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1. REPORT NUMBER CA14-2223	2. GOVERNMENT ASSOCIATION NUMBER	3. RECIPIENT'S CATALOG NUMBER
4. TITLE AND SUBTITLE Coordination of Freeway Ramp Meters and Arterial Traffic Signals Field Operational Test (FOT)		5. REPORT DATE 12/31/2013 6. PERFORMING ORGANIZATION CODE
7. AUTHOR Dr. Xiao-Yun Lu, Donyan Su, and John Spring		8. PERFORMING ORGANIZATION REPORT NO. UCB-ITS-PRR-2014-2
9. PERFORMING ORGANIZATION NAME AND ADDRESS California PATH Program Institute of Transportation Studies University of California Berkeley Richmond Field Station, Building 452 1357 S. 46th Street, Richmond, CA 94804-4648		10. WORK UNIT NUMBER 65-3763 11. CONTRACT OR GRANT NUMBER 65A0405
12. SPONSORING AGENCY AND ADDRESS California department of Transportation Division of Research, Innovation and System Information 1227 O street, MS-83 Sacramento, CA 94273-0001		13. TYPE OF REPORT AND PERIOD COVERED Final Report 7/15/2011 to 12/31/2013 14. SPONSORING AGENCY CODE Caltrans DRISI

15. SUPPLEMENTARY NOTES

N/A

16. ABSTRACT

This report describes the work conducted under the Caltrans and UC Berkeley contract # 65A0405. The objective of this project was to develop a practical coordination strategy between one freeway ramp meter and one arterial intersection traffic signal and conduct a field operational test. The project team successfully accomplished all proposed tasks.

The project started with literature review, development of a Concept of Operations (ConOps) document, site selection criteria based on several factors, and systematic data collection. The collected data was then used to calibrate a microscopic traffic system modeling using Aimsun, which is used to simulate the field operation test results prior to deployment. After achieving positive results in the simulation modeling, the coordination algorithm were then deployed in the field. The ramp meter 2070 controller running URMS (Universal Ramp Metering System) and the signal 2070 controller were linked and then coordinated. Traffic data before and after the deployment were collected and analyzed.
The test data analysis showed a net delay reduction at Taylor Street Intersection by 7%. The analysis also showed a better use of the entrance ramp storage with higher flow to the entrance ramp while avoiding queue overspill. In addition, the analysis found that the freeway mainline traffic conditions immediately upstream of the entrance ramp remained unchanged by such coordination. Due to the success of the coordination between one intersection and one ramp meter, it may be worthwhile to coordinate a freeway corridor comprised of multiple ramps and arterial signals.

17. KEY WORDS freeway ramp metering, arterial intersection traffic signal control, coordination of ramp metering and intersection signal, URMS (Universal Ramp Metering Systems) and DSCP interface using AB3418(E) protocol, site selection,	18. DISTRIBUTION STATEMENT No restrictions. This document is available to the public through the National Technical Information Service, Springfield, VA 22161	
19. SECURITY CLASSIFICATION *(of this report)* Unclassified	20. NUMBER OF PAGES 129	21. COST OF REPORT CHARGED N/A

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Coordination of Freeway Ramp Meters and Arterial Traffic Signals Field Operational Test (FOT)

Final Report

UCB-ITS-PRR-2014-2

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Acknowledgements

This work was performed as part of the California PATH Program of the University of California Berkeley, in cooperation with the State of California, Department of Transportation (Caltrans); and Federal Highway Administration. The guidance and support from the project panel (listed below) are gratefully acknowledged.

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Executive Summary

This report describes the work conducted under the Caltrans and UC Berkeley contract #65A0405. The objective of this project was to develop and test a practical coordination strategy between a freeway entrance ramp meter and an arterial intersection traffic signal. Since the implementation of the project involved two systems, the project panel formed at the beginning of the project included stakeholders representing both ramp meter and intersection signal engineers in Caltrans District 4.

Activities conducted in this project included extensive data collection, control and coordination strategy development through microscopic traffic simulation, site selection, system development, field implementation and test, and analysis of data before and after the activation of developed control/coordination strategies. To be specific, these activities are described as follows:

(1) An extensive literature review was conducted. Research areas reviewed covered both freeway ramp metering (RM) including Coordinated Ramp Metering (CRM), most recent arterial intersection signal timing strategies including Time-of-Day, Actuated Signal Timing, and Adaptive Signal Timing and Coordinated Signal Timing along an arterial corridor, and the coordination between freeway RM and Arterial Signal. The most influential paper was the one regarding the project for field implementation of the coordination of freeway RM and Arterial Corridor in Southern California [23]. The lesson learned there was proved to be very valuable to the success of this project.

(2) The concept of operations (ConOps) was developed for the proposed freeway ramp meter/street signal coordination strategy. The ConOps developed considered the following factors:

   a. system scope and function;
   b. capability of each component;
   c. theoretical and algorithmic side and practical side;
   d. current situation of the two traffic control systems in the field and the expectation to the systems of the project;
   e. what could be done technically and what was allowed to do in practice.

The ConOps development of this project was conducted iteratively and lasted almost throughout the life of the project with extensive input from the project panel.

(3) Site selection was critical to the success of the project involving field implementation and test. For this reason, site selection criteria were rigorously developed. Besides, the project team always put the institutional issue as the first consideration by inviting comments from all stakeholders. The technical side of site selection included: current situation of the two control systems (freeway RM control and arterial intersection signal control), traffic situation, sensor locations and data quality. PeMS and other data were collected in the site selection process. The selected site was the Taylor Street at SR87 among the 5 candidates in consideration. The entrance ramp receives traffic from WB left turn (LT) and EB right turn (RT) with No Turn on Red (NTOR). The issue was the spillback from the entrance ramp, which caused traffic in WB LT pocket back up, given the existence of close-by parking lot and traffic flow from San Jose City Center during peak hours. The purpose of the coordination strategy was to reduce green time for RT and therefore to give more entrance ramp space to WB LT in peak hours although LT green time was not changed. Since the demand of WB LT was higher, total delay was reduced and the entrance was better used with queue reduction for WB LT movement.

(4) The proposed strategies were first simulated before implementation for field test. In this step, a microscopic traffic simulation model was built and calibrated in Aimsun for algorithm development and evaluation. The system included freeway SR87 section upstream and downstream of Taylor Street, the intersections and all signal control strategies used in the field. The entrance ramp used lane-wise metering – the link between the intersection and the freeway. Extensive data collection was conducted for all the movements of the intersection and freeway for modeling.

(5) Developed a generic algorithm for the coordination of intersection traffic signal and freeway ramp metering. The principle of the algorithm was to optimize the performance of the system by balancing the demand and supply for each movement of the intersection subjected to the constraints of available entrance ramp spaces and given RM rate. The algorithm was simulated and evaluated with very positive results, which was not implemented due to the limit on what we were allowed to do, but it could be used in the future.

(6) System development and integration, which included hardware and software interface with both RM 2070 controller running URMS (Universal Ramp Metering System) and intersection 2070 controller running TSCP 2.17. Dedicated Short Range Communication (DSRC) at 5.9GHz was used to link the two subsystems to avoid security concerns. To avoid any negative impact on traffic operation, the system had been extensively tested before implementation in the field. The test procedure was also progressive. The field test was conducted successfully.

(7) Data analysis was conducted for both before and after the activation of proposed control/coordination strategies to evaluate the performance. The analysis showed traffic performance improvement in two areas: (a) net delay reduction at Taylor intersection by 7%; (b) better use of the entrance ramp with higher flow to the entrance ramp while avoiding queue overspill. However, freeway mainline traffic immediately upstream of the entrance ramp was unchanged. Two points can be inferred from the outcome: (i) some net benefit has been achieved with the proposed control/coordination; (ii) it is necessary to coordinate a freeway corridor instead of just one entrance ramp to improve freeway mainline traffic.

Chapter 1. Introduction

This research report documents the work performed under California Department of Transportation contract 65A0405 for the project titled "Coordination of Freeway Ramp Meters and Arterial Traffic Signals Field Operational Test (FOT)".

The project was sponsored by the California Department of Transportation (Caltrans) and undertaken by the California Partners for Advanced Transportation Technology (PATH). The project duration was from 7/15/2011 to 12/31/2013.

In current traffic operating practice, traffic control at freeway entrance ramps and arterial intersections are operated independently. Such a situation may significantly reduce performance on both roadways. It is recognized that for highly efficient and reliable traffic flow over the entire traffic network, it may be necessary to coordinate the traffic between roads of different levels due to the strong dynamic interaction between them: one of the outputs of the arterial intersection is the immediate input of the adjacent freeway entrance ramp. (This is also the case for freeway exit ramps and arterial intersections, but exit ramps are typically not under traffic control.) The efficiency of the overall traffic network relies on the performance of traffic control systems in different levels and optimal coordination as a whole.

Arterial intersection traffic control maximizes flow by progressively coordinating traffic signals over a series of intersections. Conversely, freeway entrance ramp traffic control maximizes mainline flow by restricting traffic from entering the mainline if the total demand (upstream mainline flow + expected entrance ramp flow) approaches or exceeds the capacity of the downstream mainline section. Another conflict is that arterial intersection traffic control groups vehicles into platoons, while freeway entrance ramp metering tends to break these platoons into individual vehicles – usually one vehicle per green. If an entrance ramp is subjected to a limited storage, either through high arterial demand or low entrance ramp discharge, traffic may spill back from the entrance ramp into the arterial. Balancing these two to achieve maximum flow or minimum Total Travel Time for the overall system is the critical issue.

The objectives of studying the coordination between freeway ramp metering and arterial traffic signal control are: (1) to identify when coordination is necessary; (2) to develop

coordination strategies; (3) to identify any technical hurdles in integration of the two systems for coordination (ramp metering and intersection traffic signal control); (4) to resolve the conflict of interests between freeway traffic control and arterial traffic control; (5) to optimize the control variables such as metering rate and green/cycle length, off-set, priority assignment etc. to minimize the Total Time Spent (TTS) in the system involved; and (6) to fully use real-time traffic data from freeway and arterial to estimate/predict the traffic state parameters for updating the model and the controllers. Basically, this study is a proof of concept.

Although such coordination should be conducted over a corridor level to produce optimal effect for overall corridor to achieve optimal system performance, we initiated a proof of concept project focusing on single isolated entrance ramp and intersection to test the concept before large scale implementation. The intent was to identify and resolve technical problems and institutional issues that could appear in practice such as those encountered in the project reported in [23]. In order to analyze the impacts of various coordination strategies, the research team conducted simulation study for the selected site that included

- Modeling the freeway link (section) with entrance ramp geometry and ramp metering control;
- Modeling the intersection(s) in the proximity of the entrance ramp and the traffic signal control;
- Developing a practical coordination strategy to fully use the ramp storage capacity, data from freeway traffic, and ramp metering strategy, arterial traffic demand, and intersection signal control;
- Implementing the coordination strategy for selected site including: building a reliable communication link between ramp metering (RM) controller and intersection traffic signal controller for data transfer and synchronization, interfacing with traffic controller, and over-writing default control signal etc.
- Solving any technical problems that likely appear in practice, such as the differences between sensors, traffic data types, data update rates, data processing and accuracies, control cabinets and traffic controllers, and the various methods of interface between components [23];

- Setting an example on how to deal with institutional issues involved since such coordination will need crossing jurisdiction boundaries and close cooperation between Caltrans, County and City traffic departments;
- Using this practice as a leverage to evaluate the implemented ramp metering strategy for the selected location and hopefully to improve control strategy to some extent;
- Applying the lessons learned and experiences gained as a foundation and reference for the next step in planning and implementation of corridor level network traffic system such as the I-80 Corridor Integrated Management Program.

Chapter 2. Literature Review

2.1 Introduction

For the coordination between freeway Ramp Metering (RM) and arterial intersection traffic signal control to work, it is necessary to understand the freeway and arterial traffic characteristics, the mechanism of the traffic controller used for them, and the state of practice for traffic control in Caltrans District 4 and City of San Jose. The following is a brief literature review of freeway RM, arterial traffic signal control, the algorithm for the integration of the two, and the practice conducted before for large scale implementation of coordination in Caltrans District 4.

2.2 Freeway Ramp Metering (RM)

Freeway traffic management has been developing very rapidly in recent years. There are many strategies to manage the traffic on freeways. However, RM is the most widely practiced strategy to control freeway traffic. Many RM strategies have been developed theoretically or practically: time-of-day versus traffic responsive, heuristic versus model based, local versus corridor-wide or network-wide coordinated. Those methods can be roughly classified by two strategies: data based or model based. Basically, most practically implemented RM strategies were data based. Such approach use real-time data for traffic state parameter estimation, based on which a control command is determined. The main characteristic is: there is no model-based traffic prediction involved. However, it is still possible to predict the traffic from statistical (time series) approach from both historical data and real-time data to some extent, though such prediction my not be able to capture the traffic dynamics accurately. Quite a few works on RM design uses Fundamental Diagram (FD) for traffic prediction such as those in [27]. This does not seem to be a good idea since FD is a static relationship between traffic flow (speed) and density (occupancy). Such a relationship only exists for highly aggregated data, which is suitable for planning but not operation. It is intuitive that highly aggregated data will bring significant time delay to the state parameter estimation and thus the controller, which will definitely degrade the control performance significantly. It is unlikely that the RM strategy based on FD can outperform the time of day strategy.

A good review of freeway RM approaches is found in [25]. The RM methods are mainly two: ALINEA, and Coordinated RM (CRM), with extension over traffic networks. Several RM strategies were also reviewed and compared in [46]. ALINEA, a local traffic responsive RM, is getting more and more popular in practice. Reference [32] evaluated four ramp metering methods: ALINEA-local traffic responsive; ALINEA/Q with entrance ramp queue handling; FLOW - a coordinated algorithm that tries to keep the traffic at a predefined bottleneck below capacity; and the Linked Algorithm, which is a coordinated algorithm that seeks to optimize a linear quadratic objective function. The most significant result was that RM, especially the coordinated algorithms, was only effective when the ramps are spaced closely together.

