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The objective of this project was to develop recommendations toward a statewide policy of congestion responsive freeway ramp metering (CRRM) operation. The research has been performed in the following approaches: First an empirical “before” and “after” freeway corridor performance evaluation was performed on a selected set of California’s freeway corridors that had implemented congestion responsive ramp metering. Next, other important policy and operational factors that impact the effectiveness of extended hours ramp metering were evaluated: traffic detector health and data quality and their potential impact on CRRM operation, immediate operation hours, ramp metering (RM) light setting to “Green-Ball” or “Black”, on-ramp storage capacity effects and some alternative solutions to reduce/avoid queue-override, and properly handling institutional relevant issues to gain support from local jurisdictions. The corresponding recommendations are included in this report.

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Freeway ramp metering (RM), Integrated corridor management (ICM), Coordination of Freeway Ramp Meters (CRM), Local Responsive Ramp Metering (LRRM), Performance Measurement System (PeMS)

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Congestion-Responsive On-Ramp Metering: Recommendations toward a Statewide Policy

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ABSTRACT

The objective of this project was to develop recommendations toward a statewide policy of congestion responsive freeway ramp metering (CRRM) operation. The research has been performed in the following approaches: First an empirical "before" and "after" freeway corridor performance evaluation was performed on a selected set of California's freeway corridors that had implemented congestion responsive ramp metering. Next, other important policy and operational factors that impact the effectiveness of extended hours ramp metering were evaluated: traffic detector health and data quality and their potential impact on CRRM operation, immediate operation hours, ramp metering (RM) light setting to "Green-Ball" or "Black", on-ramp storage capacity effects and some alternative solutions to reduce/avoid queue-override, and properly handling institutional relevant issues to gain support from local jurisdictions. The corresponding recommendations are included in this report.

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EXECUTIVE SUMMARY

Objectives and Methodology

Freeway Ramp Metering (RM) is widely used on California freeways. RM operation is typically activated regularly on a time-of-day basis (e.g., AM peak and PM peak) regardless of traffic conditions. Some Caltrans Districts operate RM for extended hours beyond the peak periods, but there is no guideline for RM activation based on freeway operating conditions. There is a need to systematically evaluate the need and potential benefits of extending the current peak period RM operating policy to congestion responsive Ramp Metering operation.

The objective of this project was to develop recommendations toward a statewide policy for Freeway Congestion Responsive Ramp Metering (CRRM) operations from a technical viewpoint instead of the policy itself. It is noted that, although CRRM is to operate for extended hours to address traffic congestion in peak and non-peak hours, the technology underneath is still Local Responsive Ramp Metering (LRRM) for most California freeways. Therefore, CRRM and LRRM will be used interchangeably in this report although the technology could be updated to other RM strategies such Coordinated Ramp Metering (CRM) in a later stage.

The project team first selected several freeway corridors from Caltrans Districts 6, 7, and 8 which had known start date for the operation of RM in extended hours, then collected traffic data for those corridors to evaluate the benefit of the operation in extended hours. The following table, Table 1, shows the corridors used for quantitative analysis although several other corridors were preliminarily scanned for those three Caltrans Districts.

Table 1 Corridors Selected to Serve the Study

Caltrans District	County	Freeway Corridor	Corridor Length (miles)	Number of Metered On-Ramps	Extended Hours of Operation
6	Fresno	SR-41 Northbound	3.2	6	7:00 AM – 6:00 PM
8	Riverside	I-15 Northbound	9.5	7	5:00 AM – 8:00 PM
8	Riverside	SR-91 Eastbound	20.2	19	5:00 AM – 8:00 PM
8	Riverside	SR-91 Westbound	20.5	19	5:00 AM – 8:00 PM
8	SBDO	I-10 Eastbound	10.2	11	5:00 AM – 8:00 PM
8	SBDO	I-10 Westbound	10.3	13	5:00 AM – 8:00 PM
8	SBDO	I-210: Eastbound	17.6	14	5:00 AM – 8:00 PM
8	SBDO	US-60 Eastbound	7.6	8	5:00 AM – 8:00 PM
8	SBDO	US-60 Westbound	8.6	9	5:00 AM – 8:00 PM

Besides the quantitative analysis of the benefit for the operation of CRRM in extended hours, the project team has been analyzing several other relevant factors including:

- The requirement for traffic detector and data for the operation of CRRM for 24/7

- The traffic light for RM to rest on Green or Black for Operating OFF Metering
- Immediate Operation Hours for the extension of RP operation
- The Ramp Storage Capacity: this topic is worthy to be a research topic which can lead to large projects for some specific location; this project can only make some general recommendation on this, but not for specific locations
- Institutional Issues related to the operation of CRRM for 24/7 based on the need of traffic congestion instead of only for AM and PM peak hours

Summary of the Findings and Recommendations

The majority of the study corridors showed performance improvements (increases in vehicle throughput and average traffic speeds) after implementing the extended hours ramp metering strategies. The increases in the average vehicular speeds concurred with the increases in corridor vehicular throughput Vehicle-Miles-Travelled (VMT) during the peaks and/or the midday time periods. However, there were some inconsistencies in the observed performance gains and improvements could not be shown on a number of the study's corridors.

Traffic detector health and data quality is critical for efficient operation of RM over extended hours and on the weekend. The reason is that RM switching ON and the RM rate for an on-ramp will completely depend on the correct detection of the traffic at its immediate upstream. The data quality may not be that critical for RM operation only in peak hours since the public drivers usually get used to that regardless of the traffic situation. To guarantee proper operation, it is necessary to have staff engineer to (a) regularly check the health condition of the traffic detectors which should be done remotely at TMC; (b) well-maintain the detector card and its sensitivity level; (c) properly tune the RM rate according to mainline traffic and on-ramp demand in the starting period; and (d) repair faulty loops/detectors and resolve other problems in time. Before the operation, make sure all the traffic detectors are operated correctly, particularly, the occupancy readings need to be reasonable. It would be helpful for Caltrans Division of Traffic Operation to add some APIs (Application Program Interface) in URMS for traffic data detection and management. It is also recommended to extend operation hours for LRRM from peak hours to non-peak hours and weekends progressively according to traffic detection and data quality. In principle, loop detection heath should be close to 100% and data quality is above 90%. If this cannot be satisfied in all areas/corridors, just operate on those area/corridors that satisfy those requirements. Besides, the corresponding traffic engineers need to tightly monitor the traffic data health and check if the RM "ON" and "OFF" is executed correctly.

To set on "Green Ball" or "Black (OFF)" when Ramp Metering is not activated can be determined by district engineers depending on budget. It is obvious that setting on "Green Ball" will use more energy, but it can keep the public driver alert about the operation of RM so that the drivers can be prepared in cases when the RM restriction in "ON". In this sense, setting to "Green Ball" would have better driver acceptance. Besides, if "LED" signal is used, the energy consumption will not be significant even if the light is energized 24/7. For example, an "LED" signal would consume about 48 ~ 72 [kW] for 24 hours.

It is recommended that operation of LRRM for extended hours to be conducted progressively depending on readiness of the system: traffic detection and data quality, supporting staff availability, traffic situation of the freeway corridor, and public outreach influence. Progressive means that the area or freeway corridor has healthy traffic detectors and good quality of traffic data and they are most needed to do so.

On-ramp storage is a planning problem although it could affect RM operation significantly. In general, if an on-ramp demand is high, large on-ramp storage can significantly reduce the impact on mainline traffic in peak hours. Field data showed that "queue override" action of RM can degrade the performance of RM if the on-ramp does not have adequate storage capacity. Realistically, expanding the storage capacity will be cost-prohibitive in most cases. A potential solution is integration and proper coordination of the control strategies of the two sub-systems (RM control for freeway corridor and signal controls for the relevant arterial corridors). However, beside the coordination strategy, this will need to integrate some efforts of different jurisdictions. If budget is available and land-use is feasible, expending the on-ramp storage of some critical locations may still bring significant benefit in the long run.

To gain the support of local jurisdictions along the freeway corridors selected for operating extended hours and/or weekend RM, it will be necessary to work closely with different committees from local and regional government agencies. Those committees may include: the local county and city Association of Government and its Technical Committee, Local Residence Representative Committee, etc. It is recommended to offer to participate in appropriate presentations and discussion meetings and to tailor the presentation according to the committee background to better gain their support. It is also important to be prepared to answer their unexpected questions, technical and non-technical. Basically, what they are most concerned about is whether the operation of Traffic Responsive RM would have any negative impact on their access of the freeway. It is important to explain to them that some freeway access limit by the RM will be compensated for by the Total Travel Time reduction of the overall traffic – they will get their destination in less time.

The recommendations in this report are mainly from a technical viewpoint of the researchers, which should only be used as references for Caltrans Division of Traffic Operations to develop state-wide RM policy for extending the operation hours to relieve traffic congestion caused by incident/accident and special events in non-peak hours and weekends. Besides, most recommendations can only be based on the knowledge and experience of the project team instead of on field test plus quantitative analysis.

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List of Acronyms and Abbreviations

API	Application Program Interface
ATMS	Advanced Traffic Management System
Caltrans	California Department of Transportation
CRM	Coordinated Ramp Metering
CRRM	Congestion Responsive Ramp Metering
DCRMS	Dynamic Coordinated Ramp Metering System
DRISI	Innovation and Systems Information
EB	East Bound
HERO	HEuristic Ramp metering coOrdination
HOV	High Occupancy Vehicle
ICM	Integrated Corridor Management
LRRM	Local Responsive Ramp Metering
NB	North Bound
PATH	California Partners for Advanced Transportation Technology
PeMS	Performance Measurement System
PM	Postmile
RM	Ramp Metering
SDRMS	San Diego Ramp Metering System
RMDP	Ramp Metering Development Plan
SR	State Road
TAG	Technical Advisory Group
TD	Total Delay
TMC	Traffic Management Center
TOD	Time-of-Day
TOS	Traffic Operations System
TTD	Total Travel Distance (=VMT)
TTS	Total Time Spent (=VHT)
TTT	Total Travel Time (=VHT)
URMS	Universal Ramp Metering Systems
VDS	Vehicle Detector System
VHT	Vehicle Hours Travelled
VMT	Vehicle Miles Travelled (the same as TTD)
VSA	Variable Speed Advisory
VSL	Variable Speed Limit

CHAPTER 1
INTRODUCTION

1.1 Problem Statement

Ramp Metering (RM) has been widely implemented and operated on California highways. However, most freeway corridors are still operating RM only for AM/PM peak hours. It would make better sense to better use the available RM infrastructure (traffic detector at freeway mainline and at onramps, RM controllers, and RM signals, etc.) to address traffic congestion in non-peak hours and on the weekends. The control strategy may be called Congestion Responsive RM (CRRM). In essence, it will operate in peak hours as it is now, but in non-peak hours and weekend, it will be activated when the traffic congestion has reached a certain level for a given RM location.

