-5.99%

Figure D.20 SR-99 NB Average On Ramp Detector Volumes
(Source: Caltans PeMS 5-minute averaged traffic data)