The cell transmission model (CTM) started from the nominal paper by Daganzo [4] based on the first order LWR (Lighthill-Witham-Richards) model [17], under the assumption of a triangular type of FD. Reference [24] further analyzed the CTM in detail. The model was refined into five modes for each cell according to the traffic situation. The RM strategy in TOPL (Tools for Traffic Operation Planning) [35] is designed based on CTM. The controller determines the maximum flow that an entrance ramp can release into the freeway. If no controller is assigned to an entrance ramp, its flow is restricted by the ramp capacity and available capacity of the cell to which this entrance ramp belongs. CTMSIM [15], as part of the TOPL macroscopic traffic simulation package [35], provided several entrance ramp metering control options, including ALINEA, Linear Quadratic Control with Integral action (LQI).

It is noted that the FD used in [27] and in [4, 24, 35] have quite different scope: the work in [27] fully rely on the static FD relationship, which the work in [35] uses FD to reduce the traffic dynamical model from 2nd order to 1st order density dynamics – essentially eliminated the speed dynamics. Therefore, RM design in [35] is model based while that in [27] is not.

System Wide Adaptive Ramp Metering (SWARM) is a relatively new ramp meter operating system developed by National Engineering Technology (NET) Corporation (Delcan). It is totally based on linear regression of measured data for prediction of density instead of model-based. A good review and implementation of SWARM is documented in [2]. The performance of SWARM in practical implementation is rather controversial which will not be discussed here.

The most recent implementation very successful for CRM is the HERO (HEuristic Ramp metering coOrdination) project in Australia [42]. The algorithm is essentially to maximize use of 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 entrance ramps from downstream to upstream progressively, which was claimed to be working to some extent.

Work in [29] investigated, through simulation, the traffic for the morning commute with a single route (still many Origins and one Destination). If the traffic demand change over time in response to travel delay (that is, people can choose their departure times) is considered, then a simple Bang-Bang type of control (jump between lower bound and upper bound) can be quite effective. In the extreme, you could close some ramps (or prohibit left turns, for example, in the arterial context) for a period of time, and open it with no metering for another time period, etc. This may also hold for traffic light control (prohibit certain movements during certain time windows), and can be explored in our current research.

Our comments are that such work takes the freeway as the highest priority and disregard any traffic from arterial. It may benefit the free traffic flow from upstream, but will likely be very bad to the arterial traffic where the freeway entrance ramp is completely closed. If the arterial traffic demand is high, the closure of the entrance ramp could even cause local area traffic gridlock which should always be avoided.

2.3 Arterial Intersection Traffic Signal Control

Work in [7] documented the algorithm development and field operational test of optimal coordinated intersection traffic signal control strategies along an arterial. This paper emphasized on direct online minimization of performance measures based on real-time information to improve performance. Lesson learned and experiences gained in the implementation were presented. The algorithm was developed in accordance to certain principles as a distributed strategy featuring a dynamic optimization algorithm for traffic signal control without requiring a rigid, fixed cycle time. Signal timings were calculated to directly minimize performance measures, such as vehicle delays and stops, and were constrained only by minimum and maximum phase lengths and, if running in a coordinated mode, by a virtual cycle length and an offset.

Determination of signal setting duration in the fixed-time mode is considered in detail by Webster [43, 22] and documented in details in Highway Capacity Manual (2000) [12] and Traffic Control Systems Handbook [5]. As discussed in [31], both time-of-day (fixed time) and actuated (traffic responsive) intersection traffic signal control can be used in coordinated arterial signal control [14, 30]. However, coordination of actuated signals significantly improves the traffic performance for the arterial through traffic compared to fixed-time control in all test sites. The benefits depend on the amount and utilization of the spare green time in the background cycle length. This flexibility may further be utilized in a larger scale: the coordination between freeway ramp metering and arterial traffic signal control.

As indicated in the study of Bay Area Ramp Metering and intersection traffic control [6], each individual control element handles the traffic flowing through the corresponding junctions with no consideration to its impact on other parts of the network. This type of control is most common in freeway-arterial corridors.

Work in [8] developed algorithm based on dynamic programming to coordinate oversaturated signals along an arterial that crosses multiple, parallel coordinated arterials. Signals along crossing arterials are also oversaturated. During an oversaturated period, the algorithm manages local queues by spatially distributing them over a number of signalized intersections and by temporarily spreading them over signal cycles. The simulation results with 20 intersections indicate that the algorithm successfully managed queues along coordinated arterials, made the signals share the burden of traffic, and created the opportunity for traffic progression in specified directions.

Stevanovic [33] provided a good review of Adaptive Traffic Control Systems (ATCS). ATCSs have many types and vendors. This synthesis summarizes most of their features in different aspects. SCATS and SCOOT are among them. They all have some level of adaptation to current traffic, either *responsive* (control input based on previous cycle traffic state), or proactive (using some techniques including model to predict the current step traffic demand based on upstream measurement etc. including traffic flow models). Each product has its own features although they are somehow similar in many important aspects.

The following aspects were reviewed:

- Adaptive traffic control logistics

- Detector requirement
- Compatibility with NEMA local traffic control system
- Communications required
- Computer processor and software
- User interface
- Maintenance
- Deployment situations
- User's feedback
- Vendor's opinions
- Cost and benefit

The vendor's description of the technical features is listed for those reviewed system in the end, which could be a good reference for specific product such as SCATS and SCOOT.

Interestingly, in the discussion of the reasons for shutdown of the system, lack of coordination with freeway ramp metering is one of the reasons (p.44).

A signal control plug-in was written to model control strategies with PARAMICS in [9]. It simulates non-adaptive strategies such as *pre-timed, isolated actuated, coordinated actuated, traffic responsive*, and *critical intersection control*, as well as *adaptive strategies*. The plug-in can be applied to any PARAMICS network. The plug-in is based on a control interface which allows it to communicate with arbitrary "black box" algorithms via standard *hold*, *force-off*, and *omit* messages. When connected to an external control algorithm, the plug-in acts in much the same way as a real controller, providing safety and minimum phase timing guarantees."

"A truly traffic adaptive system will adjust the settings at traffic signals based on real-time data on traffic conditions, and can respond to unexpected or unplanned events, such as incidents, special events, weather, etc., since they adapt the timings based on observed traffic data. Similarly, adaptive systems will improve performance over time-of-day plans when the traffic patterns have a high degree of variability. Finally, adaptive systems will reduce the adverse effects of offset transition, preemption, and transit priority."

We agree with the most opinions of the author. The following MOPs (Measure of Performance) are good:

- arterial through links: travel time (speed), delay, and number of stops (% vehicles stopped)
- cross-streets: queue length, and delay
- total system: VMT (Vehicle-Miles-Travelled), VHT (Vehicle-Hours-Travelled), cycle failures, fuel consumption, emissions

Our Comments are: site selection criteria should include data collection requirement, not just the microscopic data, but also macroscopic data to generate OD (Origin-Destination) table; time varying OD table is used here. Daily data for several weeks may be necessary to generate the OD Table. This is also required in Aimsun and PARAMICS. To adopt the type of performance parameter in practice will depend on what measurement is available and the focus of the performance measurement.

PARAMICS Plugin API: Some of the basic strategies included in the new plug-in were previously implemented in PARAMICS by researchers at the University of California at Irvine under a previous PATH study (9). Our plug-in can be thought of as extending the existing simulation APIs to include complex adaptive strategies such as RHODES and TUC.

2.4 Coordination of RM and Arterial Traffic Signal

The study of integrated corridor control using microscopic traffic simulation was presented in [26]. This study identified four operational strategies to integrate freeway ramp meters and arterial signals, namely local coordination, area wide ramp metering coordination, diversion and congestion strategy. They developed a list of sixteen control tactics which were claimed could be integrated to carry out any of the above strategies.

Tian et al [36] proposed a responsive ramp metering strategy and tested it with various adaptive signal control methods in a diamond interchange (freeway mainline, entrance ramp and exit ramp, and cross arterials) context based on microscopic traffic simulation. The objective is to evaluate the coordination of freeway *adaptive local traffic responsive ramp metering* and arterial *adaptive interchange signal timing*. Simulation showed that traffic operations were significantly improved compared with non-adaptive diamond control and static ramp-metering control. The strategy could be stated as: to control the ramp feeding flow through special signal timings at the diamond interchange: whenever a long queue is detected at the metered ramp, the

signal timing should be adjusted to reduce the traffic flow entering the ramp. In this way, the ramp meter will remain in operation as long as possible, which would delay the onset of queue flush (i.e., termination of ramp meter) and minimize the possibilities of a freeway breakdown. However, this work still looks at the local system instead of a corridor wide in both freeway traffic and arterial intersection signal control, which needs extension to system-wide.

Work in [38] also considered coordination of freeway ramp metering and diamond exchange operation. It proposed the following four objectives of operation:

(a) To maintain the freeway at free-flow conditions and minimize freeway breakdown,
(b) To minimize ramp queue flushes and maintain normal ramp metering operation,
(c) To control vehicle entries to the ramp meters through proactive signal control at the diamond interchange as a means of controlling queue spillback, and
(d) To store excessive demand and queues in the most advantageous locations so that all the queue storage space can be efficiently used without interfering with freeway mainline and adjacent arterial signal operations.

It modeled the diamond exchange signal timing as three phases or TTI (Texas Transportation Institute) four phase operation. There is not a mathematical modeling adopted for the intersection. Instead, detailed operational scenarios were described literally.

Our comments are that, for a diamond exchange, if the exit ramp demand is low, which is the case particularly in peak hours, (a) the exit ramp detection may not be that critical; (b) the green-time distribution could be set in favor of other movements. The control scheme here is ad hoc and there is modeling and optimization. The control logistics is just based on queue detection at entrance ramp, exit ramp and at permitted/protected left-turn pocket.

The paper concluded that: Interchange Control System (ICS) proved to be effective only within a specified traffic demand level, the medium level as defined in this study. Under the low demand scenario, in which both the freeway mainlines and the ramps have sufficient capacity, implementing ICS did not result in a significant difference in system performance. When the traffic demand was high for both the freeway mainlines and the ramps, ICS provided only marginal benefits for the freeway mainline operations by delaying the onset of flushing operations at the ramp meter. Once the traffic queues on the surface street exceed boundary limits and ramp queue flush starts, the delay savings for freeway traffic will be significantly

diminished. The non-freeway traffic would experience excessive delays and queues, which would normally outweigh the delay savings for freeway traffic.

The performance for the two control strategies, i.e. three phases (having enough storage for left-turn queue) or TTI four phases (not having enough storage for left-turn queue) had similar performance.

Here the "within a specified traffic demand level" means that the demand is medium to moderately high but not congested. Our comments are that there are three issues with this approach:

(1) Only considering local coordination at a diamond exchange without considering the cause of the congestion in freeway traffic, the only thing that could be gained is to fully use the single entrance ramp queue, and the queue in all the movement at the intersection;

(2) This paper did not analyze the cause of the congestion on freeway. If the freeway congestion is caused by other factors such as (a) too high mainline demand upstream; or (b) congestion back-propagation from downstream (for whatever reasons are), then the coordination problem is not isolated and it cannot be effective;

(3) Since the freeway traffic is a corridor level behavior, to improve the traffic performance, such as TT (Travel Time), analysis needs to be done at a corridor level instead of at a local level.

Based on the work in [27], [39] further analyzed the dynamic interaction between the feeding intersection, entrance ramp queue and freeway mainline traffic nearby. In particular, this paper focused on the modeling of freeway traffic. The model is much more complicated compared to Cell Transmission Model. This has caused some problems in the implementation and traffic analysis.

Work in [45] considered the delay reduction for a diamond exchange. The paper proposed some analytical method for delay estimation at a signalized intersection with interaction with freeway, which was a diamond exchange. Such intersection was obviously different from an isolated signalized intersection in several aspects: (1) high demand from freeway; (2) dynamic interaction between the two; (3) storage limits on the (on and off) ramps. A new analytical delay model was proposed. Several simulation packages were used to evaluate the algorithm. It was also compared with previous methods for delay estimation.

Han and Reiss [11] proposed a strategy to relieve the problem in entrance ramp storage use, which is caused by the platoon type of feeding flow into the entrance ramp from intersection and individually releasing vehicle from entrance ramp into freeway through metering. A two-level variable metering rate to reduce delay at a ramp meter signal is investigated. The problem is modeled as minimizing total ramp delay. It is felt that such an approach has captured some aspects of the essential part of the problem since entrance ramp storage does play a critical role in ramp metering strategy, particularly in peak hours. However, this approach needs to be extended to account for the coordination of multiple entrance ramps of a corridor level. Besides, some other factors also need to be taken into account such as traffic flow optimization along the arterial intersection.

The paper [23] documented a systematic evaluation of the performance and effectiveness of a field operational test (FHWA's city of Irvine advanced traffic control system intelligent vehicle-highway system FOT) of an integrated corridor-level adaptive control system, including RM and intersection traffic signals, was attempted from fall 1994 through spring 1999 in Irvine, California. It examined the technologies, circumstances, events, and results. The paper identified several issues that could hinder the successful integration of freeway and arterial traffic control: (a) technically integrating diverse technologies and systems from a variety of competing vendors into the same platform; (b) severe institutional limitations on programming, implementing, and operating ATMS (Active Traffic Management System) technologies; (c) the lack of a systems approach for project planning and management of different vendors and stakeholders; and (d) too ambitiously large scale implementation without sufficient understanding of the functionality and performance of each subsystem. Those lessons have been learned and similar problems will be avoided in this project.

In Part II of the report [13], the coordination between the ramp meters with its direct feeding intersection's signals was discussed. Two numerical algorithms were proposed. The global strategy aimed at optimizing corridor performance while taking into account all control elements and the traffic conditions throughout the corridor. However, only time-of-day intersection traffic signal control was considered. Furthermore, it was assumed that cycle length and phasing sequences are fixed. Besides, the ramp metering strategies are also very simple. The performance of the integrated corridor management plans was compared with that of the control plan obtained from optimizing each individual signal and ramp meter.