The algorithm popularly used is Local Responsive Ramp Metering (LRRM) which determines the ramp metering rate at an on-ramp entrance simply based on the mainline occupancy and volume measurements from mainline detectors located immediately upstream. The LRRM technology will still be inherited in the CRRM operation at this stage. The relationship between the occupancy and volume thresholds and the RM rate may change depending on the traffic situation and time-of-day during operating periods in some Caltrans districts. Based on the discussions with Caltrans District freeway traffic operation staff, current operation of RM can be classified in four ways:

- Operation in the AM and PM Peak (fixed time) periods in most freeway corridors, with RM rates established from lessons learned in the past and local real-time and historic traffic detector data
- District 4 (D4) is also using system wide metering including DCRMS (Dynamic Coordinated Ramp Metering System) and Modified Fuzzy Logic. D4 has also extended metering hours on the I-80 ICM (Integrated Corridor Management) corridor, from 5 AM to 8 PM, 7 days a week
- Operation over long or extended periods of the day, including weekends and holidays as it is done in District 7 and District 6
- Operating hours are completely determined by mainline historical traffic detector data, including workdays and weekends such as District 5; it is noted that this strategy is not operating on real-time detection yet and it does not require high fidelity of real-time traffic detection.

1.2 Project Objectives

The objective of this research project was to develop recommendations for the field operation of CRRM. In particular, the project needs to address the following issues:

- How RM operation is to be operated in non-peak hours and weekends to address non-recurrent congestions?
- Any technical pitfall or issues need to be addressed or any preparation is necessary before operation?

- Whether RM signal should be set to Green or Black if mainline freeway traffic occupancy or volume drops below a predefined volume rate (as determined by the mainline occupancy/volume at the immediate upstream mainline detector station), i.e. no RM as the traffic is not congested?
- How to make sure practices are updated to be consistent with the current (AM & PM) peak period RM operations that are used to address recurrent congestion?
- How the onramp length would affect the RM operation and how to overcome the difficulty of insufficient onramp length with high demand from arterial or surface streets? Accordingly, how to reduce or completely remove queue over-ride based on on-ramp queue occupancy detection?
- How to handle the institutional issues by gaining the support of local jurisdictions?

1.3 Research Approach

The statewide RM policy recommendations should be based on a data-driven quantitative evaluation. Since some Caltrans Districts were operating LRRM systems at some level, it was proposed to use Performance Measurement System (PeMS) or Advanced Traffic Management System (ATMS) data, whichever was more accurate with less time delay, to perform a set of "before" and "after" comparisons to facilitate a quantitative evaluation where we could infer potential outcomes of proposed RM strategy/policy changes. These evaluations by comparing "before" and "after" scenarios would provide the quantitative results necessary to support policy recommendations, without performing expensive and time-intensive field tests on multiple freeway corridors. The following performance measures will be used to evaluate the effectiveness of ramp metering during extended hours:

a) Mainline freeway bottleneck and discharge flow, and corridor vehicle-miles-travelled (VMT)

b) freeway delays and vehicle-hours-travelled (VHT)

c) Travel-time reliability: The 80^{th} or 95^{th} percentile of the travel time distribution.

The recommendations from the research recognized and accommodated the differences between Caltrans Districts and/or between freeway corridors in the same District. The differences included but are not limited to the following:

- Traffic volumes and capacities and (Volume/Capacity) ratios on freeway corridors
- Current infrastructure status including traffic controllers (e.g. 2070 vs. 170), ramp meter control software (e.g. URMS -Universal Ramp Metering Systems, TOS - Traffic Operations System, and SDRMS - San Diego Ramp Metering System), and data/information system such as PeMS or ATMS data acquisition
- Varieties of RM rates for different traffic demand levels for mainline detections
- Traffic detector health (detection accuracy and reliability) and data qualities, and accommodation/incorporation of other private data (such as cellphone data) for better detection and traffic state estimation (such as District 3)

The project was mainly performed with eight major tasks below, which will be expounded in detail in the following chapters:

- Task 1. Freeway corridor selection for quantitative analysis
- Task 2. Traffic data collection and analysis
- Task 3. Develop policy recommendation on traffic detector and traffic data requirements
- Task 4. Investigate "pros" and "cons" for using Rest-in-Green or Black as meter OFF
- Task 5. Develop policy recommendations on immediate operation hours
- Task 6. Develop policy recommendation on the on-ramp storage capacity from a control viewpoint
- Task 7. Develop policy recommendations addressing institutional issues
- Task 8. Project report including Final Report

1.4 Organization of the Report

This document is the final report for the project. Each chapter of the report describes the work performed and the findings for each project task. Chapter 2 describes the site selection process and the empirical "before" and "after" performance evaluation. The findings from the empirical evaluation at the selected sites are presented in chapter 3. Chapter 4 describes the work performed and the policy recommendation on traffic detector and traffic data requirements. The "pros" and "cons" of using Rest-in-Green or Black as meter are presented in chapter 5. Chapter 6 presents the policy recommendations on immediate operation hours. The policy recommendations on the on-ramp storage capacity are described in chapter 7. Addressing institutional issues are discussed in chapter 8. The final chapter briefly summarizes the study findings and recommendations.

CHAPTER 2
FREEWAY CORRIDOR SELECTION FOR QUANTITATIVE ANALYSIS

This chapter describes the selection of the freeway corridors to assess the 24/7 ramp metering operation. First the research team and Caltrans staff from Headquarters (HQ) Division of Traffic Operations and districts established a set of selection criteria. Candidate test sites were selected and screened based on the selection criteria. Next, detailed information on RM operating strategies was collected on the candidate freeway corridors, and an investigation was performed on their data quality and detector health.

2.1 Freeway Corridor Selection Criteria

The following study corridor selection criteria are established:

Ramp metering control: the freeway corridor's ramp metering control needs to operate under a Local Responsive Ramp Metering (LRRM) strategy. Ideally, the corridor's ramp metering strategy would have been switched over from a static fixed time-period AM and PM peak period ramp metering to operate for longer or extended metering time periods, preferably to CRRM metering, within the past 1 to 3 years.

Corridor geometrics: the selected freeway test sites should be sufficiently long and contain multiple interchanges with metered on-ramps (e.g., four or more miles). Also, it is desirable not to have an unmetered freeway-to-freeway interchange within the study area. Unmetered freeway-to-freeway connectors tend to deliver large uncontrolled volumes into the study corridor and make it much more difficult to isolate the benefits of the metered on-ramps.

Corridor traffic operations: It is desirable for the study corridors to contain at least one recurrent active bottleneck, to measure any changes in bottleneck capacity (vehicle throughput at the bottleneck). The corridor congestion must be caused by the active bottleneck within the corridor, not from downstream bottleneck queuing that backs up into the study corridor.

Data availability and quality: It is essential to have good data from loop detectors and other sources to estimate the freeway's performance "before" and "after" the LRRM strategy update. Additional data include information on construction activities (resurfacing, bridge work), expansion projects, infrastructure improvements or other major activities along the corridor that might have affected motorist's travel times, delays and bottleneck activity.

2.2 Identification of Candidate Freeway Study Corridors

The research team considered several potential study corridors from Caltrans Districts 4, 5, 6, 7, 8, 11 and 12. Caltrans HQ and Districts staff were instrumental in providing information on their current ramp metering strategies and operation. The required LRRM strategy and the shift from peak periods to extended hours metering limited the set of candidate corridors.

District 4 identified only one on-ramp meter with extended hour metering hours (Table 2.1). This site was dropped from further consideration as it only contains one metered on-ramp.

Table 2.1 District 4 Identified Corridors with Extended Hours of CRRM Operation

County	Route	Post Mile	Direction	Ramp Meter Location name	Extended hour (Y/N)	Conversion Date (Month/year)
Contra Costa	SR-4	City of Pittsburg	EB & WB	Railroad Avenue	Y	10/2017

District 6: There are six on-ramp meters with extended hour metering on northbound SR-41 (Table 2.2). The extended hours of the ramp metering operations were from 7:00 AM to 6:00 PM. District 6 uses the LRRM strategy for all metered on-ramps.

Table 2.2 District 6 Identified Corridors with Extended Hours of CRRM Operation

County	Route	Post Mile	Direction	Ramp Meter Location Name	Extended hour (Y/N)	Conversion Date (Month/year)
FRE	41	25.39	NB	McKinley Ave	Y	10/28/2015
FRE	41	26.41	NB	EB Shields Ave	Y	10/28/2015
FRE	41	26.59	NB	WB Shields Ave	Y	10/28/2015
FRE	41	27.55	NB	Ashlan Ave	Y	10/28/2015
FRE	41	28.42	NB	EB Shaw Ave	Y	10/28/2015
FRE	41	28.57	NB	WB Shaw Ave	Y	10/28/2015

The PeMS detector health report for October 2015 showed that many of the mainline detectors were not functional for SR-41 through the segment where the ramp metering hours-of-operations was extended. Table 2.3 shows the Caltrans PeMS detector health report for SR-41 in Fresno County at the time the corridor switched to extended hours of operation.

Table 2.3 PeMS Detector Health Report--District 6, SR-41 Northbound (October 2015)

Fwy-Dir	VDS	CA PM	Abs PM	Name	County	Lane1	Lane2	Lane3
SR41-N	614163	31.5007	133.25	NEES AVE	Fresno	Card Off	Card Off	Card Off
SR41-N	601542	30.931	132.68	ALLUVIAL AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601540	29.9705	131.72	SIERRA AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601417	29.58	131.33	BULLARD DT 41 NB	Fresno	Good	Good	Good
SR41-N	614161	29.5005	131.25	BULLARD AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601538	28.9805	130.73	BARSTOW AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601415	28.58	130.33	SHAW DT 41 NB	Fresno	Good	Good	Good
SR41-N	614160	28.5007	130.25	SHAW AVE 41 NB	Fresno	Line Down	Line Down	Line Down
SR41-N	601416	28.42	130.17	SHAW LP 41 NB	Fresno	Good	Good	Good
SR41-N	601536	27.9805	129.73	GETTYSBURG AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601414	27.55	129.30	ASHLAN DT 41 NB	Fresno	Good	Good	Good
SR41-N	614159	27.5005	129.25	ASHLAN AVE 41 NB	Fresno	Line Down	Line Down	Line Down
SR41-N	601534	26.9505	128.70	DAKOTA AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601215	26.5605	128.31	SHIELDS AVE DT 41 NB	Fresno	Good	Good	Good
SR41-N	601214	26.4005	128.15	SHIELDS AVE LP 41 NB	Fresno	Card Off	Good	Good
SR41-N	601532	25.8805	127.63	CLINTON AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601213	25.3405	127.09	MCKINLEY AVE DT 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601530	24.9705	126.72	FLORADORA AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	614166	24.7005	126.45	OLIVE AVE 41 NB	Fresno	Ctlr Down	Ctlr Down	Ctlr Down
SR41-N	601256	24.68	126.43	EB-WB 180 TO NB 41 CONNECTOR	Fresno	Good	Good	Good

Legend: Detector Health Lane Report
Good
Card Off
Controller Down
High Value
Line Down
Insufficient Data
Intermittent

Further investigation revealed only short periods of recurrent congestion in the PM peak period along this stretch of SR-41. Figure 2.1 shows the relative levels of weekday traffic congestion for the same time-period.

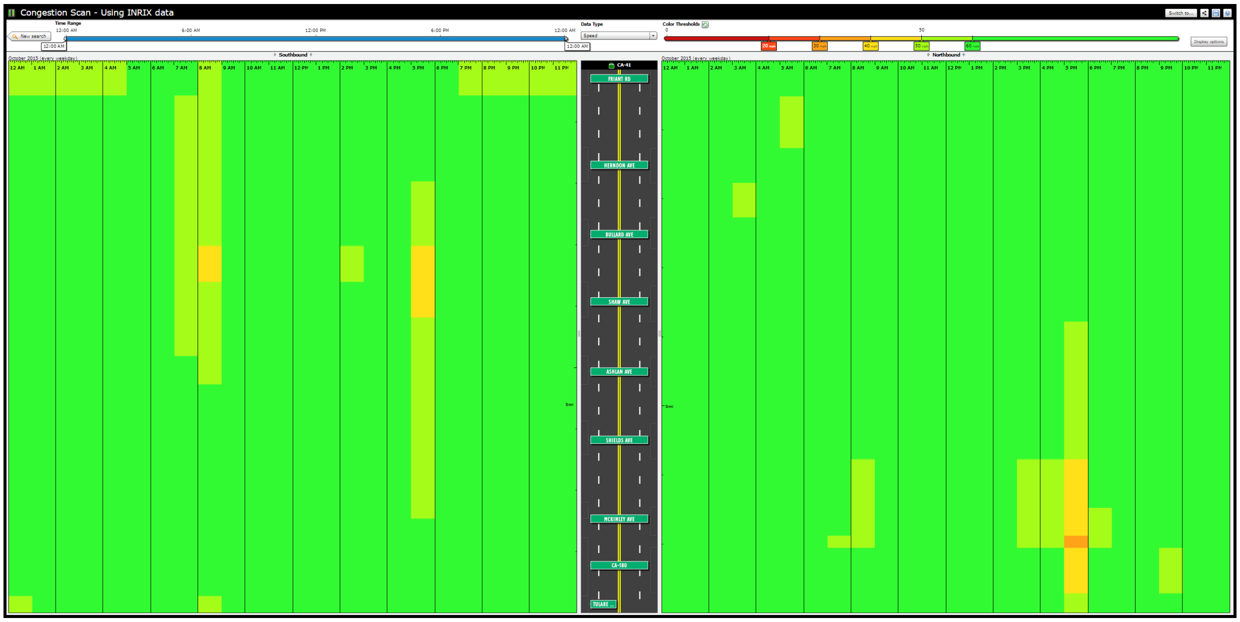

Figure 2.1 Congestion Scan for SR-41 (North of the SR-180 Interchange)

District 7 contained multiple candidate corridors. Further inquiries revealed that some of the required information documenting the District's historic on-ramp metering implementation strategy was unavailable, i.e., it is unknown when the corridor ramp metering was switched from weekday peak periods to extended hours of operation. Without being able to clearly delineate between the "before" and the "after" periods, further investigation on freeway corridors in District 7 was not pursued.

District 8 started extended hours operations for all ramp meters beginning January 2009. All of the District 8 ramp meters are traffic responsive from 5AM to 8PM, seven days a week. District 8 operates a LRRM strategy for all metered on-ramps. We reviewed the Caltrans District 8 (2009) Ramp Metering Development Plan (RMDP) to obtain information on the corridors where on-ramp metering was implemented at the time that the District switched from peak period only metering to the extended-hours metering (January 2009). Table 2.4 shows the number of metered on-ramps for potential test corridors where ramp metering was implemented in 2009.

The January 15, 2009 PeMS detector health data report was reviewed to identify corridors with sufficient detector coverage to serve as study corridors. For many of the District 8 corridors, the PeMS detector health report showed sufficient mainline detector coverage with many of the mainline detectors reported in "good" condition. Table 2.4 also shows the Caltrans PeMS detector coverage (number of mainline PeMS detector stations reporting "good" data) for the potential test corridors.

Traffic congestion mostly occurs during the peak periods and on the midday traffic periods. Figures 2.2 through 2.9 display the PeMS generated congestion scans (average mainline vehicular speeds in the time-space plane) for each of the potential study corridors in District 8 with good detector coverage. One of the study corridor criteria was the presence of recurrent traffic congestion or the presence of a recurrent bottleneck in at least one location on the corridor. Reductions in mainline traffic delays or recurrent congestion attributable to changes in ramp metering policies cannot be obtained and monitored unless there is at least some level of recurrent congestion on the corridor.

Table 2.4 District 8 Freeway Corridors with Metered On-Ramps

County	Freeway Direction	Begin PM	End PM	Begin On-Ramp	End On-Ramp	Metered On-ramps	Good PeMS Stations	PeMS Stations per Mile
RIV	15 NB	38.91	48.37	Ontario Ave	Limonite Ave	7	19	2.01
RIV	60 EB	11.80	16.60	Main St	Perris Blvd	5	0	0.00
RIV	60 WB	13.39	16.14	Day St	Perris Blvd	5	0	0.00
RIV	91 EB	1.07	21.30	Green River Rd	La Cadena Dr	19	27	1.33
RIV	91 WB	1.00	21.47	Green River Rd	Spruce	19	20	0.98
SBD	10 EB	0.81	10.98	Monte Vista Ave	Etiwanda Ave	11	17	1.67
SBD	10 WB	0.58	10.84	Monte Vista Ave	Etiwanda Ave	13	15	1.46
SBD	60 EB	1.49	9.10	Ramona Ave	Haven Ave	8	11	1.45
SBD	60 WB	1.17	9.75	Ramona Ave	Milliken Ave	9	9	1.05
SBD	71 NB	0.87	8.23	Chino Ave	Euclid Ave	8	1	0.14
SBD	71 SB	1.10	8.00	Chino Ave	Euclid Ave	8	1	0.14
SBD	210 EB	0.10	17.68	0.1 M e/o Co-Line	Ayala	14	20	1.14
SBD	210 WB	1.40	20.76	Mountain Ave	State	16	9	0.46
SBD	215 NB	5.12	6.94	Orange Show Rd	4th St	6	1	0.55
SBD	215 SB	5.43	7.30	Orange Show Rd	5th St	6	0	0.00

Note: Green highlighted rows are the best suited study corridors in District 8 (sufficient number of metered on-ramps, overall corridor length and number of functional PeMS stations).

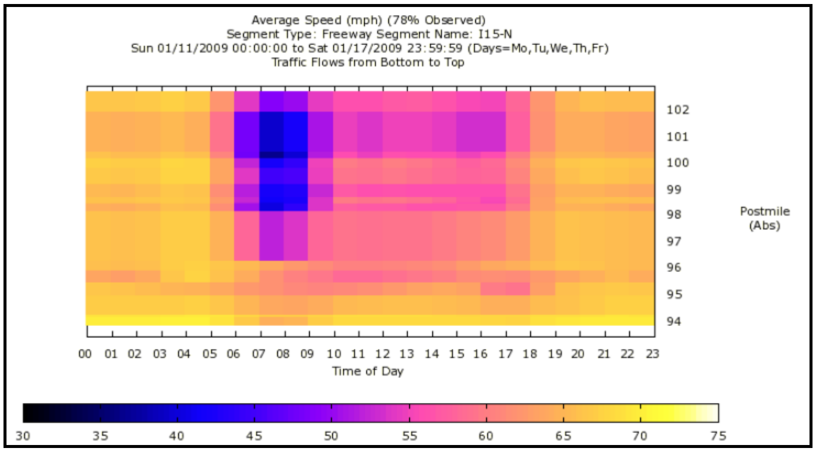

Figure 2.2 Congestion Scan for NB I-15 (Riverside County)

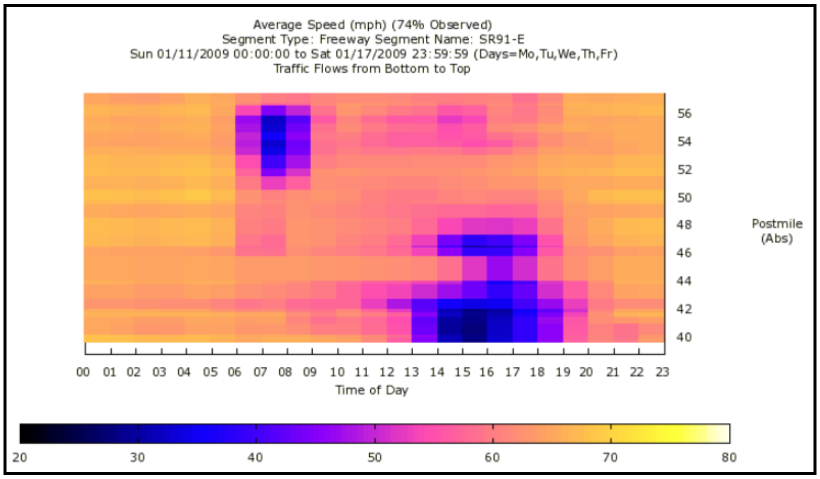

Figure 2.3 Congestion Scan for EB SR-91 (Riverside County)

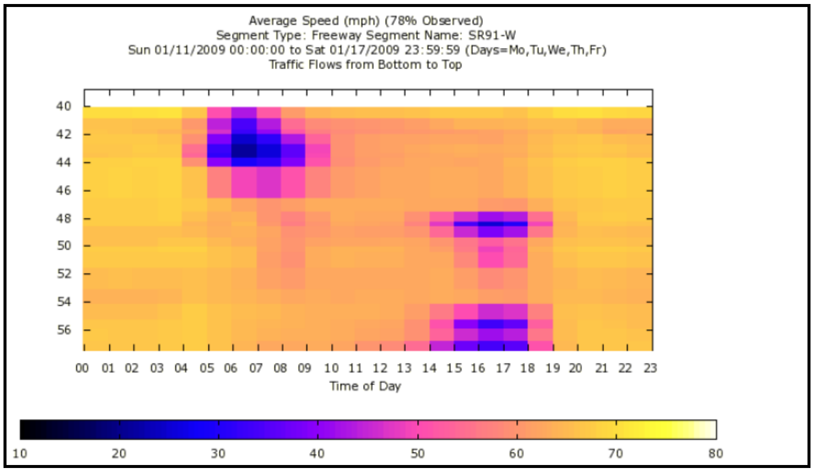

Figure 2.4 Congestion Scan for WB SR-91 (Riverside County)

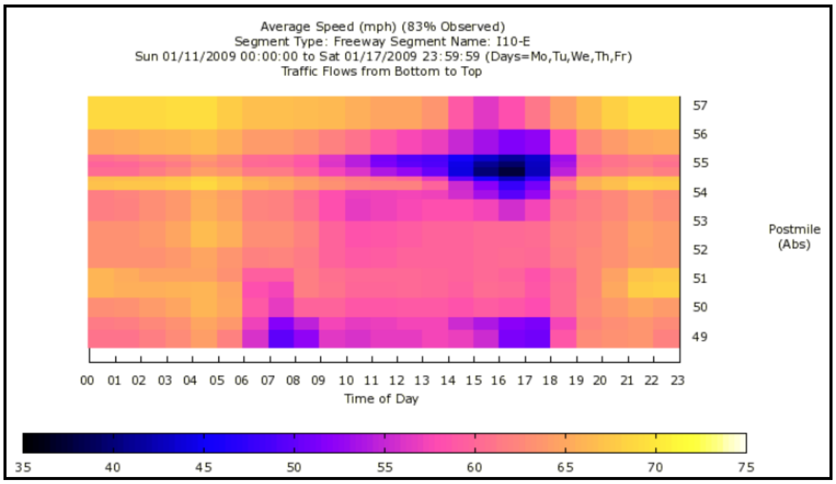

Figure 2.5 Congestion Scan for EB I-10 (San Bernardino County)