In practice, intersection traffic signal controls implemented are mostly traffic activated instead of time-of-day strategy. Ramp metering strategies are moving towards coordinated instead of time of day or local traffic responsive. This indicates the need for developing coordination algorithm for the coordination of more advanced freeway ramp metering strategies and advanced arterial intersection traffic control strategies.

The work in [27] claimed to have developed a corridor level model for a coordinated freeway ramp metering and arterial intersection traffic signal control. The methods proposed can be summarized as follows:

- Restricting control parameters that are manageable in 170 or 2070 traffic controller which were used in practice;
- Estimation of traffic in a proximity of the intersection close to the freeway entrance ramp with ramp meter and intersection storage capacity;
- Prediction of traffic arrival from upstream of the target intersection;
- Total delay taken into account in the performance evaluation: intersection delay, ramp delay, and freeway delay—in terms of a set of control variables (gap settings, maximum green settings, and ramp meter headway settings);
- The typical advantage of an adaptive signal controller, i. e., the cycle length, phase splits, and even the phase sequence, may vary from cycle to cycle, to satisfy current traffic demand pattern in a maximum degree; for the functionality of truly adaptive controllers, a set of on-line optimized phasing and timing parameters are needed;
- To facilitate the adaptive traffic signal control at intersections, traffic flow prediction model is developed based on the actuated phase control strategy and other features, such as minimum green time, unit or vehicle extension and maximum green time, together with related detector information gleaned from actuated-signalized upstream intersections to estimate the future arrivals at downstream intersections, as well as intersection storage capacity etc.

Those are the positive point of the work. The author seems familiar with intersection traffic signal control and coordination, but less familiar with freeway traffic control. For example, the author proposed that for intersection traffic signal control, it was necessary to use vehicle actuated detector information, signal timing plan and current signal phase information which are all dynamic. This idea is contradictory to what the author proposed about freeway

traffic modeling and control in which a static Fundamental Diagram model was adopted. Specifically, this work is weak in the following aspects:

- It lacks a systems approach: the ramp meter rate should not only be determined by the feeding intersection, but also be jointly determined by the traffic flow from mainline upstream. In fact, there should be a trade-off between the two according to different traffic situations, which is the crux of the coordination;
- It would require an accurate real-time traffic estimation/prediction for both freeway and arterials for certain period of time with minimum time delay. The freeway traffic model adopted in the work is the traditional triangular type FD model which is rather old and planning oriented. It is not even suitable for freeway traffic estimation, lest say prediction. The reason is simple: the FD is a static function relationship between flow (speed) and density (occupancy) based on highly aggregated data in both time and space. Without certain time period aggregation, such a characteristic does not exist. Aggregation implies a significant time delay induced in traffic state parameter estimation. For example, data aggregated over 10 minutes period will induce average time delay at least 5 minutes. Since traffic system is a fast changing dynamical system, FD does capture the system dynamics, particularly in transition phases such as speed drop which is the most interesting phase for traffic control. This is why there are so many models for FD but they are all only suitable for planning purpose. Using an FD model for freeway traffic to design RM is similar to equipping a 21st century car with a 19th century engine: it will work to some extent but it is impossible to have high performance.
- The ramp metering reference input is the downstream capacity, and the metering headway is computed as that corresponding to a ramp flow rate that would lead to the total downstream demand being less than or equal to capacity. This is very crude and basic control strategy in the following sense:
    - There is no coordination even within the freeway corridor for optimal freeway traffic flow;
    - The strategy is not always feasible, for example when the mainline and entrance ramp are high in peak hours, it is not possible to keep the mainline downstream flow of the ramp meter below the capacity flow. The reason is very simple: where to store the main-line and entrance ramp vehicles to achieve that?

- It seems the author did not recognize that freeway traffic flow is determined by bottleneck flow and maximizing the freeway traffic flow is to maximize the flow at bottleneck(s), and that the best outcome one could achieve for freeway traffic control is to regulate the traffic at bottleneck(s) to its (their) maximum flow(s) possible [19, 3].
- There is a lack of proper coordination in a larger corridor system level including both arterial intersections and the freeway(s).

- Most importantly, the proposed optimization strategy is not feasible: The author proposed to use multi-objective minimization function - minimization of freeway/ramp delay and minimization of arterial signal delay, and to develop solutions for optimal control that specify the efficient frontier; i.e., the set of non-dominated control options. However, such strategy is not feasible mathematically: multi-objective minimization is usually converted to a single objective function by a weighted sum of all the objective functions for numerical treatment. Equivalently, some balance and trade-off between those objective functions must be given as *a priori*.

Those weak points need to be addressed in the proposed tasks and in future work.

In the work of [28], the strategy is still using the default traffic parameters of the 170 or 2070 controllers, i.e. phase minimums, maximums and gap settings. Here phase minimums and maximums can be the bounds of green time; gap setting is a force-off action by the controller. Those control variables are different from the set: split, cycle length, and off-set, as used in modern ATCS.

From the literature, each 170 and 2070 controller has default software which basically determines the bounds of control variables from an ATCS. In upper level control, the control variables are: split, cycle length, phase sequence, and off-set;

Now the questions are:

- How different they are in affecting traffic flow?
- Could split, cycle length, and off-set be implemented in upper level ATCS software?
- How to quantify their effects?

It seems that there is an optimization process:

"Based on maximum cycle length restrictions, phase maximums are selected based on Webster's functions, accounting for any spillover from previous cycles of operation. These maximum green settings provide constraints for the decision of *optimal phase splits*, which are determined by solving a non-linear optimization problem with the objective to be minimizing total intersection control delay per cycle. The expression for delay is given by Darroch (1964), which is a generalization of the well-known Webster formulation. These optimized phase splits are used to *determine optimal minimum green and gap settings*. All these timing parameters will be used for the upcoming control cycle as well as providing signal timing data for further optimizations."

This indicates that they modify the lower level default control of the 170 or 2070 controller in an "optimal way".

An adaptive ad hoc method is developed in [16] for practical coordination of freeway local RM and the feeding intersection traffic signal: the metering module continuously adjusts the adaptive policy depending on the congestion level of the adjacent intersection, while the intersection module explicitly reflects the traffic conditions at ramp areas in determining signal phases. There is prediction and no model. It is only based on congestion levels 0~10. It could work somehow if the demand is too high or if the detection is crude.

The work in [47, 48] proposes a Local Synchronization Control (LSC) scheme to manage queues at those critical locations through coordinating neighboring intersection traffic signals and freeway entrance ramp meters. By reducing the amount of traffic feeding into and increasing the amount of traffic discharging from heavily queued sections, the scheme can prevent a queue from evolving into the seed of a gridlock and thus improve the overall system performance. With the help of a network kinematic wave traffic flow model, the local synchronization scheme is implemented and tested on a computer for two sample networks, one small synthetic corridor network and one large, real corridor network. The numerical results indicate that this control scheme can improve the overall operational efficiency in both corridors considerably, with as much as 50% travel time savings. This control scheme appears to perform best under incident conditions, and somewhat a surprise, compares favorably against a more complex global optimal control scheme.

This modeling part follows the idea of Hong Lo using CTM (Cell Transmission Model) for intersection traffic modeling. The main contribution of this paper is to use such modeling for the coordination of freeway ramp metering and intersection traffic control. This is a sample application paper for using the model for traffic prediction in the coordination of arterial intersection and freeway ramp metering.

This paper emphasizes on the synchronization of local arterial traffic signal and freeway ramp metering to release local queue. The queue could be on freeway entrance ramp, exit ramp and arterial intersection(s). In case there is any local congestion or queue.

For a special type of network (many origins and a single destination), it is able to prove that the best control is to meter traffic at the boundary, and leave traffic free-flow inside the boundary (no queues inside the boundary) if capacities are constant over time. This may not hold if there are accidents (hence capacities vary). The results may not hold if we have multiple destinations. Intuitively, it may be advantageous to hold flow from certain origin/destination pairs at certain nodes inside the network to reduce travel time. These findings can be useful when we design feedback control laws.

Our Comments are:

(1) Such action may affect other parts of the traffic. Therefore the coordination should be system-wide.

(2) Homogenizing the density over the system could be a good idea to accommodate more vehicles in the system and keep traffic at higher sustainable flow, but that is not the main theme of this paper.

"Typical road sections that require synchronization treatment are those short ones that are controlled on either end or both ends and carry large interfacing flows. Example sections are entrance ramps with either ramp meters downstream or traffic signals upstream; exit ramps leading to signalized intersections; and roadway sections that have signals on both ends."

(3) The CTM has no speed dynamics. The function of the speed could be to predict how many vehicles practically moved from one cell to the next sections. However, if we have loop detectors at the stop line or at the exit, we can estimate the practical number of vehicles moved in each cycle from a given cell to the one downstream. Therefore for the estimate of the current traffic state, there is no need to use the speed as traffic state, or simply use the posted speed limit in street. Suppose we are going to predict the traffic in the next few steps

(cycles), it would be difficult to predict how the traffic moves simply based on the flow model. If we have posted speed limit and estimated speed, it would be easier to predict the number of vehicles moved from one cell to the next. Besides, knowing speed would benefit the coordination of traffic signals of multiple intersections.

(4) The speed of traffic flow for arterial intersections could be represented by a variable structure function which incorporates the starting delay after Green light is activated. This is equivalent to a solution of some speed dynamics. The fluctuation of real speed could be modeled as the posted speed limit with some additive uncertainties.

(5) There is a lane reduction bottleneck designed in the simple synthetic network. The simulation framework is suitable to simulate our freeway control strategies, which is to maximize the bottleneck flow. If we can combine this freeway traffic control strategy with proper arterial traffic signal control, greater benefit could be achieved.

The *Coordinated Freeway and Arterial Operations Handbook* by Urbanik et al [41] is a good and comprehensive guidance book. This report defines the coordination of freeway and arterial operation in a larger scope: "*Coordinated freeways and arterials (CFA) operations is the implementation of policies, strategies, plans, procedures, and technologies that enable traffic on freeway and adjacent arterials to be managed jointly as a single corridor and not as individual, separate facilities*." It includes planning and operation. The operation also includes incident management and traffic control:

- Traffic incident management.
- Work zone management.
- Planned special event management.
- Day-to-day or recurring operations – traffic control

This report recognizes that the challenges to the integration also include complicated institutional issues besides technical and system compatibility problems.

The need for coordination can be viewed and conducted in different angle:

- Agency perspective: all the agencies need to know traffic situation particularly incidents/accidents (times and locations), and to divert the traffic using local arterials and streets which the commuter are familiar with;

- Driver perspective: compliance to agents advisory and control for shortest travel time, but information is necessary;
- Systems perspective: Only a systematic coordination between agencies and drivers have been realized, it is possible to achieve system optimal.

Table 2-1. A Good Mindset

Thinking…	**Instead of…**
Coordinated	Isolated
System	Jurisdiction
Customer focus	Project focus
Regional	Local
Proactive	Reactive
Comprehensive	Piecemeal
Real-time information	Historical information
24/7 operations	8/5 operations
Performance-based	Output-oriented

Study in [18] focused on the coordination of freeway and arterial corridor in incident/accident scenarios, the so called non-recurrent bottleneck. This is a model-based approach. Routing is main technique for detouring, which is obviously road geometry dependent – different road geometry determine different system configuration and therefore different coordination approach. It was claimed that the model and algorithm have features: 1) modeling explicitly the evolution of detour traffic along the ramps and surface streets with a set of dynamic network flow formulations to capture the local bottlenecks caused by demand surge due to diversion operations and to properly set the responsive signal timing plans, and 2) developing a Multi-objective optimization framework to maximize the utilization of the available corridor capacity via detour operations but not to incur excessive congestion on the arterials and ramps. This study employs a genetic algorithm (GA)-based heuristic to efficiently yield the reliable solution, depending on the decision maker's preference. Extensive simulation on a segment along the I-95 corridor with its neighboring arterials has been used to demonstrate the potential benefit of the approach.

Our comments are: GA is a way for large scale system optimization but outcome is uncertain sometimes due to the scale of the problem. The computation load for GA is enormous in general. Real-time application would require a simpler model and efficient algorithm.

Chapter 3. Test Site Selection

The objective of this project was to improve traffic flow from an overall system level which consist of both freeway and arterial/surface street traffic subsystems. It was essentially to regulate the dynamic interaction of the traffic flow between the two. In Phase I, the project was limited to the coordination of a *single entrance ramp metering* with a *single intersection* traffic signal control. To ensure the success of some performance improvement, it was necessary to identify a location where the congestion of the freeway and/or the arterial intersection was mainly caused by such dynamic interaction. Otherwise, performance improvement could not be achieved just by the coordination of a single Ramp Metering and single arterial traffic signal control.

3.1 Site Selection Criteria

Many factors would affect the performance of coordination between freeway traffic control (currently ramp metering) and traffic signal control at the arterial intersection. Among others, we identified the following factors as the main criteria for site selection:

(1) There was a regular congestion in peak hours in workdays (recurrent bottleneck);

(2) System Isolation: It was necessary to isolate the system from other factors other than the traffic flow from arterial. Here isolation meant that the system congestion was mainly caused by the interaction of freeway and arterial traffic flow. The following four parameters determined traffic flow in a section with an entrance ramp:

   (a) Capacity of the section: The physical capacity of a section was fixed except for lane reduction caused by lane closure due to incident/accident;

   (b) Freeway demand upstream: If the demand upstream was too high compared to the capacity, the coordination could not achieve significant performance improvement;

   (c) Traffic condition downstream: To make sure the congestion at the site was not caused by the traffic back-propagation of a downstream bottleneck. It was obvious that the downstream bottleneck traffic was unlikely to be improved through the coordination at the subject site;

(d) Traffic Flow on Exit ramps: To make sure the exit ramp immediately downstream of the location did not have traffic spills back to the subject site. This was for isolating the system and the problem.