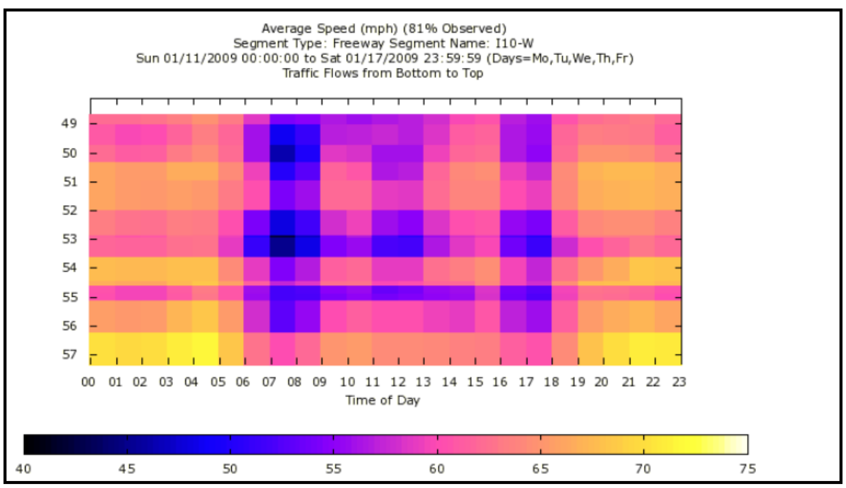

Figure 2.6 Congestion Scan for WB I-10 (San Bernardino County)

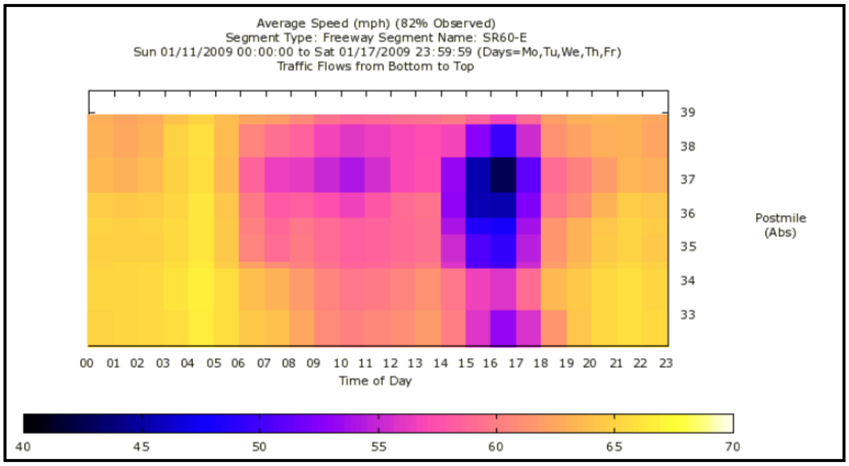

Figure 2.7 Congestion Scan for EB SR-60 (San Bernardino County)

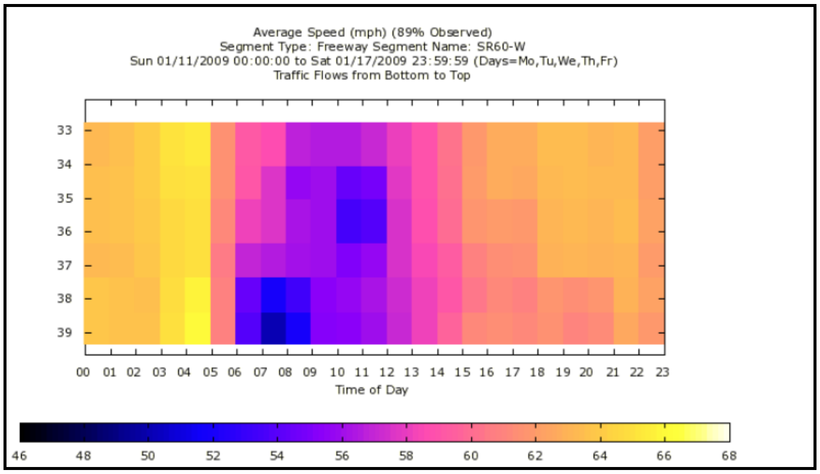

Figure 2.8 Congestion Scan for WB SR-60 (San Bernardino County)

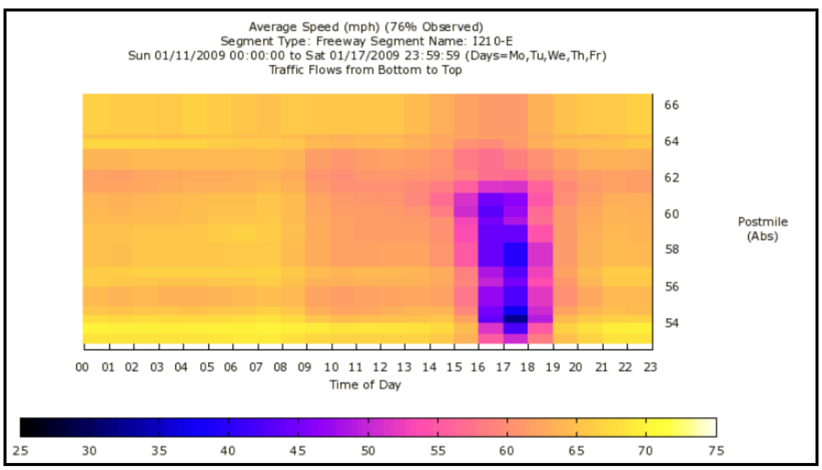

Figure 2.9 Congestion Scan for EB I-210 (San Bernardino County)

2.3 Selected Analysis Corridors

The District 6 SR-41 corridor was slightly shorter than ideal (less than 5 miles) but otherwise met all criteria (at least 5 miles in length with 5 or more metered on-ramps), contained at least one recurrent bottleneck, and had adequate functional PeMS mainline stations to quantify mainline traffic congestion. The eight study corridors selected from District 8 met the study's requirements.

The nine freeway corridors listed in Table 2.5, one in District 6, and 8 in District 8, were selected for the empirical performance evaluation of the impacts of the extended-hours local responsive ramp metering strategies.

Table 2.5 Corridors Selected to Serve the Study

Caltrans District	County	Freeway Corridor	Corridor Length (miles)	Number of Metered On-Ramps	Extended Hours of Operation
6	Fresno	SR-41 Northbound	3.2	6	7:00 AM – 6:00 PM
8	Riverside	I-15 Northbound	9.5	7	5:00 AM – 8:00 PM
8	Riverside	SR-91 Eastbound	20.2	19	5:00 AM – 8:00 PM
8	Riverside	SR-91 Westbound	20.5	19	5:00 AM – 8:00 PM
8	SBDO	I-10 Eastbound	10.2	11	5:00 AM – 8:00 PM
8	SBDO	I-10 Westbound	10.3	13	5:00 AM – 8:00 PM
8	SBDO	I-210: Eastbound	17.6	14	5:00 AM – 8:00 PM
8	SBDO	US-60 Eastbound	7.6	8	5:00 AM – 8:00 PM
8	SBDO	US-60 Westbound	8.6	9	5:00 AM – 8:00 PM

CHAPTER 3
DATA ANALYSIS

This Chapter describes the freeway corridor performance evaluations for the congestion responsive ramp metering strategies for the selected test sites described in the previous chapter. The Caltrans PeMS or ATMS databases served as the primary data sources for this corridor level performance evaluation, providing 24-hours/7-days traffic volume, occupancy and speed data at each freeway mainline Vehicle Detector Station (VDS) location along each selected study corridors.

From the corridor selection process described in the previous chapter, the nine test corridors selected from District 6 and District 8 (listed in Table 3.1) were used in this corridor level performance evaluation:

Table 3.1 Empirical Study Corridors

District & County	Freeway & Direction	Begin PM	End PM	Length (miles)	Begin On-Ramp	End On-Ramp	Metered On-ramps
6 - FRE	41 NB	25.39	28.57	3.2	McKinley Ave	Shaw Ave	6
8 - RIV	15 NB	38.91	48.37	9.5	Ontario Ave	Limonite Ave	7
8 - RIV	91 EB	1.07	21.30	20.2	Green River Rd	La Cadena Dr	19
8 - RIV	91 WB	1.00	21.47	20.5	Green River Rd	Spruce St	19
8 - SBDO	10 EB	0.81	10.98	10.2	Monte Vista Ave	Etiwanda Ave	11
8 - SBDO	10 WB	0.58	10.84	10.3	Monte Vista Ave	Etiwanda Ave	13
8 - SBDO	60 EB	1.49	9.10	7.6	Ramona Ave	Haven Ave	8
8 - SBDO	60 WB	1.17	9.75	8.6	Ramona Ave	Milliken Ave	9
8 - SBDO	210 EB	0.10	17.68	17.6	0.1 M e/o Co-Line	Ayala Dr	14
8 - SBDO	210 WB	1.40	20.76	19.4	Mountain Ave	State St	16

Figures 3.1 and 3.2 show the general locations of these test corridors.

3.1 Data Collection and Analysis

The basic source of field data was the 5-minute aggregated traffic count, speed and occupancy detector data which was downloaded from the Caltrans PeMS website. Three months of data were analyzed for the "before" evaluation, and another three months of data for the "after" evaluation. In District 8, the "before" period was from October 1st to December 30th 2008 workdays only, and the "after" period was from October 1st to December 30th 2009 workdays only. In District 6 the "before" period was from August 28th to October 28th 2015 workdays only, and the "after" period was from August 28th to October 28th 2016 workdays only.

The PeMS 5-minute data were downloaded and filtered to include the typical workdays (i.e., non-holiday weekdays). Further, only data from detectors that were operational in both the "before" and "after" periods were used to ensure that no biases were introduced into the analysis by different detector spacing or from using detectors with different calibration properties.

Next, the PeMS data were filtered and validated; missing and suspect data points were identified and replaced with valid data from neighboring upstream and downstream detectors. Likewise, outliers (suspect data) in the datasets were identified and replaced with imputed values. Typical causes for outliers in freeway traffic datasets include very disruptive freeway accidents or other unusual conditions such as work zone lane closures. Sometimes outliers exist because of hardware or software malfunctions in the traffic monitoring systems. The outlier data points were inspected then replaced with valid imputed data as deemed appropriate.