(e) The demand from current entrance ramp (eventually coming from arterial): To make sure the congestion at the subject site was mainly caused by the interaction of the freeway traffic flow and the arterial traffic – the demand from the arterial needed to be high enough.

(3) Entrance ramp length: Compared to the demand from arterial, if entrance ramp storage was not an issue, probably such coordination might not be necessary. In general, shorter entrance ramp length would need more coordination between freeway traffic control and arterial intersection signal;

(4) Arterial Intersection Traffic Signal Control (Turning movement of the nearest intersection to the entrance ramp): It was necessary to look into the turning movement at local intersections, so that one could trace where the entrance ramp demand came from. If the entrance ramp demand was too high because of the platooning, we might be able to adjust the intersection signal timing. If the entrance ramp demand was too low and freeway downstream bottleneck had more capacity, we could adjust the signal timing and ramp metering to let more vehicles enter the freeway;

(5) Sensor Location and Data Quality: In the analysis, data quality from the detector stations was considered as critical for the study; it was obvious that the data quality of detectors of both freeway and arterial needed to support ramp metering, arterial signal control and the coordination between them;

(6) Jurisdiction: The jurisdiction was a critical factor since different jurisdictions of the subsystems needed to work closely to get the overall system integrated. After integration, there was a need for a joint mechanism for sustainable operation, maintenance, upgrading the system and resolving new problems that might occur in the future operation.

3.2 Summary of Site Selection Considerations

This summary of site selection concentrates on the following 5 candidate sites based on extensive data analysis and input from Caltrans and the project panel:

- I280-Saratoga
- SR87-Taylor
- SR85-Camden
- I-280-Lawrence
- SR101-DeLaCruz

These five candidate sites were reduced to two sites after the first round: SR85-Camden and SR87-Taylor based on the site selection criteria.

In the following tables, the following terminologies are used:

- **Storage capacity**: 250 vehicles per mile per lane assumed
- **Isolated**: It means that the congestion is unlikely to be caused by traffic from downstream through back-propagation; or exit ramp spills back.

Table 3-1. Site Selection Summary

Site		**I280-Saratoga**				**SR87-Taylor**			
Interested Directions		**SB**		**NB**		**SB**		**NB**	
		Frwy	Arterial	Frwy	Arterial	Frwy	Arterial	Frwy	Arterial
Traffic demand upstream & entrance ramp [veh/h/ln]	**AM**	1500	1600	1800	1000	1000	677	1800~2000	266
	PM	1800	1200	1650	750	2000	1718	1000~1200	200
Upstream exit ramp flow [veh/h/ln]	**AM**					N. A.		1535	
	PM					N. A.		970	
Average Speed [mph] in Peak hours	**AM**	50~65		**20**		65		**25~30**	
	PM	**25**		65		**20~25**		65	
# of lanes		4		4		3		3	
Ramp lanes/length (storage capacity)		2 lane/240m (74 veh)		2 lanes/352m (109 veh)		3 lanes/350m (163 veh)		3 lanes/400m (186 veh)	
Sensor location and density		1 LDS		1 LDS		1 LDS		1 LDS	
Data quality		OK	OK	OK	OK	08/11 better than 09/11	OK	08/11 better than 09/11	OK
Controller			2070						
System isolation		Difficult to isolate		Difficult to isolate		Some congestion Dwn		No sensor Dwn	
System complexity		complicated	complicated	complicated	complicated	simple	simple	simple	simple
Jurisdiction		Caltrans District 4	San Jose City	Caltrans District 4	San Jose City	Caltrans District 4	Caltrans District 4	Caltrans District 4	Caltrans District 4
Likelihood of performance improvement in Phase I		Very difficult		Very difficult		possibly		possibly	
Comments									

(Table 3-1 continued on next page)

Site		SR85-Camden				I280-Lawrence				SR101-DeLaCruz			
Directions		SB		NB		SB		NB		SB		NB	
		Frwy	Arterial	Frwy	Arterial	Frwy	Arterial	Frwy	Arterial	Frwy	Arterial	Frwy	Arterial
Upstream and arterial demand [veh/hr]	AM	1500	604	1700~1800	1024								
	PM	1680	845	1200~1500	969								
Ave Speed [mph] in Peak Hours	AM	65		15									
	PM	40~60		65									
# Lanes		3		3									
Ramp lanes/length (storage capacity)		2 lanes 210m (65 veh)		2 lanes 115m Veh 36))									
Sensor location and density		1 Up entrance ramp		1 Up entrance ramp									
Data quality		OK		OK		OK		OK		OK		OK	
Controller													
System isolation		Isolated if data correct		Isolated if data correct		No		No		No		No	
System complexity		simple		simple		Too complicated		Too complicated		Too complicated		Too complicated	
Jurisdiction		Caltrans District 4	San Jose city	Caltrans District 4	San Jose city	District 4	SCL	District 4	SCL	District 4	SCL	District 4	SCL
Likelihood of performance improvement in Phase I		Unlikely		Possibly		Unlikely				Unlikely			

3.3 Recommendation

Through comparison of the two candidate site, i.e. SR85-Camden and SR87-Taylor, we decided to use SR87-Taylor as the first stage simulation site. The reason to do so was that SR85-Camden was more complicated and the congestion at Camden could not be separated from the congestion back-propagation from the downstream, as well as from the too high demand from the upstream. If we could not isolate the problem of congestion caused by the interaction between the freeway and the arterial at Taylor, coordination between the two would not have much effect. However, SR87-Taylor was slightly better since upstream demand was not always high and the congestion back-propagation from the downstream happened only occasionally in peak hours. This made it possible for us to isolate the problem from congestion at Taylor caused by upstream and downstream traffic at least in some time periods. The other three candidate sites were not selected due to large systems scope which the current phase of the project could not handle since the funding was very limited. This had been agreed by the Project Panel at the project meeting on Jan 30, 2012.

Chapter 4. Concept of Operations and Systems Engineering Management Plan

4.1 Concept of Operations (ConOps)

The freeway and intersection road geometry for the selected site is depicted in Figures 4-1 and 4-2. As shown in Figure 4-1, the freeway has more lanes downstream near Julian, but two close entrance ramps imply large demand to freeway. The weaving effect plus high entrance ramp demand could potentially cause congestion downstream, which has been observed by traffic data from PeMS.

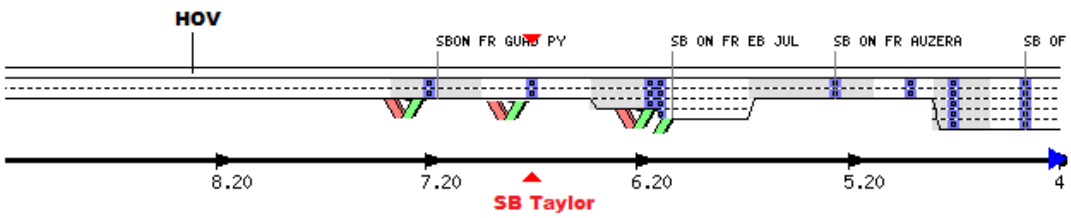


Figure 4-1. Freeway SR87 Geometry near Taylor

As shown in Figure 4-2, since SB exit ramp and NB entrance ramp have relatively low volume in PM peak hours, and they have long enough storage, they can be decoupled from SB entrance ramp and NB exit ramp in this period.

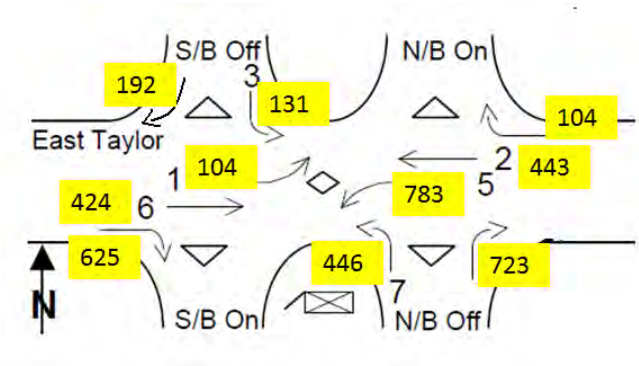


Figure 4-2. SR87-Taylor intersection movement geometry and typical PM peak (5-6pm) volumes

The following describes the coordination (operational) logistics of the two control subsystems: freeway RM and arterial intersection traffic signal timing. The coordination logistics is determined by freeway traffic condition. The reasons for doing so are as follows:

- the objective is to dump the traffic on the freeway as fast as possible to reduce total travel time;
- the traffic flow to be maximized is moving from arterial to freeway ➔ high freeway flow would relieve the congestion faster provided that other movements of arterial traffic (other than the feeding flow to the freeway entrance ramp) should not be blocked although their Level of Service (LOS) might be sacrificed if unavoidable;
- it is expected that the intersection will be able to inject traffic into freeway entrance ramp at the desired rate to reduce Total Time Spent;

4.2 SEMP (System Engineering Management Plan)

A System Engineering Management Plan was preliminarily developed as shown in the V-diagram (Figure 4-3), which would need to refined with the development of the project in different phases.

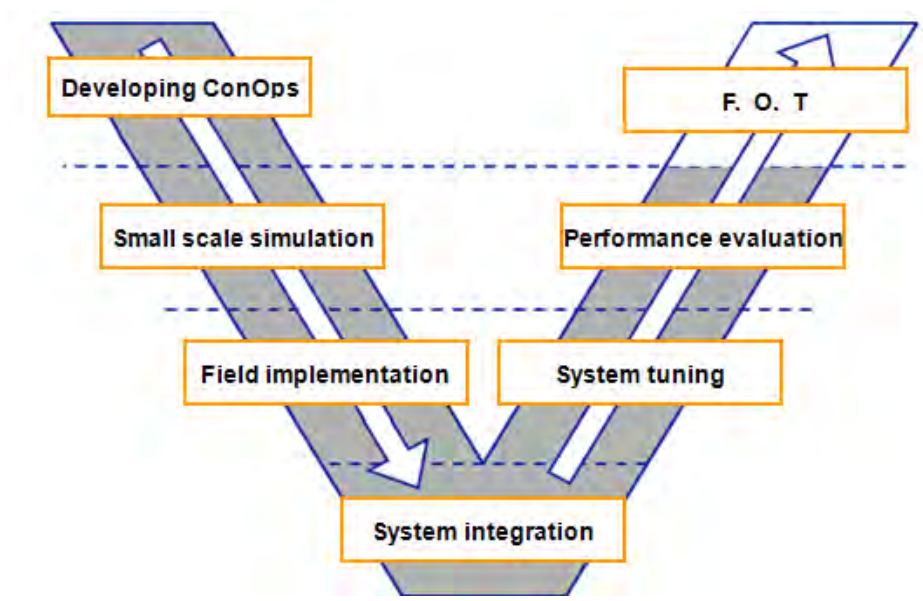


Figure 4-3. Systems Engineering Management Plan (SEMP) of the project

It is the highest level blueprint for all phases of the project for a progressive development of an Integrated (Coordinated) Freeway Ramp Metering and Arterial Traffic Signal Control in a systems approach.

4.3 Work Plan

The work plan detailed to some extend the components of SEMP particularly for current phase of the project. It included the following stages which paved the way for future large scale control and coordination development and implementation:

(1) Develop ConOps: The ConOps included the system structure, operation concept, implementation procedure, system integration, tuning and operation. For convenience, it was necessary to divide the ConOps into High Level and Low Level. The High Level ConOps described the relationship between different components (activities of the project), which was used for project management. The Lowe Level ConOps depicted the physical system to be developed, which was the blueprint for the design and construction of the system;

(2) Develop small scale simulation: Developing coordination algorithms over selected location with one RM (ramp metering) and 1-2 arterial intersections for field implementation purpose, taking into account the RM and intersection traffic control;

(3) Field implementation: Field implementing all components, hardware, software and the coordination and control strategies for the selected site, and testing for their functionalities;

(4) System integration: Integrating of all components into a single system and testing for compatibility of all components and the functionality as a whole system – hardware and software;

(5) System tuning: Systematic tuning for improving coordination between RM and intersection signal control strategies recursively to some extent;

(6) Performance evaluation: Performance evaluation of the implementation based on predefined traffic performance criteria with data analysis;

(7) Field Operational Test (FOT) and data analysis.

Different components and their logical relationships of the Work Plan are depicted in Figure 4-4.

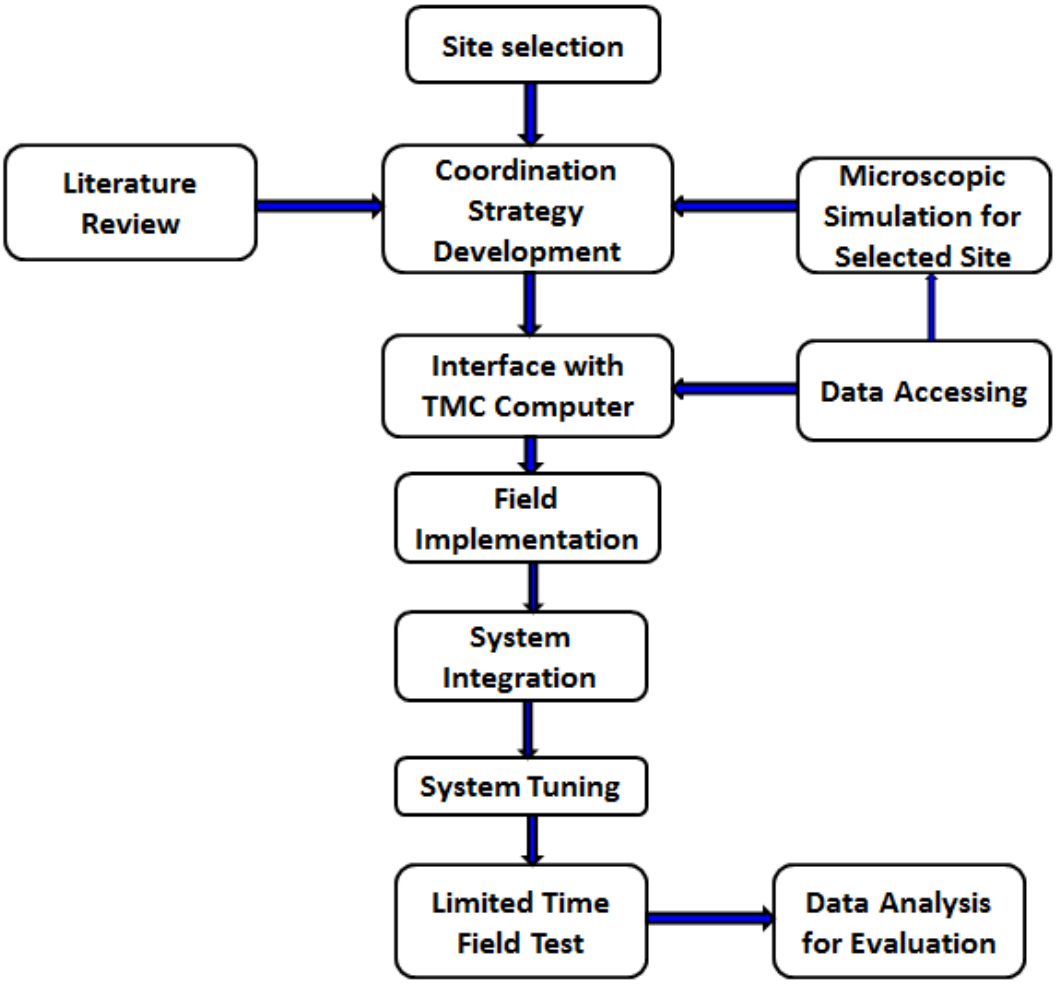


Figure 4-4. Work Plan: Functionality of components and their relationships

4.4 Lower Level System Structure

ConOps was developed for current phase of the project in Lower Level and in more details on how the hardware/software system would be structured, which was related to physical implementation (Figure 4-5). To coordinate the intersection traffic signals and freeway ramp metering signals at the selected site, it was necessary to have the following functions:

- Controlling freeway ramp metering locally, with PATH Computer interfacing directly with the 2070 control cabinet running URMS (Universal Ramp Metering System) at Taylor entrance ramp to SR87;

- Using the direct communication link between Caltrans District 4 TMC and 2070 controller at the entrance ramp fulfill the following tasks:
    - To get traffic detector data as in previous system;
    - To monitor what was happening at the ramp meter controller
    - To take over the PATH computer for controlling the freeway traffic if necessary – dropping back to the original control strategy;
- Running the TSCP control software at Taylor intersection with 2070 controller (under District 4 control);
- Running the Fourth Dimensions Traffic control software at San Pedro and First Street Intersections 2070 controller (under City of San Jose control).

Those interfaces are briefly described respectively in this section.

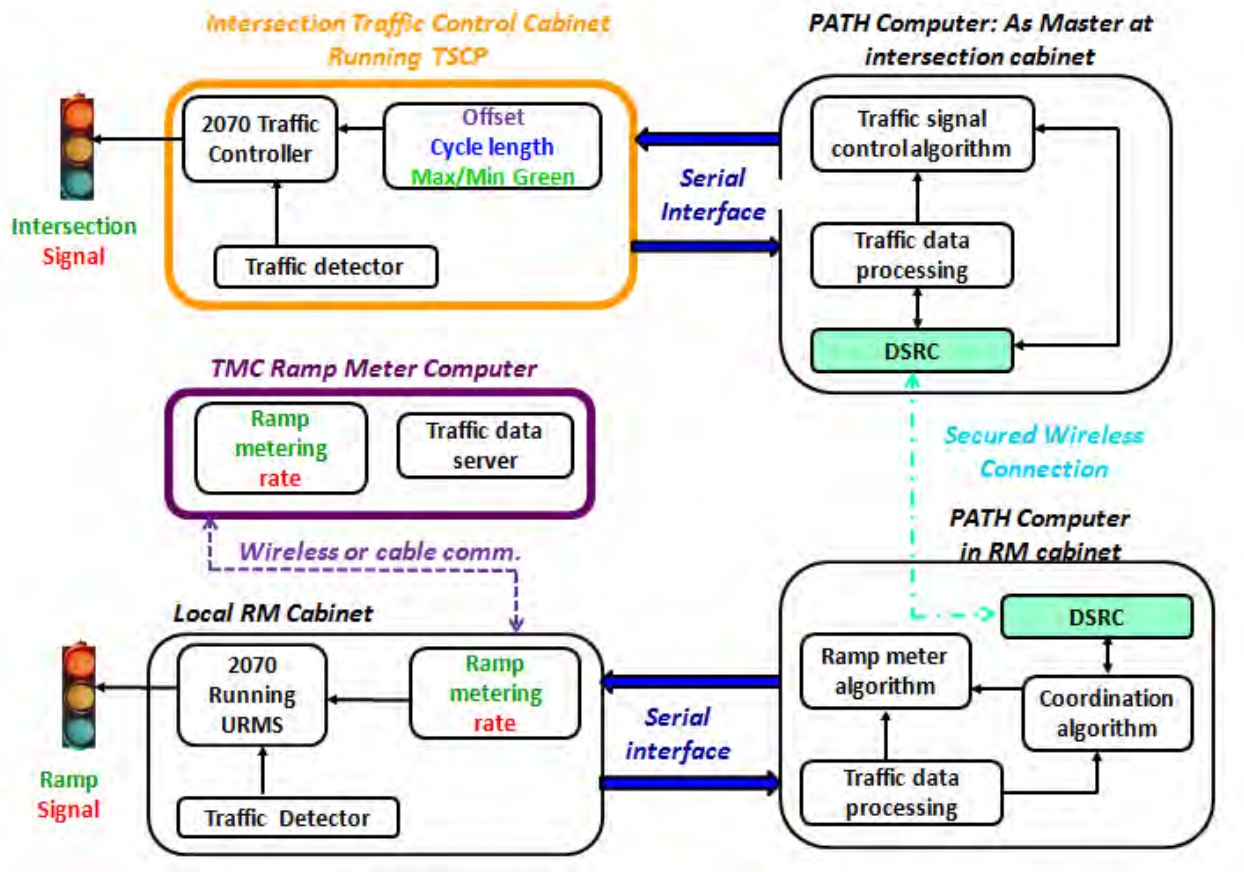


Figure 4-5. Low Level ConOps: Interface with Caltrans 2070 Traffic Signal Controller at Taylor

Figure 4-5 depicts how the coordination of freeway ramp metering and arterial traffic signal control was implemented as related to the field hardware. It contains the main hardware blocks and the relationship between them. Figure 4-6 has the functionalities for each block. Project team already had the capability to develop the necessary interface to integrate the systems.

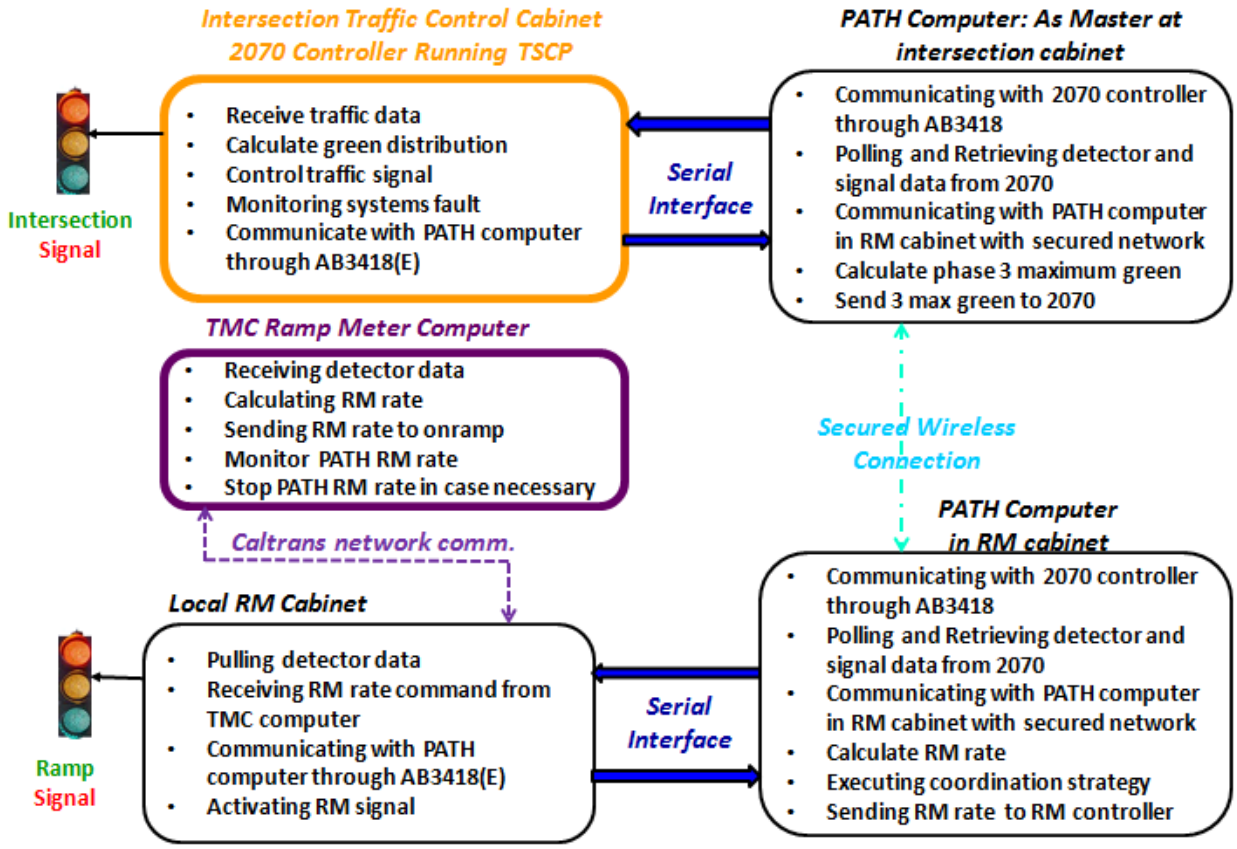


Figure 4-6. Low Level ConOps: Overall System Structure – functionalities of Each Component

A PATH computer sat in the control cabinet with the 2070 controller getting real-time data from it and sending back the desired ramp metering rate. A communication link between PATH computer and the TMC Ramp Metering Control Computer was built up as shown in the lower part of Figure 4-5 and Figure 4-6.

Detailed systems development is presented in Chapter 7.

Chapter 5. Control and Coordination Strategy Development

A rather generic algorithm was developed for the coordination of a freeway entrance ramp metering and an arterial intersection signal with typical lane geometry. Instead of using quadratic programming (nonlinear), our approach intended to formulate the problem linearly for efficiency and feasibility of practical calculation. The algorithm includes three parts: intersection Optimal Adaptive Signal Timing to collectively minimize the gap between demand and supply of all movements subjected to entrance ramp and link storage limits. Entrance ramp metering used ALINEA to achieve local adaptive RM. The coordination strategy of the two traffic control system was formulated as adjusting some parameters in the objective function of the optimization procedure. The basic idea is to adjust the green times of the intersection according to the space available at the entrance ramp. The flows of the movements to the entrance ramp are controlled such that their flow would match with the space available at the entrance ramp. Redundant green times will be given to other movement not leading to the entrance ramp for overall system performance improvement. To achieve this, queue estimation of all the major movement is assumed. To fully implement the algorithm, it is necessary to measure traffic in all movements and to measure entrance ramp queue and to control the green times of all the movements. Due to sensor detection limit, Actuated Signal Timing as the current control system at the selected site, and what we were allowed to do, the coordination/control strategy has been greatly simplified in the practical implementation and test.

5.1Assumptions

The following assumptions are made for simplicity. Some may not be met completely in practice. In this case, we consider an approximation:

(a) Entrance ramp queue detectors are available: both departure detector at the meter and arrival detector at about 20~30% to the entrance ramp entrance depending on the ramp length; if it is not available or detector has data error, time-based (in 1~2 min resolution, for example) historical data for peak hours would be used as entrance ramp queue;

(b) Intersection detector of each movement are available: both departure loop and advance loop (further upstream of the link) are available, which means that flow and queue for each

movement can be detected/estimated; if it is not available or detector has data error, time-based (in 1~2 min resolution, for example) historical data for peak hours would be used as entrance ramp queue;

(c) Downstream sections of the subject intersection can accept all the flows into it;

(d) Queue spillover on the exit ramp (true for Taylor intersection based on video data observation) is ignored here for simplicity;

(e) All the vehicle types are converted to equivalent car units in queue and storage capacity estimation.

5.2 Nomenclatures:

Timing:

Ramp metering unit time and intersection cycle length are independent; but they both are integer multiples of fundamental unit time *T*; and ramp metering rate may assumed to be constant within a cycle of the entrance ramp timing, but it may change from cycle to cycle; it may also be time varying with each cycle. In the latter case, the average metering rate in a cycle could be used;

k - index of selected unit time steps

$t = kT, \quad k = 0,1,2,...$ - time evolving;

T – unit time interval – could be *1 [s]*, but RM interval and cycle length should inter multiples of *T*;

For entrance ramps:

$U_{on,\max}$ – storage capacity of the object entrance ramp (unit: number of vehicles)

$U_{on}(k)$ - current queue length (number of vehicles)

$r(k)$ – ramp metering rate of previous cycle period (control parameter)

$\overline{r}_j$ – average ramp metering rate of cycle

For Feeding Intersection:

$i \in \phi$ - index of phases, $i=1,2,...,N_\phi$

N_ϕ - the number of phases for traffic control at the intersection

$j = 0,1,2,...$ cycle index

$i_r \in \phi_r \subseteq \phi$ - index that all/partial (movements) flows in phase *i*, which can go to the subject entrance ramp (feeding movements), like phase 2 right turn.

$i_s \in \phi_s \subseteq \phi - \phi_r$ is an index that flow in phase *i* doesn't go to the entrance ramp.