The following performance measures were computed for each traffic corridor "before" and "after" the ramp metering operation:

- Traffic throughput (traffic volumes)
- Vehicle mile travelled (VMT)
- Vehicle hours travelled (VHT)
- Corridor travel times
- Average freeway speeds

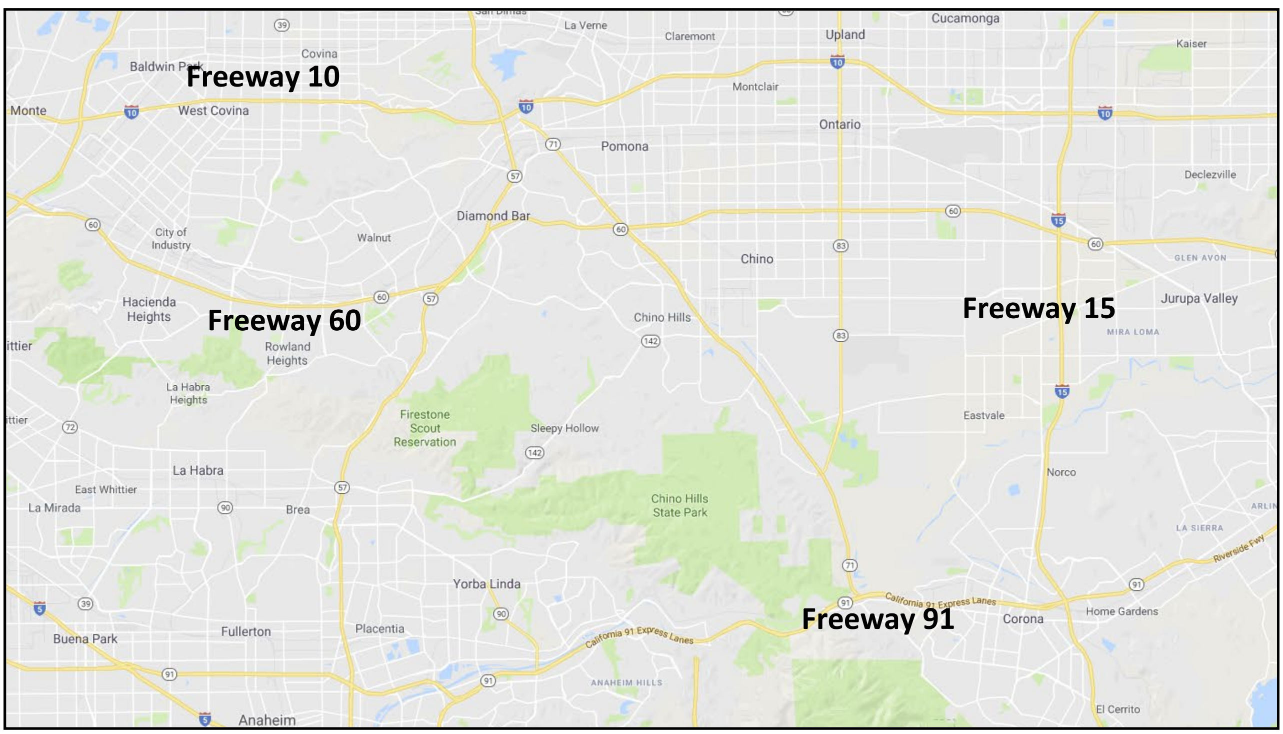

Figure 3.1 Selected Test Corridors - District 8

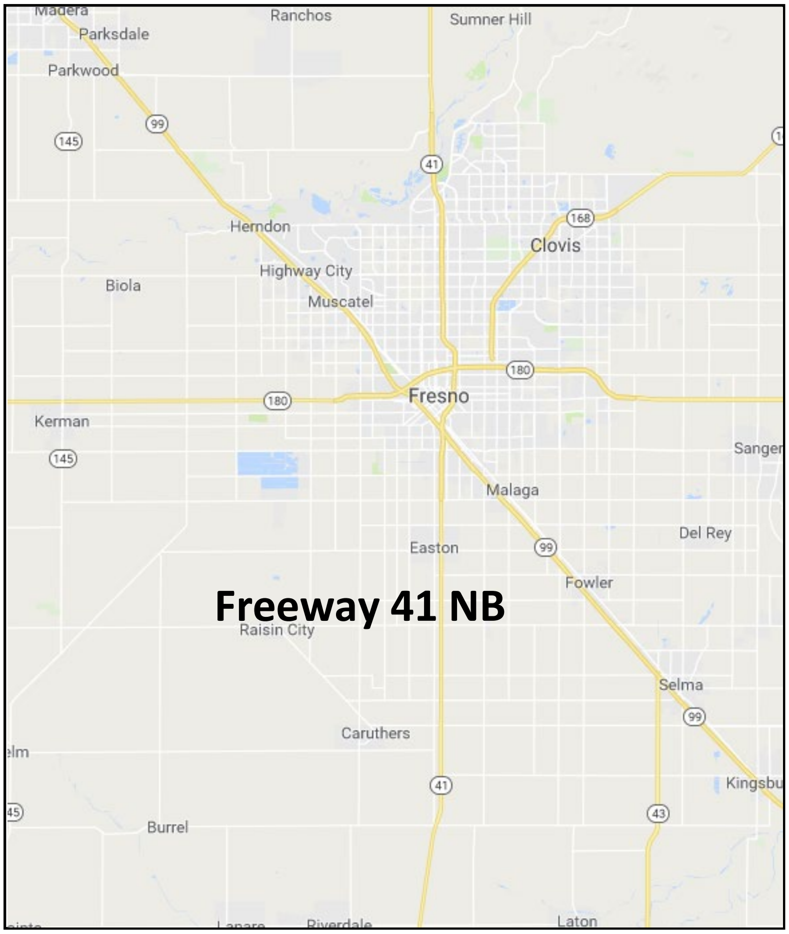

Figure 3.2 Selected Test Corridors - District 6

To aid in the empirical evaluation, input-output (or queueing diagrams) were created to visualize the extent of the traffic congestion in both the before and after conditions, and to measure the corridor's vehicle throughput. In the first step of the process, cumulative vehicle count (volume) curves were created from the PeMS traffic volume data. The vehicle count curves were then used to create typical input-output diagrams to assess "before" vs. "after" differences in the corridor's vehicle throughput. Background volume and speed values were subtracted from the cumulative curves to visually magnify the differences in both measures. The resulting input-output diagrams were used to quantify the corridor's throughput.

Figure 3.3 illustrates the process and shows the resulting input-output diagrams for EB SR-91 in District 8. It shows the VMT and speed plots "before" and "after" the extended hours ramp metering strategy for the EB SR-91 freeway. Figure 3.4 shows the cumulative plots of cumulative VMT and speed curves for the same freeway.

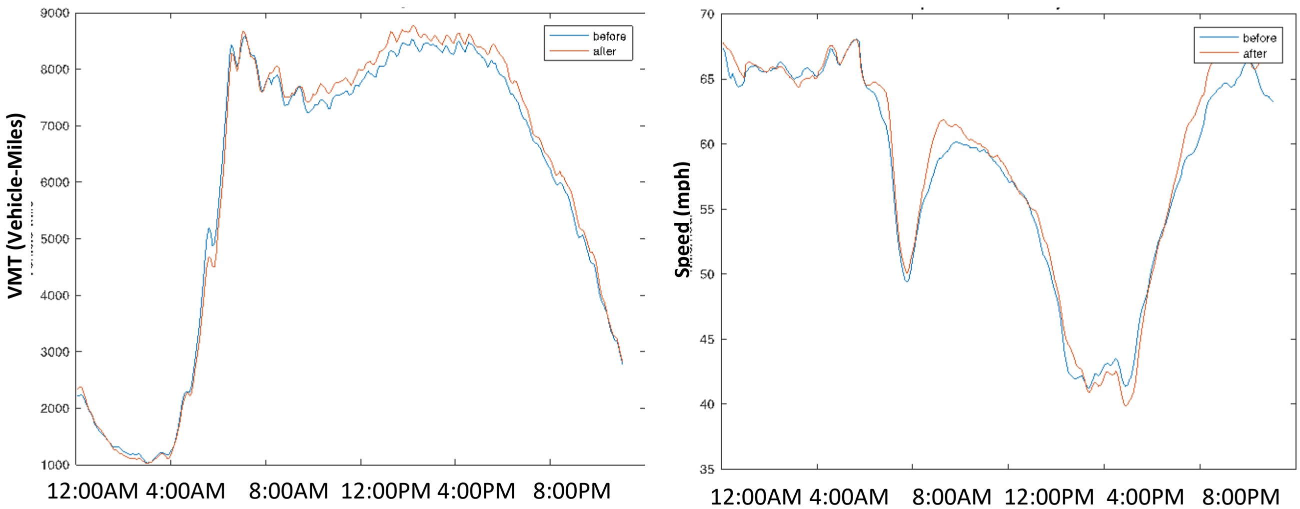

Figure 3.3 VMT and Speed – EB SR-91

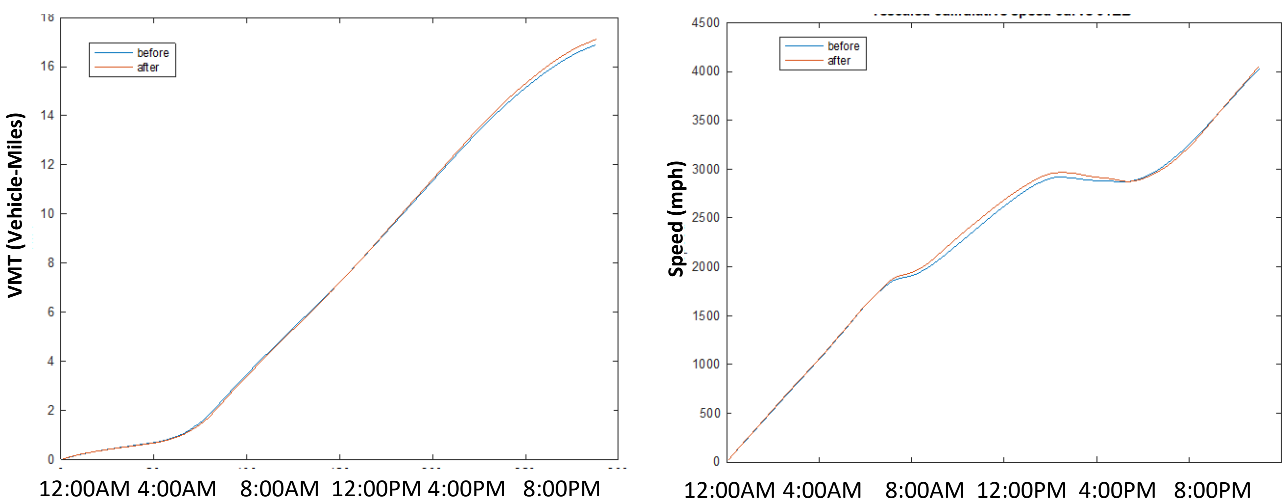

Figure 3.4 Cumulative Curves VMT and Speed – SR-91 EB

The corridor's VMT was estimated by using the PeMS measured traffic flows and the PeMS station length of influence. The VHT was estimated from the VMT and the average speed from the PeMS mainline freeway detectors.

3.2 Findings

Overall, the majority of the study corridors showed performance improvement after implementing the extended hours ramp metering strategies. The increases in the average vehicular speeds concurred with the increases in corridor vehicular throughput (VMT) during the peaks and/or the midday time periods. However, there were some inconsistencies in the observed performance gains, and improvements could not be shown on a number of the study's corridors. For presentation of the results, the test sites (corridors) were grouped into four general categories depending on the observed corridor-level performance gains:

Category 1: District 8 SR-91 Eastbound, SR-91 Westbound, SR-60 Westbound, and I-210 Eastbound corridors. Vehicle throughput increased during the day, and the average corridor speeds increased in the off-peak period.

Category 2: District 8 I-10 Eastbound, I-10 Westbound, and I-15 Northbound corridors. The study's performance evaluation revealed a decrease in throughput (VMT) and an increase in average corridor speeds during the majority of the midday (off-peak) period. These observed increases in the corridor average speeds could simply be from the decreased traffic demand and cannot be directly attributed to the ramp metering strategy change to extended metering hours.

Category 3: District 8 SR-60 Eastbound corridor. The performance evaluation produced mixed results. Average speeds and VMT improved during portions of the day. No consistent trends were identified in most time periods.

Category 4: District 6 SR-41 Northbound corridor. The corridor average speeds increased before the AM peak period and after the PM peak period, with no noticeable performance gains during the peaks or midday. Some inconsistencies were observed, as findings were not stable across the off-peak periods.

CHAPTER 4
POLICY RECOMMENDATIONS ON
DETECTOR AND DATA REQUIREMENT

4.1 Introduction

Data quality is critical to the successful operation of CRRM. It is more so for non-peak hours than in peak hours as the status quo. This chapter will discuss the data dependency of CRRM.