$C(j)-$ cycle length of the feeding intersection (integer number of [s]), fixed for now, $C(j) = N_c(j)T$, which means that $N_c(j)$ is constant;

$C_i(j)-$ time length from the starting of the phase to the end of the green of phase *i*;

$U_i(j)$ - current queue for phase/movement *i* at intersection (known – based on sensor detection and estimation);

$U_{i,\max}$ - maximum storage for phase/movement *i* at intersection (unit: number of vehicles)

$d_i(j)$ - demand flow rate to movement/phase *i* from nearby intersections or from exit ramp of the freeway (unit: veh/hr; known from sensor detection);

$f_i(j)$ - out- flow rate for movement/phase *i* (unit: veh/hr; known from sensor detection);

$f_{sat,i}(j)$ - discharge flow for phase/movement *i* at intersection;

$\beta_i(j)$- split ratio for flow from phase r going into the entrance ramp;

$G_{\min,i}$ - min green time for phase *i*;

$g_i(j)$ - green time for phase *i* (the control variables to be determined).

5.3 Coordination Strategy

Two approaches are presented here: Approach 1 is heuristic which is intended for Phase I of the project with one entrance ramp and 1~2 intersections; and Approach 2 is a system-wide optimization approach which is intended for the next phase of the project for a large scale system including a freeway corridor and relevant arterial(s). The Approach 1 is described in details and Approach 2 is only a high level concept.

Approach 1: Heuristic

The freeway traffic condition is divided into five phases according to the traffic volume, which, in turn, determines the higher level coordination and lower level control of RM rate and arterial intersection timing (green distribution) as listed below:

Phase 1: Freeway Mainline with Low Traffic volume (freeway mainline $Occ \le \sigma_1$; e. g. $\sigma_1 = 4\%$:

- Entrance ramp metering:
  - RM is all time green
- Intersection traffic signals:
  - Feeding movements have higher priority into the freeway

Phase 2: Freeway Mainline with Medium Traffic to high traffic volume (freeway mainline $\sigma_1 < Occ \le \sigma_2$; e. g. $\sigma_2 = 8\%$ - *critical occupancy*): Keep freeway at its capacity flow as long as possible

- Entrance ramp metering:
  - Proportional RM control strategy (ALINEA): regulate the occupancy of the immediate downstream of the entrance ramp (merging area) close to the critical occupancy. (e. g. $\sigma_c = 8\%$)
- Intersection traffic signal:
  - Balance the demand/supply ratio of all the movement subjected to entrance ramp storage limit (implicitly using intersection storage)

Phase 3: Freeway Mainline with High Traffic Volume ($\sigma_2 < Occ \le \sigma_3$; e. g. $\sigma_3 = 20\%$): If traffic congestion back-propagate from downstream:

- Entrance ramp metering:
  - RM rate is proportional to mainline occupancy (ALINEA): regulate the occupancy of the immediate downstream of the entrance ramp (merging area) close to a certain threshold, such as $\sigma_o = 15\%$, to delay the freeway traffic breakdown if the entrance ramp and intersection storage permit it to do so without gridlock;
  - Fully use entrance ramp storage

- Intersection traffic signal:
  - Green time distribution to balance the demand/supply ratio of all the movements subjected to entrance ramp storage limit (See Appendix).

Phase 4: Freeway Mainline with Traffic over capacity ($\sigma_3 < Occ \leq \sigma_4$; e. g. $\sigma_4 = 30\%$)

- Entrance ramp metering:
  - RM using ALINEA to regulate the occupancy of the immediate downstream of the entrance ramp (merging area) close to certain threshold such as $\sigma_o = 25\%$; the objective is to stabilize the freeway traffic even if the density is high;
  - Fully use the entrance ramp storage
- Intersection traffic signal:
  - Fill up the intersection storage first
  - Reduce green times of the movements to the entrance ramps (Use the storage of upstream intersection if necessary without gridlock)
  - Balance the demand/supply of other movements except the movements to entrance ramp (see Appendix).
  - Use extra cycle time for other movements

Phase 5: Freeway Mainline with Saturated Traffic ($Occ > \sigma_4$): Such traffic congestion is likely caused by downstream back-propagation; otherwise, the coordination with feeding intersection should have resolved it.

- Entrance ramp metering: Since the traffic congestion is likely caused by its downstream back-propagation, the following metering strategies could be possible alternatives:
  - Increase the ramp meter release rate - however, the number of vehicles that can practically enter the freeway is determined by the acceptance of mainline and merging characteristics;
  - Using the minimum metering rate – hoping that freeway congestion could possibly discharge quicker if downstream is in discharging phase; but if the downstream is not in a discharging phase, this might not be a good option;
  - Fully use entrance ramp storage
- Intersection traffic signal:

- Fully use intersection storage to the extent that gridlock will not be incurred;
- Arterial upstream intersection storages may also need to be used;
- Green time distribution to balance the demand/supply ratio of all the movement except those leading to the freeway entrance ramp.

The occupancy threshold parameters $(\sigma_1, \sigma_2, \sigma_3, \sigma_4)$ need to be tuned based on traffic situation.

Approach 2: System-wide Optimization

This is essentially a simplified optimal control approach based on some simple models of traffic flow on freeway and arterial(s) with a proper objective function (such as the weighted difference of VHT and VMT) to determine VSL (Variable Speed Limit), CRM (Coordinated Ramp Metering) rate for all entrance ramps of the freeway corridor, and traffic signal timing at intersections of the arterial corridor(s) for system-wide optimization.

CRM: to balance the entrance ramp demand and storage capacity, and mainline traffic while avoiding spillback to arterials; the objective is to minimize the weighted difference of TTS (Total Time Spent) and TTD (Total Travel Distance);

VSL: to jointly use VSL with CRM for most downstream bottleneck flow maximization;

Arterial intersection traffic signal: to balance the traffic flow into freeway at all the entrance ramps, to inject more traffic upstream of the freeway in the planned staging area, and to discourage traffic into the planned discharging section to guarantee freeway bottleneck is operated close to its capacity flow.

Advantages:

- Computation is simple if model and the objective function are linear;
- To optimize system wide Total Time Spent (TTS) including freeway and arterial corridors;
- Freeway section upstream of the bottleneck could be used as storage as long as exit ramps are not blocked;
- Not sensitive to sensor data health – except some critical points
- Able to adapt traffic dynamics in all phases
- This method must work for system-wide but not locally

Requirements:

- All the intersection controllers and sensor data need to be centralized (at TCM or at a Regional Master Computer) for such coordination and control;
- A well-developed traffic state parameter estimation based on sensor measurement is necessary to support the model based approach;
- Exception handling need to be developed to deal with the cases when some sensor data error appears;

5.4 Control Problem Formulation

5.4.1 Entrance ramp modeling:

(i) Entrance ramp Dynamics

In the ramp dynamics, metering rate is a control variable. It is the link between the entrance ramp dynamics and the feeding intersection. This integrates the coordination in a single formulation.

$$U_{on}(j) = U_{on}(j-1) + \sum_{i_r \in \phi_r} f_{i_r}(j) * \beta_{i_r}(j) * g_{i_r}(j) - C(j-1) * \overline{r}_j \qquad (5\text{-}1)$$

The second term is the number of vehicles feeding into the entrance ramp, and the third term is the number of vehicle exit from the entrance ramp at the beginning of cycle *j*.

The average ramp meter rate is defined as follows:

$$\overline{r}_{j-1} = \frac{\sum_{\sum_{l=1}^{j-2} C(l) < kt \le \sum_{l=1}^{j-1} C(l)} r(k)}{C(j-1)}$$

If the cycle length is constant, say $C(j) = cT$, then

$$\overline{r}_{j-1} = \frac{\sum_{\sum_{l=1}^{j-2} C(l) < kT \le \sum_{l=1}^{j-1} C(l)} r(k)}{C(j-1)} = \frac{\sum_{(j-2)cT < kT \le (j-1)cT} r(k)}{cT} \qquad (5.2)$$

Comment 5.1. Introducing the concept of average ramp metering rate is very important to decouple the ramp metering process from the intersection timing plan optimization since those two processes are in different time scales.

5.4.2 Intersection Modeling

(i) Intersection Queue Dynamics – number of vehicles at the end of cycle *j*:

$$U_i(j) = U_i(j-1) + C(j)d_i(j) - f_i(j)g_i(j) \qquad (5.3)$$

The second terms in the right hand side is the flow from near-by intersection or from the freeway exit ramp; the third term is the number of vehicles leaving phase *i* during cycle *C(j)*.

(ii) Constraints:

$$(1):\ g_i(j) \geq G_{\min,i},\ \ i \in \phi$$

$$(2):\ g_i(j) \leq \frac{\left[U_i(j-1) + d_i(j) * C(j)\right]}{f_{sat,i}(j)},\ \ i \in \phi$$

$$(3):\ \sum_{i_r \in \phi_r} f_{i_r}(j) * \beta_{i_r}(j) * g_{i_r}(j) \leq RA(j)$$

$$(4):\ f_i(j) \leq f_{sat,i}(j) \qquad (5\text{-}4)$$

$$(5):\ f_{i_r}(j) \leq f_i(j)$$

$$(6):\ \sum_{i \in \phi} g_i(j) = C(j); \quad \text{or:} \quad \sum_{i \in \phi} g_i(j) \leq C(j)$$

$$(7):\ U_i(j) \leq U_{i,\max}$$

Explanation:

(1). is obvious: the minimum green tine constraint to be satisfied;

(2). is the time needed to discharge all the vehicles in phase *i* at the intersection; the green time to be assigned to that movement should not exceeds what it is needed;

(3). the left hand side is the total number of vehicles feeding into the entrance ramp in cycle *k*, which should be limited to the acceptance capability of the subject entrance ramp calculated as follows:

$$RA(j) = U_{on,\max} - U_{on}(j) + C(j-1) * \overline{r}_j$$

(4). is also obvious: the flow of phase I should not exceed the saturated flow of that

movement;

(5). is also obvious: the feeding flow to the freeway entrance ramp is only part of the total flow of phase *i*;

(6). there are two possible ways to use the cycle length: the first way is to use it all regardless (all red phases are intently ignored here for simplicity); and the second way is to use the green as necessary which may end up with some extra green time. An immediate question is how to assign the extra green;

(7). is clear; however, if movement *i* storage is full, one has to either reduce the demand from its upstream d_i of increase the corresponding green time to dump traffic faster.

The question is: How to assign the remaining green to other phases?

The answer could be in several ways:

- assign the extra green to historically recorded movement with the longest queues;
- assign the extra green to major movement in peak hours regardless of the queue lengths of the minor movements;

5.4.3 Optimization Problem Formulation

The objective of the intersection section timing strategy is to bring capacity to demand ration $g_i(j) \Big/ \frac{U_i(j)+d_i(j)*C(j)}{f_{sat,i}(j)}$ as close to 1 as possible, which is equivalent to say that $\frac{U_i(j-1)+d_i(j)*C(j)}{f_{sat,i}(j)}$ and $g_i(j)$ are as close as possible.

With

$$g_i(j) \le \frac{U_i(j)+d_i(j)*C(j)}{f_{sat,i}(j)}$$

added as constraints,

$$\frac{U_i(j-1)+d_i(j)*C(j)}{f_{sat,i}(j)} - g_i(j) \ge 0$$

The first approach is to formulate a Linear Programming (LP) problem to minimize

$$J(j)=\sum_i \left| \frac{U(j-1)+d_i(j)*C(j)}{f_{sat,i}(j)} - g_i(j) \right|$$

$$\min_{\mathbf{g}(j)} J(j)$$

$$\mathbf{g}(j)=\left[g_1(j),\ldots,g_{N_\phi}(j) \right]$$

or a quadratic programming problem to minimize

$$J_2(j)=\sum_i \left(\frac{U(j-1)+d_i(j)*C(j)}{f_{sat,i}(j)} - g_i(j) \right)^2$$

$$\min_{\mathbf{g}(j)} J_2(j)$$

The decision parameters are the green time distribution among all the phases of the intersection.

Comment 5.2. To consider the overall system including both freeway and arterial intersections, the decision parameter needs to include ramp metering rate. It means that the system-wide optimization should be conducted jointly. However, for this phase of the project, only one entrance ramp is taken into consideration. The ramp meter rate is determined to control the merging area of the entrance ramp to its maximum flow possible. This only needs a local adaptive ramp metering such as ALINEA. The ramp meter rate is only determined by freeway mainline traffic situation, without considering intersection traffic. However, in higher level coordination strategy, intersection traffic has been taken into account.

The above algorithm has been implemented in simulation with well-calibrated model and with performance evaluated, which will be presented in Chapter 6.

5.5 Simplified Coordination and Control Strategy

Due to the limit on what we are allowed to do, we propose to further simplify the coordination and control strategy as follows for practical implementation.

5.5.1. Freeway Ramp Metering on SR87 Entrance ramp at Taylor

Mainline occupancy based ALINEA method is used to generate the RM rate. Due to entrance ramp queue detection sensor problem, queue override is not included. For ALINEA

implementation, the detector should be at entrance ramp merge area. In practice, they were located immediate upstream of the entrance ramp.

5.5.2. Practical Intersection Traffic Control at Taylor

Figure 5-1 shows Taylor intersection near SR-87 with vehicle count on 04/02/2012. At the time of field test, the EB RT into freeway SR-87 SB was overlapped with both Phase 6 and Phase 7 for operation. From Figure 5-1, it could be observed that, for traffic counts to freeway, Phase 5 WB left turn was obviously higher (782 veh/hr) than EB right turn from Phase 6 (625 veh/hr). However, since Phase 7 demand was rather high, Phase 6 RT green was the total of Phase 6 through movement green and Phase 7 green times, which was very large. With so long green time, EB RT traffic had more priority to take the space in the entrance ramp in peak hours. Therefore, in PM peak hours, even if WB RT (Phase 5) had enough green time, entrance ramp did not have enough space to accommodate the vehicles from it. As the consequence, Phase 5 LT pocket queue was very long in PM peak hours. With the default overlap setting for operation, it was impossible to control the RT independently. Therefore, the project team proposed to change the overlap of EB RT movement to Phase 6 Through movement and Phase 3 in PM peak hours. The reasons to do so are: (a) there was no other simpler way to redesign the phase diagram without affecting the primary phases; (b) Phase 3 had very light traffic in both AM peak and PM peak hours; with such assignment, it was possible to change the green time of Phase 3 according to the need for EB Right turn. This was the essential part of the coordination between freeway ramp metering and arterial traffic signal control.

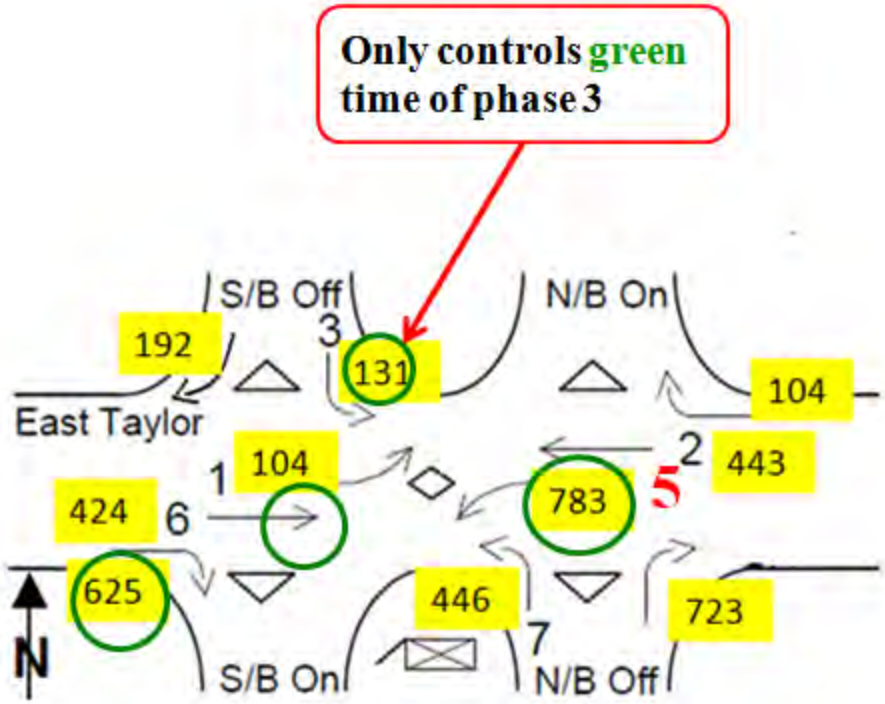


Figure 5-1. Phase assignment and vehicle count on 4/3/2012 at Taylor intersection

Chapter 6. Microscopic Simulation Development

6.1. Systematic Data Collection

Extensive data collection at SR87-Taylor was conducted for control/coordination strategy developed in microscopic simulation for the coordination of freeway RM and Arterial Traffic Intersection Signal control.

The road geometry of the section of SR87 near West Taylor Street with traffic detector IDs is shown in Figure 6-1 with loop detector locations on freeway.

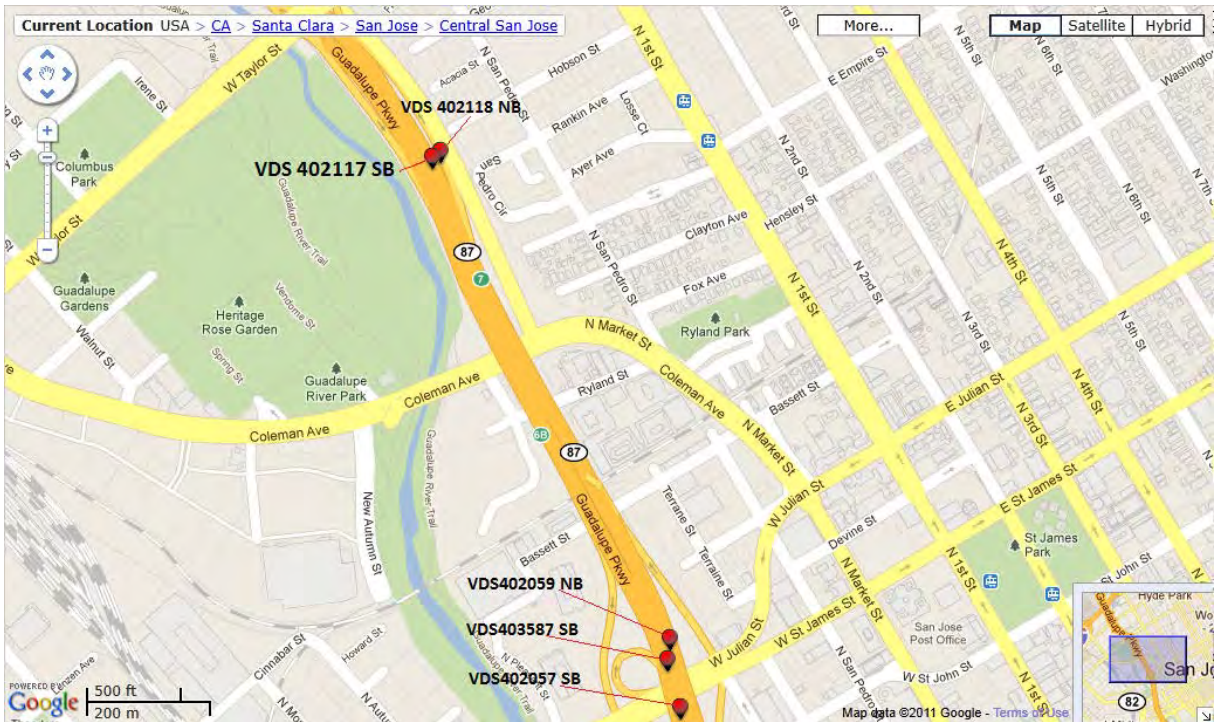


Figure 6-1. Road geometry and sensor locations near SR87-Taylor; no sensor upstream of Taylor SB.

The four data collection activities are described below. The first three times only used PATH video cameras to cover the intersection at Taylor (without San Pedro) and the corresponding entrance ramp (Figure 6-2). The fourth time used both Miovision units loaned from Caltrans and PATH Cameras.

6.1.1 Video Data Collection for the Intersection:

The video cameras were used to collect the intersection data for all movements. The locations of the cameras are shown in the following Figure:

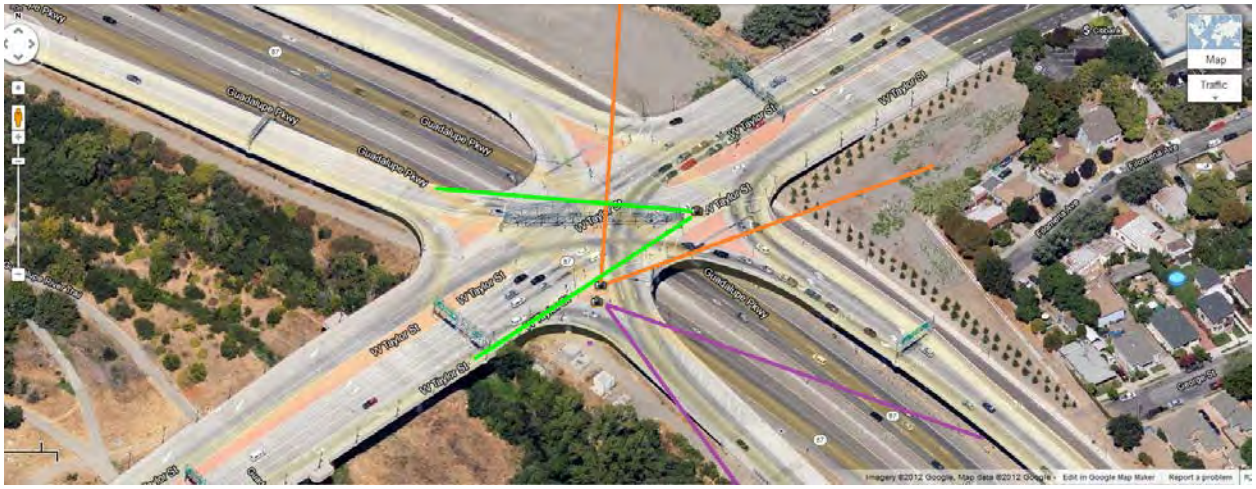


Figure 6-2. Location of the three video cameras for all movements of Taylor Intersection

The data were collected for about 85min on three working days:

- **04/03/12** (Tuesday): data collection was successful; traffic became heavy around 4:40pm; data collection started around 4:45 pm; entrance ramp queue back up was observed several times; the intersection was not blocked because drivers seemed to be familiar with the traffic conditions;
- **05/14/12** (Monday): data collection was not very successful. The Sony Camera stopped after 30 min and restarted at 5:14pm; SB entrance ramp was filled up due to mainline congestion from downstream traffic; the traffic was almost stop & go until 6:00 pm;
- **05/17/12** (Thursday): data collection was successful. The start time for the three cameras were recorded as follows (synchronized time based on cellphone):
    - Black Video camera: 4:29 pm (San Pedro direction)
    - White video camera: 4:30 pm (Entrance ramp)
    - Sony camera: 4:27 pm

Large entrance ramp queue was observed from 5:23 pm due to mainline congestion back-propagated from downstream traffic, which was similar to that observed on other two days.

There was an incident (engine stopped working for an old car – first place of left turn pocket from San Pedro – removed by police in about 10 min). Some entrance ramp back-propagation was observed but it was not as serious as those cases observed on 04/03/12.

All collected data were processed manually by project research team. The aggregated data for each movement was used for the first round traffic modeling and calibration.

6.1.2 PeMS Data and Caltrans District 4 Provided Freeway Data:

30s and 5min PeMS data were collected for teach VDS. Caltrans District 4 traffic engineers also provided the 04/03/2012 SCL-087 station data. Essentially, the data sets were similar to what we obtained from PeMS Systems.

6.1.3 Data Collection Using Miovision Systems on 09/05/12 (Wednesday) at Intersection

The objectives for data collection on 09/05/12 were to cover both Taylor and San Pedro intersections, freeway entrance ramp and left turn pocket between San Pedro and Taylor so as to capture an overall picture of traffic movement in the modeling. This was made possible due to the support from Caltrans HQ and District 4Traffic Operations.

Road Geometry and coverage

The road geometry of the system is shown is Figure 6-3 and Figure 6-4. The data sets covered all the movements at Taylor intersection (Figure 6-3) and feeding movement from San Pedro (Figure 6-4) into W. Taylor St. The traffic was heavy on 09/05/12. Spill-backs were observed on both entrance ramp and left turn pocket between Taylor and San Pedro St.

Figure 6-3. Overall road geometry of the system: (a) intersection at Taylor St., Intersection at San Pedro, and SB entrance ramp from Taylor to SR87

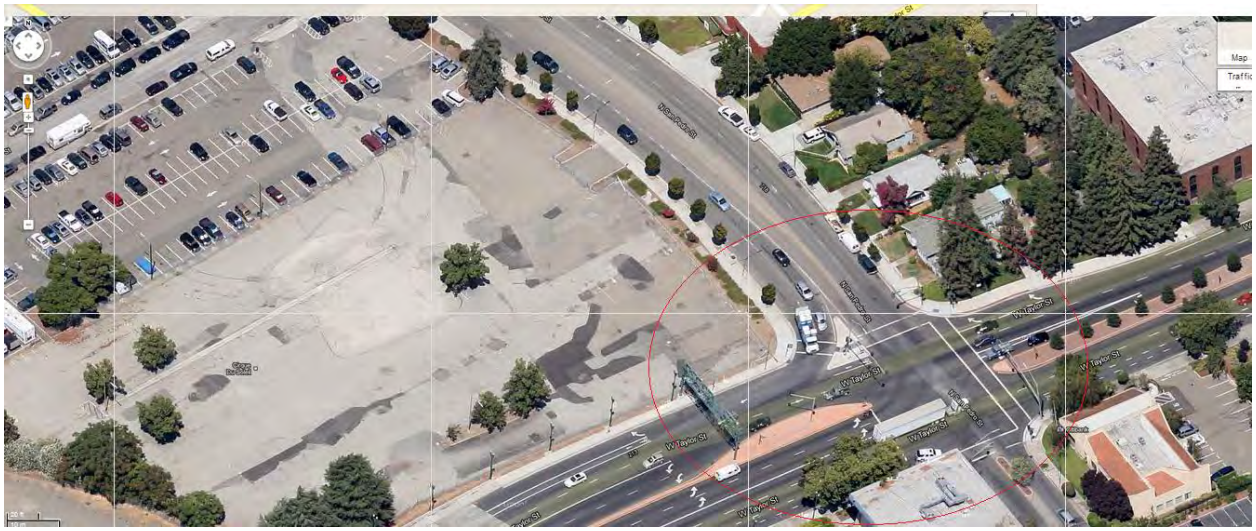


Figure 6-4. San Pedro Intersection

Since there was a large parking lot close to San Pedro, as shown in Figure 6-4, and the WB traffic came from First Street from San Jose City Center, the traffic flow was significant.

6.1.4 Camera Layout Scheme

Scheme with 3 Miovision Units (red circles) and 2 PATH Cameras (green beams) were shown in Figure 6-5.