4.2 Data Requirement for CRRM

Higher quality traffic management needs adequate and good quality data. In general, for a given implemented RM algorithm, better real-time traffic data quality will lead to better RM control performance. However, traffic detector data always have some errors which vary in Caltrans from district to district. The data error may be caused by many factors, to name a few: loop detector malfunctioning temporarily or consistently (broken), loop detector card malfunctioning or broken, communication error between the physical loop circuits in the road and the corresponding traffic controller in the cabinet at the roadside, and power outage. Therefore, it is necessary to keep some persistent maintenance effort so that the data will have reasonably good quality. It would be difficult to give a quantitative number to describe the heath of the real-time data. However, for the operation of CRRM for extended hours, it would be necessary to keep the detector data health at 90% level or above at critical locations which include the sections with high demands and high incident/accident rates. The reason is that the activation of the RM for extended hours will completely depend on the traffic detector data. If the detector is wrong, the RM activation and its metering rate will be wrong. This is different from what would happen in AM or PM peak hours in that, in peak hours, traffic demands are reasonably consistent and most drivers get used to the RM operation. Even if RM rate at some locations are somehow not reasonable, it would be rare for public driver to complain.

The technology underneath of the CRRM is still the LRRM. Therefore, we need to have a look at what is needed for the operation of LRRM. Since most Caltrans freeway operation still depends on loop detector station, the following discussion will mainly focus on such traffic detectors. LRRM operation completely depends on the data quality of its immediate upstream traffic detector station. The measured state parameter used is the "occupancy". It is the percentage of average vehicle dwell time over the loop detector circuit buried in the road. The data health depends on several factors [5, 6, 7, 8, 9] as mentioned above. Furthermore, the connection of the traffic controller to regional TMC, whether through modem or cable needs to be well maintained so that freeway traffic operation engineers can regularly and remotely check the health status of the loop detector stations in the field.

4.3 Minimum Data Requirement

Minimum data requirement can be described as follows for mainline and on-ramp respectively.

For mainline detectors: occupancy detection for each lane including General Purpose (GP) lane and HOV lane; vehicle count or flow for each lane is a plus; speed detection is not used in Local Responsive Ramp Metering but could be used for more advanced traffic management in a long run;

For on-ramp detectors:

- Detectors before the stop line: occupancy of GP lane is critical for RM signal operation; flow/count is useful for better handling of on-ramp queue;
- Detectors after the stop line: it is not critical for GP lane, but vehicle counts may be useful for more advanced traffic managements strategies in a long run;
- Detectors for HOV lane is not critical, but may be helpful in a long run;
- Advance detectors at upstream of the on-ramp: they are important for on-ramp queue detection and handling.

4.4 Maintenance Requirement

As discussed above, data quality is critical for the operation of CRRM in extended hours since the ramp meter activation will solely depend on the data quality. If the latter is wrong, the activation of the RM will be wrong which could induce negative impact of traffic flow and cause complaints from public drivers. It might lose the support of local jurisdictions. Therefore, traffic detector maintenance should be the major tasks of the freeway traffic engineer who is responsible for the operation of CRRM.

4.5 Developing Simple Detector Data Fault Checking and Handling Functionality in URMS

Since the LRRM operation usually does not have traffic data fault detection and handling, it would be very helpful to develop some Application Modules in URMS for simple data health checking and fault management for better CRRM operation:

- Check of traffic flow (or vehicle count) with the *Law of Conservation* for adjacent detector stations: the total flow of detectors of all main lanes plus the flow from on-ramp should be similar to the sum of its immediate downstream detector station total flow and off-ramp flow; if they are significantly different, then one of the detector stations has a health problem;
- Check the occupancy of the detectors of all lanes: normally, the occupancy and speed curve should be similar to the Fundamental Diagram (when the occupancy is below 13%, the speed should be above 45 mph; if occupancy is over 40%, the speed should be below 30mph), otherwise, either speed or occupancy detection may have a fault or are not accurate enough; however, only one-lane with high occupancy and low speed may be reasonable if the traffic congestion is caused by off-ramp queue back-propagation.

If one lane detector data (particularly, occupancy) has a fault, use its adjacent lane data to replace it. If the whole detector station (all lane occupancies) data has a fault, use the average of upstream and downstream detector station data to replace it. In doing so, the data system will be more reliable with respect to some temporary fault. Of course, permanent data fault of a loop detector station needs to be resolved as soon as possible by freeway traffic engineers in-person to ensure high quality of operation of LRRM.

4.6 About Other ITS Data

ITS (Intelligent Transportation System) data application is on the horizon of some Caltrans Districts such as D3 and D4. Since the operation of CRRM heavily relies on the traffic data quality, it is beneficial to incorporate the ITS data with the loop detector data to obtain better quality and reliability of traffic state parameter estimation.

ITS data including cellular phones will definitely help in traffic state parameter estimation for more advanced RM strategy such as corridor-wide Coordinated Ramp Metering [10].

Other traffic data such as connected vehicle (such as cellphone) data still cannot be directly used for LRRM yet unless the control logic is changed. The reason is that LRRM determines the RM rate inversely proportional to the occupancy of the immediate upstream loop detector station. Looking ahead, if Caltrans Traffic Operation Division intends to use Coordinated Ramp Metering strategy to manage freeway traffic, then traffic speed and flow at different fixed locations, as well as traffic density of each section, will be very important. Connected vehicle data can be used for speed and density estimation. Roadside sensor such as loop detector will still be necessary for flow (or vehicle count) estimation.

4.7 Recommendations

Operation of CRRM in non-peak hours and weekends to address traffic congestion caused by incidents, accidents and special events would require traffic detector (usually inductive loops) health to be 100% of time in proper normal operational condition, and the accuracy to be 90% or above at critical locations which include the sections with high demands and high incident/accident rates where it is the most needed. According to PeMS system report and the previous projects on loop fault detection, the health of loop detection is way lower than this criterion and varies significantly from district to district. Therefore, the physical condition for the operation of CRRM in the large in California is ready yet.

To avoid this problem and for data quality improvement, we recommend two strategies: (a) to improve URMS software for better traffic state parameter estimation; and (b) to progressively operate CRRM. More specifically, it would be helpful for the software group of Caltrans Division of Traffic Operations to add some APIs (Application Program Interface, or module) in URMS for traffic data fault detection and management, which could potentially save a significant amount of time than doing this at the district level. Therefore, extending operation hours for CRRM from peak hours to non-peak hours and weekends needs to be conducted progressively with the following steps:

Step 1: Identify the areas and freeway corridors which could have high traffic volume in extended hours and on the weekends and improve the traffic data quality to the required level. Then apply CRRM in those areas and corridors first.

Step 2: Assign a traffic detector engineer particularly responsible for the data quality monitoring and improvement; the engineer needs to report to the Traffic Operation Chief of the TMC about the health status of following:

- Loop circuit
- Traffic controller functionality

- Loop detector cards
- Connection between the circuit buried in the lane and the controller in the cabinet
- Connection between the controllers in the field and the TMC traffic monitor
- Data quality based
    - observation (compared to field video camera observations) monthly
    - quantitative analysis (every 6 months)

Step 3: Repairing the faulty loops, correcting faulty data, and resolving any data link problems as soon they have been found

Step 4: Conduct adequate public outreach before CRRM switching ON with district Public Information Office (PIO) through website, roadside message sign, public meeting, and local government association

Step 5: Progressively switching ON the operation:

- Choose one corridor to switch ON the CRRM for some extended hours which are likely to have congestion
- Check if the traffic state parameter, particularly the occupancy measurement is reasonable
- Evaluate if the CRRM "ON" time corresponds to traffic congestion in the field in the sense that the actual traffic congestion on the freeway corridor actually active the RM at right time and location; this need to be conducted in the following way: (a) find a location or several locations covered by video camera with link to TMC which can be used to monitor the real traffic; (b) to watch the RM activation time and location in TMC; and (c) to evaluate if such activation is reasonable. If the evaluation gives positive answer for a week, then CRRM can put in operation; otherwise, check the data system and the LRRM system to find out problem.

Step 5: Regularly checking physical traffic detector station operational condition: including circuit buried in the lane, traffic controller, detector card operating status and its sensitivity, all connections (cable and wireless modem)

Step 6: Regularly investigating traffic detection accuracy in peak hours using probe vehicles: to drive probe vehicles in the traffic on a well-selected freeway corridor for traffic observation; compare the observed traffic with traffic detector data; this can be achieved with some data logging and displaying equipment on the probe vehicle which is linked with roadside traffic controller for retrieving real-time detector data; if the speed data of the loop detector is reasonably match (within 5~10% threshold) with the probe vehicle speed, the traffic detector health is considered satisfactory.

CHAPTER 5
REST-IN-GREEN OR BLACK FOR OPERATING OFF METERS

This research was supposed to investigate the effectiveness of setting the ramp meters on "Rest-in-Green" or Black in general, when they are not in operation, considering energy consumption and driver acceptance. Since this project does support field operational test, the project team is not able to gauge the driver's preference. The project team also searched literature and could not find any study focusing on this topic before. Therefore, this chapter could only provide some recommendations in general.

5.1 RM Signal Lights

RM Signal Heads—The signal heads used for ramp metering are either two-section or three-section heads. Two section heads have green and red indications. Three section heads include the yellow indicator and may be more familiar to most drivers [11].

Single or Multi-Lane Metering—Single lane metering allows only one vehicle to enter the freeway during each signal cycle. Multi-lane metering requires two or more lanes to be provided on the ramp and a signal head dedicated to each lane. After the stop bar, the lanes are required to merge into a single lane before merging onto the freeway. For Multi-lane metering, the green times for each lane could be alternated for easier merge of released vehicles.

Single or Dual Release Metering—One vehicle per green (or single release metering), operates with a shorter green time than with two vehicles per green (or dual release) approach. Dual release allows for two vehicles to enter the freeway each cycle but requires a longer green time. The dual release metering approach usually increases ramp capacity under metering. However, whether using one-vehicle-per-green or two-vehicle-per-green will depend on the acceptance capability of the mainline traffic volume upstream and on-ramp demand.

5.2 Power Consumption Analysis

The following are the main factors for the choice of turning the RM traffic lights to "OFF" or setting it to constant green (or a Green Ball) when the RM is not actually activated:

- Power consumption
- Public drivers' understanding/misunderstanding and acceptance

It is clear that setting the RM traffic light to Green Ball will consume more power. However, such setting tends to bring more attention to the public drivers and to alert them that the ramp meter is still "ON" but the drivers do not need to stop at the meter. Psychologically, the drivers would be more prepared for the RM to come back anytime.

Turning the traffic light completely "OFF", on the other hand, will surely save power. However, it tends to make the drivers believe that the RM is really turned off, and that RM will not be "ON" until the next peak hours as they experienced before, which at least will last for quite a while. If the RM suddenly turned on in non-peak hours or in the weekends, most public drivers may not get used to it. Some of them may not pay enough attention, and even commit violations.

The following is a quantitative estimation of energy consumptions for the two scenarios, i.e. setting to Green Ball or switching off when the RM is not activated, if LED traffic light is used. It is assumed that RM will be ON for AM and PM peak hours. Then the only time intervals for comparison are off-peak hours and weekends. The parameters are referred the work in [12, 13, 14]. The following assumptions are made for example:

- Incandescent Lamps or LED lights are used
- Operation strategy
  - Using Green Ball if RM is not activated
  - Switching OFF RM signal and assuming average of 10% extra time ON
- Total extended operation hours (128 hours in total) are in each week including:
  - 7:00 PM – 6:00 AM (week days)
  - 9:00 AM – 2:00 PM (weekdays)
  - Weekends (Saturday and Sunday: 48 hours in total)
- For peak hours, the RM system will be operated as the status quo:
  - 6:00 AM – 9:00 AM (week days)
  - 2:00 PM – 7:00 PM (weekdays)

Table 5.1 Estimation of a single RM signal energy consumption for different operation scenarios

Traffic light type	Power	Green Ball if not activated	Switch OFF if not activated with 10% on-time	Life cycle
LED Light	15-25 [W]	1.92-3.2 [kW.hr]	0.192- 0.32 [kW.hr]	100,000 [hr]
Incandescent Lamps	150 [W]	19.2 [kW.hr]	1.92 [kW.hr]	2000 [hr]

Based on this table, one can easily estimate the cost of LRRM operation for extended hours in different scenarios.

5.3 Drivers Perspective

Since this project did not include field test of driver acceptance and there is no other study focusing on the driver preference for the RM signals when it is not metered, the project could only provide some viewpoints on this topic which may not reflect the truth.

The following is a summary of pros and cons for the two approaches for the ramp metering signal.

Setting to Black as RM is OFF

- Pros:

- Saving energy: 0.2 ~ 0.3 [kW] per hour per light
- Less traffic light maintenance will be required

- Cons:
  - Driver would have less attentiveness
  - It will take longer time to get used to RM in extended hours and in the weekend

Setting to Green Ball as RM is OFF

- Pros:
  - More energy will be consumed: 0.2 ~ 0.3 [kW] per day per light
  - More traffic light maintenance will be required
- Cons:
  - Driver would have more attentiveness and will be ready to react if RM is activated in extended hours and in the weekends.
  - Drivers tend to believe that the RM is on 24/7; in the long run, this approach would lead to higher compliance rate.

5.4 Recommendation

It is recommended that energy consumption and effectiveness of RM should be the main factor for the operation of LRRM in extended hours. LED light will significantly reduce energy consumption (up to 80% reduction) with increased life cycle compared to Incandescent Lamps although the first investment would be higher. Whether to adopt "Green Ball" or "Black (OFF)" when Ramp Metering is not activated will also depend on the budget and staff support availability. This can be different from District to District. It is not necessary to have state-wide regulation.

CHAPTER 6
POLICY RECOMMENDATIONS ON IMMEDIATE OPERATION HOURS

6.1 Introduction

The principal function for LRRM is to be locally responsive to peak hour traffic by reducing the traffic flow into the freeway mainline to mitigate traffic congestion. The ramp meter rate is the maximum number of vehicles to be released into the freeway mainline. The mechanism for the determination of the average RM rate of an on-ramp is completely determined by the traffic detection immediate upstream mainline. It is clear that proper operation of LRRM for traffic improvement in peak and non-peak hours relies on two factors:

- The accuracy of the traffic detection (mainly occupancy and flow/count)
- The LRRM algorithm: how the occupancy thresholds are determined with respect to the RM rate to be executed
- Other exception handling strategies such as queue over-write

6.2 The Difference for LRRM Operation in Peak Hours and Non-Peak Hours

As formerly discussed, for non-peak hours operation of LRRM, the traffic detection accuracy requirement needs to be very high to avoid wrong activation/deactivation. Therefore, the LRRM operations for extended hours should be operated progressively on a freeway corridor from ***low level*** to ***high level*** (fully traffic responsive) depending on traffic detector health (accordingly, real-time traffic data quality). The following progressive strategy is suggested considering the limit of maintenance staff:

- Selected freeway corridors which have significant non-recurrent congestions in off-peak hours and weekends
- Checking the traffic detector and data systems, and conducting necessary repairs and maintenance to make sure the traffic data quality is high
- Adjust the loop detector sensitivity to make sure the LRRM activation/deactivation is reasonably correct
- Progressively switching on LRRM for extended hours

6.3 CRRM Algorithm Implementation and Performance Limit

Actual field implementation of CRRM is still LRRM which is completely determined by the understanding of the traffic by the local RM engineers. This understanding is the result of long-term cumulative observation and experience. The traffic engineer usually determines the occupancy thresholds with respect to the RM rate for each lane of an on-ramp. Therefore, the look up table is usually different from Caltrans district to district and even different from freeway corridor to corridor in the same Caltrans district. It is very important for the freeway RM engineer to understand the traffic from a corridor level instead of for individual on-ramps.

The reason is that the traffic pattern at different locations of freeway corridors affect each other dynamically. However, LRRM can only respond the traffic of the immediate upstream of the on-ramps. This is the performance limit of the LRRM, which cannot be overcome by simply tuning the occupancy thresholds and the corresponding RM rates.

6.4 Recommendations

Extending operation hours for LRRM from peak hours to non-peak hours and weekends needs to be conducted progressively with the following approaches:

Step 1*:* Conducting adequate outreach activities for the extended hour-operation to gain support from the public and local jurisdictions;

Step 2*:* Selecting freeway corridors which have significant non-recurrent congestions in off-peak hours and weekends;

Step 3: Making sure that the data system meets the requirements for CRRM operation in extended hours and in the weekends;

Step 4*:* Conducting dry-runs – with traffic detection data and RM rate data logged and without field activation of RM signal for extended hours; this need to be continued for at least a month or more; then conducting a data analysis to find out if the RM switching ON events are reasonable; if not, the RM plan may need to be revised;

Step 5**:** Properly setting RM rates for non-peak hours with respect to the occupancy thresholds based on the experiences and observation of local freeway RM engineer;

Step 6*:* Field test of LRRM operation for some extended hours with tight monitoring of the traffic to find out if the activation of LRRM in extended hours is reasonable; tuning the system if necessary;

Step 7: After accomplishing all the steps above satisfactorily, CRRM can be operated regularly;

Step 8: Gradually apply similar approach to other freeway corridors.

CHAPTER 7
POLICY RECOMMENDATIONS ON THE ON-RAMP STORAGE CAPACITY

7.1 Introduction

Freeway on-ramps are used as a buffer to store vehicles from arterial and surface streets. The ramp meter controls the actual flow from the on-ramp into the freeway mainline according to the traffic situation of the mainline. Mainline traffic will become unstable when the mainline density reaches a certain level, and will break down becoming congested if the volume is too high. On-ramp could be used to store some vehicles to alleviate such a situation to some extent.

7.2 Relationship between On-ramp Storage Capacity and Mainline Traffic

Freeway traffic throughput is mainly determined by bottleneck capacity. On-ramp merging area is generally recognized as the most likely bottleneck locations if the on-ramp demand is high. This is mainly because of several effects to the target lane traffic: (a) merging vehicle lane changing behavior would mainly affect the traffic flow of 1st lane (target mainline) and somehow the 2nd lane; (b) density would increase which implies speed would decrease if it is over the critical density according to the theory of Fundamental Diagram; and (c) the level of cooperation in merging area: if more vehicles move to the 2nd or 3rd lane leaving more space to the 1st lane for the merging vehicles, the negative impact on the target lane traffic will be smaller. Other factors that also play roles in merging vehicle behavior include the road geometry, e.g. if there is an acceleration lane or not, and perception capability of the target lane traffic by the merging vehicles.

The function of RM is to reduce the demand from the on-ramp into the mainline traffic and therefore improve mainline traffic in those aspects. It is clear that if the demand from the on-ramp is high, it is necessary for the on-ramp to have more storage capacity to be able to handle the traffic with more flexibility. There are two possible ways to store the arterial/surface street traffic before injecting into the freeway:

- To store traffic in arterial pockets
- To store traffic in the on-ramps

The main factors that affect the on-ramp storage capacity needs include but are not limited to the following:

- Mainline traffic volume
- On-ramp demand
- Effectiveness of freeway traffic management and control
- Relevant arterial/surface street traffic volume and how it is managed/controlled
- Arterial pocket that could be used for storing traffic to be injected into the freeway

- Effectiveness of arterial traffic management/control
- Effectiveness of coordination mechanisms between freeway traffic management and arterial or surface street traffic signal control

To provide quantitative measure of the on-ramp storage capacity need is a very difficult issue which needs to be supported by a large project for analysis through simulation. This chapter only conducts some qualitative analysis and induced recommendations.

7.3 Using Arterial (or Surface Street) as Storage in Operation

On-ramp storage capacity is very important for the performance of LRRM. Larger storage capacity to store more vehicles during peak periods to avoid the conflict of interests on freeway mainline traffic and arterial traffic maybe required to achieve adequate RM gains. However, extending the storage capacity of an on-ramp can be cost prohibitive, and can be seriously limited by roadway geometry and available right-of-way. Recent research at PATH and other entities nationwide indicated that more effective use of on-ramp storage could be achieved through better real-time coordination of freeway RM and relevant arterial traffic signal control. This can effectively reduce the on-ramp storage demands while maintaining higher performance levels for both the freeway and relevant arterial streets, which will be considered in a separate project. However, the minimum requirement for on-ramp storage from a control viewpoint is necessary to consider although the Ramp Metering Design Manual already considered this from a planning viewpoint. The project will also propose a cautious use of "queue-override".

For RM purpose, the storage requirement mainly depends on the demand of the on-ramp. In principle, higher demand from the on-ramp would require larger storage capacity. However, it also depends on the mainline traffic flow and capacity. Higher mainline capacity and/or lower mainline traffic volume would need relatively lower on-ramp storage capacity.

Those factors are worthy of investigation of an extensive research which is outside the scope of this project. The project will only focus on the effect of on-ramp length on the traffic the operation of LRRM assuming that road geometry for merging is fixed.

In general, to keep the freeway mainline traffic throughput higher, larger on-ramp storage capacity would be preferable. Higher storage capacity would require higher investment of infrastructure modifications. Enlarging the storage capacity sometimes may not be possible in some urban areas such as Highway 101 in San Francisco.

Enlarging the storage capacity is possible in rural areas or wherever the land is available. Enlarging the capacity can be conducted by addition of lane(s), by extending the length of the on-ramp, or a combination of both.

Technology solution: proper coordination of freeway RM and arterial traffic signal control can maximize the utility of the infrastructure.

During peak hours, freeway ramp metering restricts the flow of on-ramp traffic entering the freeway mainline in order to reduce the conflict between on-ramp and mainline traffic. Such an approach mitigates or prevents capacity drop at locations with high on-ramp demand, and therefore maximizes the capacity of the freeway (mainline and on-ramp). However, under independent operation, the arterial traffic signals facilitating freeway access fail to recognize that the metered on-ramps are oversaturated due to reduced capacity and limited storage space. Instead, the arterial traffic signals respond to the peak hour demand by providing long cycles therefore long green durations and progressively coordinating traffic signals along the major arterial that channels traffic entering the freeway, in order to maximize arterial capacity. This may lead to platoons of arterial traffic advancing to the oversaturated on-ramps and thus excessive queues on the on-ramps, which can cause spillback on the adjacent arterial. The queue spillback will not only impede the conflicting directions of the arterial traffic, it will also necessitate queue override at the metered on-ramps, which releases the on-ramp queue onto the freeway and reduces its capacity.

It is noted that the proper coordination of the two control systems can maximize the utility of the infrastructure system. If the traffic demand of the road network is too high and far over the capacity of the network, such coordination will not be able to completely resolve the problem. The reason is as follows:

Since the on-ramp storage capacity is also limited, the extra vehicles have to be stored somewhere: either on freeway or in arterial. To avoid arterial grid lock, queue over-ride strategy is usually used, i.e. operate the RM at the maximum rate if the on-ramp queue is too long which would immediate cause traffic spills back to the arterials. It is known from a rigorous data analysis [15] that on-ramp queue over-ride operation will definitely worsen the freeway traffic.

7.4 Cost and Benefit for Extension of On-ramp Storage

The recent research result of the HEuristic Ramp metering cOordination (HERO) algorithm can be found in [16], [17], [18] and [19]. The principle of the HERO algorithm is essentially to maximally use the entrance ramp storage if both mainline and entrance ramp demand is too high to reduce the input to mainline. The coordination strategy is to fill up the on-ramps from downstream to upstream progressively, which was claimed to work very successfully.

Landman et al. [16] propose a heuristic based synchronization-ramp metering coordination algorithm, which aims at saturating as many upstream local on-ramps as possible before the downstream on-ramps run out of lane storage space. This ramp metering coordination concept is similar to the coordination scheme HERO. The difference between this synchronization algorithm and HERO is that the algorithm is to equally fill the ramps during over-saturated conditions and thus that the storage space at the ramps runs out at approximately the same time.

Faulkner et al. [17] make field implementation of traffic-responsive feedback control strategy HERO (HEuristic Ramp metering cOordination) at the M1/M3 Freeway in Queensland, Australia. Their field implementation results achieve the following improvement in AM peak: 1. Average travel speeds have increased by 7% from 70 km/h to 75 km/h; 2. Average traffic flows have increased by 4% with an additional 150 vehicles per hour throughput; 3. Average travel productivity has improved by 8%; 4. The proportion of trips with good reliability has improved by 37%.

The following is a summary of HERO project in 2008 [20, 21] with the following characteristics:

- 15 km long freeway corridor of M1 Freeway in Melbourne, Australia
- Combined Coordinated Ramp Metering (CRM), Variable Speed Limit (VSL) and Lane Management (LM)

- Expanded on-ramp storage capacity

The performance comparison of the before and after the implementation is listed in the following Table 7.1:

Table 7.1 HERO Project: performance comparison for "before" and "after" scenarios

Performance Indicators	Values		Improvements*
	Fixed Time	HERO	HERO
Average Flow (pcu/h/lane)	1731	1816	+4.9%
Travel Speed (km/h)	48.9	66	+34.9%
Average Delay (min/km)	0.49	0.17	-65.3%
100% Productivity (%)	29.4	72.3	+145.9%
Less than 20% Speed Variation (%)	26.3	65.4	+148.7%
Grade One Reliability	22.4	40.8	+82.1%

The following are some quantitative numbers:

- Flow at bottlenecks of 2166 pcu/h/lane
- Net saving of 4 min 48 sec per vehicle over 15km section
- Equivalent to 1900 [veh.hrs] of delay savings p/day
- Equivalent in time of driving 190,000km (119,000 miles) at 100km/h each day
- (Driving from Los Angeles to New York 43 times)
- Savings of 16,500 litres of petrol a day
- Reduction in Greenhouse Gas of 40 tonne per day
- Reduction of casualty crashes by >30%

The following Table 7.2 is a summary of Economic Benefits: Travel Time + Vehicle Operating Costs (VOC). The project team claimed that the cost was paid back in 11 days after full operation of their integrated traffic management system.

Table 7.2 Economic analysis of the HERO project

Timeframe	Delay Reduction on Freeway (veh.h)	Extra Delay on Ramps (veh.h)	Net Delay Reduction (veh.h)	Saving	Total Saving per Day
6:00 to 10:00 AM	1694	283	1411	$40,323	$54,116 + $39,501 VOC = $93,617
4:00 to 7:00 PM	513	30	483	$13,793	

7.5 Recommendations

Based on the analysis above, there are two options to promote the RM operation:

- Optimally using the current infrastructure by proper coordination of freeway RM and relevant arterial (or surface street) traffic signal controls
- Extending physically the on-ramp storage capacity with increased length and/or the number of lanes

The following are some recommendations for the selection of the two options:

1) If the freeway traffic volume is medium to high, but not saturated: It would be more appropriate to adopt a traffic management approach such as the coordination of freeway RM and arterial (surface street) traffic signal control; basically, the traffic signal control strategy could be based on the following strategy: (a) it feeds traffic to the freeway on-ramp as much as it could take without significantly deteriorating the freeway mainline traffic; (b) using arterial turning storage or even upstream sections to store traffic as much as possible to the extent that it would not affect traffic of other phases/movements; and (c) leaving extra greens of the movement to the on-ramp to other movements to relieve the load of the intersection.

2) If the freeway traffic volume is high and saturated: In this case, there are two options: (a) if the land is available and budget is available, it is suggested to increase the on-ramp storage by extending the length and/or the number of lanes; (b) if the land is not feasible for the extension of the on-ramp storage capacity, the approach of integrated freeway and arterial traffic management should be adopted; and (c) for other intermediate situations, the combination of (a) and (b) could be adopted.

Care must be taken, however. The HERO project is just an example. The approach may not be applicable in general. Besides, the reported traffic improvement may be caused by the joint effect of combined Active Traffic Management strategies (CRM, VSL and LM) instead of just by on-ramp storage capacity increase.

CHAPTER 8
POLICY RECOMMENDATIONS FOR ADDRESSING INSTITUTIONAL ISSUES

8.1 Introduction

Due to the dynamic interaction between freeway traffic and arterial traffic, conflicts of interests may arise when attempting to improve the performance of the freeway system or trying to improve the performance of the arterial or surface street intersection traffic signal control systems. Therefore, some local jurisdictions may be skeptical about recommending their agency to support freeway on-ramp RM operations, or making any change in the RM operation hours and/or strategies. It would be advantageous to Caltrans to have a systematic approach for addressing these institutional issues. Effectively handling these issues and obtaining local agency cooperation and support are critical for the success of implementing CRRM. This will become more critical as Caltrans migrates from locally controlled RM strategies to more integrated and advanced ramp metering strategies in the future.

Each freeway corridor in a Caltrans District may pass one or more counties and cities. To operate RM in a certain period of time, it is necessary to get the permission of local, county and/or city government and local communities. This requires Caltrans District RM engineers to directly communicate with them. There are several organizations to work with including local government association and its related committees.

8.2 Gaining Support from Local County and City Government Association

Local County and City Government Association: for example, for freeway US-101 in San Mateo County, the City/County Association of Governments of San Mateo is the first organization to work with for gaining their support. Usually, it is necessary to give a presentation to the committee member regarding the new activities to be conducted in the RM. This committee is most concerned about the benefit and cost to them for the new control strategy. The Power Point files the project team presented before were about the operation of RM in extended hours on freeway US-101 in the section within San Mateo County:

It is necessary to convince the local government association through an approach without much technical details.

8.3 Meeting with the Technical Committee of the Local Government Association

The second committee to work with is the technical committee of local government association. The Technical Committee members in this committee usually have some transportation and traffic control background and even some experience of traffic management. Their main concern may include the technical feasibility and reasonability of the operation of CRRM operation for extended hours. To convince this committee, it is necessary to conduct a technical presentation to emphasize the benefit from a technical approach and its feasibility based on current infrastructure. It is also necessary to explain that the CRRM operation will still use the LRRM which they are familiar with, which will be unlikely to have negative impact on their local traffic management such as arterial/surface street intersection traffic signal control. In particular, it is necessary to explain the benefit of using the currently available infrastructure to address non-recurrent congestions in off-peak hours and in the weekends. This committee member is interested in the activation of queue-override strategy for ramp metering. This committee will likely be interested in the integration of Ramp Metering and arterial traffic signal controls.

8.4 Meeting with the Committee of Local Residence Representatives

The third committee to work with is composed of the local residence representatives. Those committee members are unlikely to have professional engineering backgrounds in transportation and traffic control. Most members of this committee are mainly interested in the direct effect on and/or benefit of the operation of CRRM to their local communities, in particular, to the access of freeways. The presentation to this committee would be better to focus on those points. Their most concern is that RM could potentially impede their local drivers to access freeway. Although we tried our best in this approach, there was one member of this committee voted against the CRRM operation. Our experiences indicated that this committee was the most difficult one to gain support from.

The main strategies for convincing this committee are suggested to be: (a) RM may limit the number of vehicles to get into the freeway in a short period of time, but the traffic improvement on mainline will eventually benefit the local drivers regarding Total Travel Time if the travel distance is long enough; (b) LRRM has the function of queue over-ride functionality which can be activated to avoid the queue back-propagation from the on-ramp to arterial or surface street.

8.5 Public Outreach

It is important that Caltrans District Public Outreach Office to conduct adequate information distribution through:

- Media (Television, radio stations, post videos at Caltrans website and YouTube, Facebook, Twitter, …)
- The committee of residence representatives of the local government association
- Broadcast information through local media such as TVs, radios, and newspapers.
- Local city council public meetings

The information includes but is not limited to: (a) the objectives for operation of CRRM for extended hours and weekends; (b) technology and infrastructure readiness for doing so; (c) benefit for doing so in the interests of the public drivers; (d) the impact on local road users; and (e) how the RM signal will behave when CRRM is in operation; and (f) a progressive procedure for extending the operation hours of CRRM.

8.6 Recommendations

It is very important to work closely with several committees of the local government association of counties and cities to gain their support. Those committees include:

- Committee of Local Government Association
- Committee of Technical Committee

- Committee of Local Residence Representatives

Each committee represents different group of people with somewhat different interests and concerns. Those interests may have some overlap. It is important to address concerns adequately when working with those committees. Besides, it is also important to conduct adequate public outreach through Caltrans District PIO and through local cities and counties.

CHAPTER 9
CONCLUSIONS

Most RM operations in California highways are currently for peak hours only. It would be beneficial to fully use the current infrastructure for RM to address non-recurrent congestions in off-peak hours and on the weekends. This research effort successfully showed that potential gains could be realized through the thoughtful implementation of a CRRM strategy.

Before the extension of RM operation hours beyond the PEAK hours, it is recommended to update the traffic detector system to deliver good quality traffic data for RM operation. This is very critical since the "ON" and "OFF" time will completely depend on the traffic data input to the RM algorithm, particularly the occupancy of the immediate upstream detector of the on-ramp. The operating hours could be extended progressively depending on the criticality of the location and data quality. It is very important to have supporting staff to regularly maintain the traffic detector stations and to keep them in good health condition and to produce high quality traffic data. It also helpful if URMS has an API with the capability of fault data detection and handling in each 2070 controller.

Field experiments indicated that RM queue-override function would deteriorate its performance. Therefore, larger on-ramp storage capacity would definitely improve RM performance if the demand is high. However, the extension of the onramp for freeway RM is cost prohibitive. A more economical way to remedy this is to conduct the proper coordination of RM with the corresponding arterial traffic signals control, which can improve overall system performance by fully and properly using the storage to reduce or to completely avoid the use of "queue override". Practical implementation of a feasible coordination strategy at an onramp or along a freeway corridor will depend on road geometries and traffic situation of both freeway and arterial corridor.

To successfully implement CRRM, it is also important to work closely with local jurisdictions such as government associations and their committees to gain their support. Different strategies would be necessary for different committees. The public outreach is also important to the success of CRRM.

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