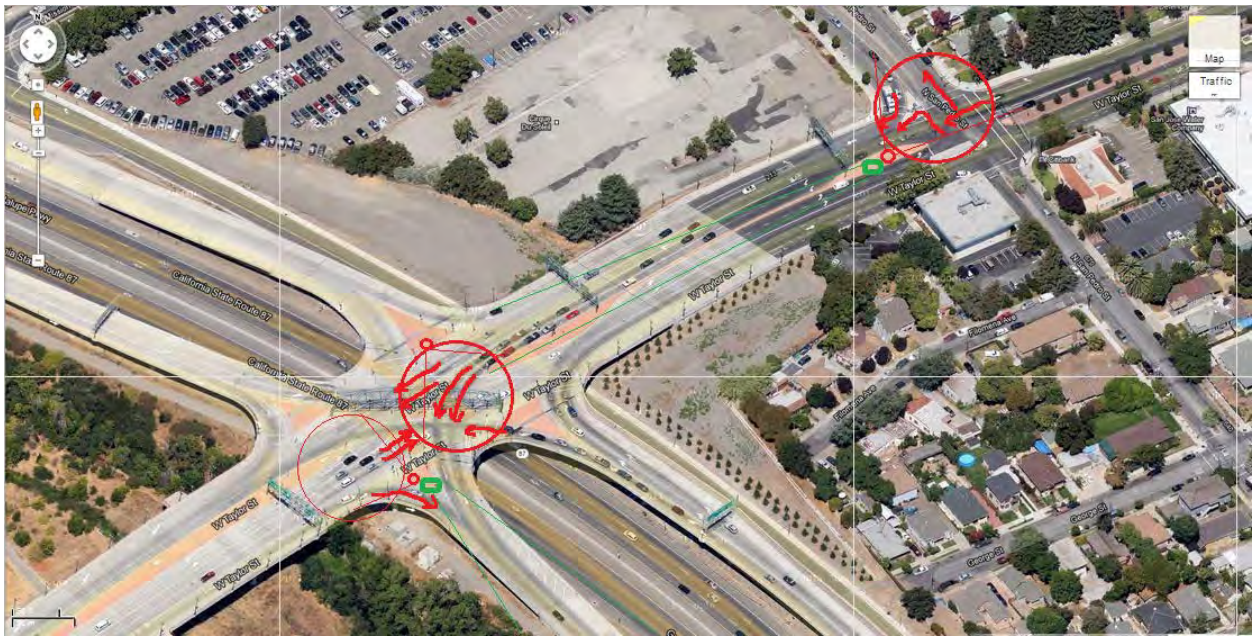


Figure 6-5. Data collection scheme with 3 Miovision Units plus 3 PATH Cameras; arrows indicating the main movement focused on; Miovision unit coverage and traffic movements

6.1.5 Data Covering Time

The research team decided that the data collection around PM peak (4:00 PM to 7:00 PM), instead of all day, due to limitation of equipment used, would still be adequate for simulation modeling purposes.

Data processing resolution

Manual vehicle count was around 30s level. Then we aggregated with 1~5min level for modeling. Miovision traffic movement count was 1min level of resolution by default.

Requested traffic Movement Counts

The movement counts we requested from Miovision (in their data processing) are listed below as shown in Figure 6-5:

- For Taylor Street EB: (1) through movement; (2) right turn movement into SB entrance ramp;
- For Taylor Street WB: (1) through movement; (2) Left turn movement into SB entrance ramp; (3) Left turn from NB exit ramp;
- For San Pedro: (1) Right turn on to Taylor (SB); (2) Left turn onto Taylor (NB); (3) through movement to Taylor (WB from First Street); (4) through movement (NB);

- Freeway entrance ramp queue length and Taylor intersection left turn (into entrance ramp) queue length.

6.2 Network Modeling and Model Calibration

A microscopic simulation model was built in Aimsun in order to evaluate the performance of the proposed control method. This simulation model covered one freeway segment and two intersections. The freeway segment is from about 1800 meters north of Taylor St to the Julian St entrance ramp (the Julian St entrance ramp was southbound downstream ramp of the Taylor St entrance ramp). Both directions of freeway and all the ramps within this region were included. The two intersections modeled are the interchange of SR-87 & Taylor St and the intersection of Taylor St & San Pedro St. Even though the intersection of Taylor St & San Pedro St was included, the proposed control design was only for the interchange in this study. This intersection was covered in order to evaluate queue spillovers. The geometry and speed limits of the roads in the simulation model were exactly the same as in reality.

To accurately re-create traffic conditions, field-implemented traffic control plans and field-collected traffic volumes were utilized in the simulation model. Traffic control plans were obtained from maintenance agencies. According to these control plans, ramp meter and signal control were both time-of-day plans. The ramp metering rate was selected from a set of values based on freeway mainline occupancy. Two intersections were in actuated control, but they were not coordinated. Traffic volumes were obtained from two sources. One data source was the intersection data from the Miovision system mentioned in the previous section. The data covers 4:15pm - 7:00pm, and volumes were given on a one-minute interval. The volumes of WB LT and SB RT were missing in the intersection data, because they were not captured by the cameras. However, the missing data did not affect the accuracy of the simulation model. This was because the demands for these two movements were much lower than the others (about 5 vehicles every 2 minutes for each movement). The westbound right-turn had very long green time and the southbound right-turn was stop-controlled. There was usually no queue present at these two movements, and the interaction of vehicles in these two movements and those in the others were very limited. Freeway traffic data from PeMS including flow, occupancy and speed, were obtained with detectors located upstream of entrance ramps. There was no ramp data provided by

PeMS, but it could be computed from intersection data. The intersection data and freeway data were aggregated over five minute intervals as the demand profile in the simulation model.

Model calibration was conducted before we used the model to evaluate the proposed control. The criterion for calibration used here was selected from [49, 50]. In order to capture the dynamic pattern, flow and speed on the freeway mainline and link flows at intersections were compared with real traffic measurements every 10 minutes. At least 85% of the flows were required to be acceptable and GEH<5 (with GEH to be defined below). A simulated flow quantity is said to be acceptable if it satisfies the requirement below.

- Link flow quantity
  - If 700vph < real flow < 2700vph, simulated flow has an error within 15%;
  - If real flow < 700vph, simulated flow has an error within 100vph;
  - If real flow > 2700vph, simulated flow has an error within 400vph.

In this sense, the percentage of flows with an acceptable error is that of simulated flows falling within the allowable error range mentioned above. The GEH statistic is computed by the equation below [49].

- $GEH(k) = \sqrt{\frac{2(M(k)-C(k))^2}{M(k)+C(k)}}$

In this equation, M(k) is the simulated flow and C(k) is the corresponding flow measured in the field at time k. A satisfactory calibration requires that the simulated flow quantities can satisfy the condition GEH(k)<5 for least 85% of time points k.

For speed, the simulated speed needed to be close to the real speed. An error within 5mph would be acceptable. As a result, we required at least 85% of the simulated speed values fall in the range of ±5mph of the corresponding real speeds.

We ran the simulation model with 20 different random seeds. Table 6-1 shows a summary of calibration results for intersection movements at SR-87 & Taylor St. It can be seen that, on average, all movements have more than 85% of the time points at which the flow is within the required error range. The percentages of flows for all movements with GEH<5 also reach 85% or higher. Row 3 and Row 4 show the standard deviation of the percentages. Notice that one data point accounts for 6.25% in the simulation. It is observed that the deviation is in an acceptable range. Table 6-2 shows the result for the freeway. It shows that the percentage of flows meeting the allowable error and the percentage of flows with GEH<5 are higher than 85%

again. Besides, more than 85% of the speed values are less than 5mph error. In summary, Table 6-1 and Table 6-2 indicate that the model calibrations for both the intersection and the freeway are satisfactory.

Table 6-1. Calibration Result of Intersection Movements

	EB Left	EB Through	EB Right	WB Left	WB Through	SB Left	NB Left	NB Right
Mean percentage of flows with acceptable error	100.00%	100.00%	92.10%	89.20%	98.30%	100.00%	100.00%	96.70%
Mean percentage of flows with GEH<5	100.00%	100.00%	97.10%	92.10%	99.20%	93.80%	100.00%	99.20%
Standard deviation of percentage of flows with acceptable error in best run	0.00%	0.00%	6.20%	5.80%	2.80%	0.00%	0.00%	5.00%
Standard deviation of percentage of flows with GEH<5	0.00%	0.00%	3.90%	4.20%	2.10%	4.00%	0.00%	2.10%

Table 6-2. Calibration Results for Freeway

	Flow	Speed
Mean percentage of flows with acceptable error	93.40%	NA
Mean percentage of flows with GEH<5	90.30%	NA
Standard deviation of percentage of flows with acceptable error	1.40%	NA
Standard deviation of percentage of flows with GEH<5	3.10%	NA
Mean percentage of speeds with error<5mph	NA	89.70%
Standard deviation of percentage of speeds with error<5mph	NA	3.1%

6.3 Control/Coordination Performance Evaluation through Simulation

The proposed control strategy and the field-implemented control plans were compared through microscopic simulation. The calibrated microscopic model mentioned in previous section was used, and the proposed control was implemented in the simulation with Aimsun API (Application Program Interface). Twenty simulation runs with different random seeds were conducted to obtain an average performance. Delay and total travel distance that were collected from simulation runs for individual movements and the overall system were compared.

Table 6-3 shows the simulation result. Columns 2 - 4 present the performance aggregated over 20 runs, and columns 5 - 7 present the standard deviation of the performance measures in 20 runs. In each entry, the value without parentheses is delay in hours, while the value inside the parentheses is travel distance in kilometers. It can be observed that the difference of travel distance is very small when the proposed control is applied. There is no vehicle lost and withheld in the simulation. With the proposed control, total delay in the system was reduced by 1.37%, but the intersection delay was reduced by 8.11%, which was much more significant. EB right-turn, WB left-turn, WB through and NB right-turn had significant reductions in delay. Even though SB left-turn showed 17.05% increase in delay, the traffic flow for this movement was very small and the increase in absolute value was acceptable. From this table, it can be seen that the delay of the movements with significant values in total delay, is decreased by the proposed control. This reduction out weights the small delay increase of movements with small values in total delay.

The small delay reduction in the overall system and significant improvement at the interchange can be explained as follows. The entrance ramp bottleneck causes the major delay in the network. Given the high traffic demand in the mainline and at the entrance ramp, it is unlikely to resolve freeway congestion without causing queue propagation in the interchange if ramp metering is the only control influencing freeway flow. Intersection delay only accounts for a small portion in the system due to relatively small volume. Therefore, its significant reduction does not make a large change in the total delay. To get larger improvement in the overall system, multiple neighboring ramps need to be coordinated. However, this is beyond the project scope.

Table 6-4 presents the maximum queue lengths recorded in the simulation. The queue lengths were collected for individual movements at the intersection and they were aggregated over lanes. The unit for queue length is number of vehicles. Columns 2 - 4 give the average values in 20 simulation runs and columns 5 - 7 present the standard deviation. The changes in the mean maximum queue lengths are not significant. In the simulation, queue spillover at WB left-turn was still observed in the proposed control method, but it was slightly better than that in the currently field-implemented control. This spillover was difficult to avoid because of a large traffic demand of this movement and congestion on the entrance ramp. Queue spillovers for other movements do not appear in the simulation.

Table 6-3. Performance of Proposed Control

	Mean			Standard deviation		
	Total delay (travel distance) in current control plans	Total delay (travel distance) in proposed control plans	Change in delay (travel distance)	Total delay (travel distance) in current control plans	Total delay (travel distance) in proposed control plans	Change in delay (travel distance)
EB Left	2.52 (-58.13)	2.62 (-58.05)	3.83% (-0.15%)	0.06 (-0.77)	0.09 (-0.77)	4.22% (-0.61%)
EB Through	10.28 (-254.3)	10.31 (-256.08)	0.23% (-0.70%)	0.21 (-1.49)	0.29 (-1.7)	3.75% (-0.66%)
EB Right	18.95 (-1.89E+03)	17.48 (-1.89E+03)	-7.72% (-0.09%)	2.97 (-3.38)	1.95 (-3.79)	19.65% (-0.07%)
WB Left	57.4 (-3.67E+03)	51.83 (-3.67E+03)	-9.69% (-0.07%)	5.08 (-8.84)	4.67 (-10.1)	9.24% (-0.12%)
WB Through	5.25 (-233.82)	3.95 (-231.03)	-24.77% (-1.19%)	0.4 (-3.06)	0.2 (-2.44)	5.94% (-1.14%)
SB Left	2.21 (-49.45)	2.59 (-49.4)	17.05% (-0.10%)	0.06 (-0.79)	0.11 (-0.76)	4.50% (-0.44%)
NB Left	10.36 (-702.67)	10.39 (-702.56)	0.36% (-0.02%)	0.17 (-4.05)	0.41 (-4.43)	4.12% (-0.17%)
NB Right	7.62 (-910.94)	6.12 (-911.11)	-19.72% (-0.02%)	0.14 (-4.78)	0.19 (-4.97)	2.92% (-0.11%)
Intersection total	114.59 (-7.76E+03)	105.29 (-7.76E+03)	-8.11% (-0.00%)	4.67 (-12.06)	6.53 (-13.08)	5.84% (-0.05%)
Network total	685.07 (-4.78E+04)	675.66 (-4.78E+04)	-1.37% (-0.02%)	11.92 (-35.91)	13.57 (-48.77)	2.10% (-0.10%)

Table 6-4. Comparison of Queue Length

	Mean			Standard deviation		
	Maximum queue length in current control plans	Maximum queue length in proposed control plans	Change in maximum queue length	Maximum queue length in current control plans	Maximum queue length in proposed control plans	Change in maximum queue length
EB Left	4.67	4.67	0.00%	0.58	0.47	17.29%
EB Through	12.89	12.83	-0.43%	1.2	0.69	9.25%
EB Right	29.11	29.67	1.91%	2.42	3.87	14.08%
WB Left	45.06	44.89	-0.37%	4.61	4.77	15.98%
WB Through	9.83	8.83	-10.17%	0.69	1.26	14.89%
SB Left	5.56	6	8.00%	1.01	1.05	24.30%
NB Left	16.5	16.83	2.02%	1.01	1.64	11.42%
NB Right	18.22	15.28	-16.16%	1.96	1.76	10.44%

Chapter 7. Hardware and Software Development and System Integration

This chapter documents the limited field operational test that was conducted in this project including development of hardware and software systems, communication interface, control algorithm, and data flows.

7.1 Hardware and Software Systems Structure

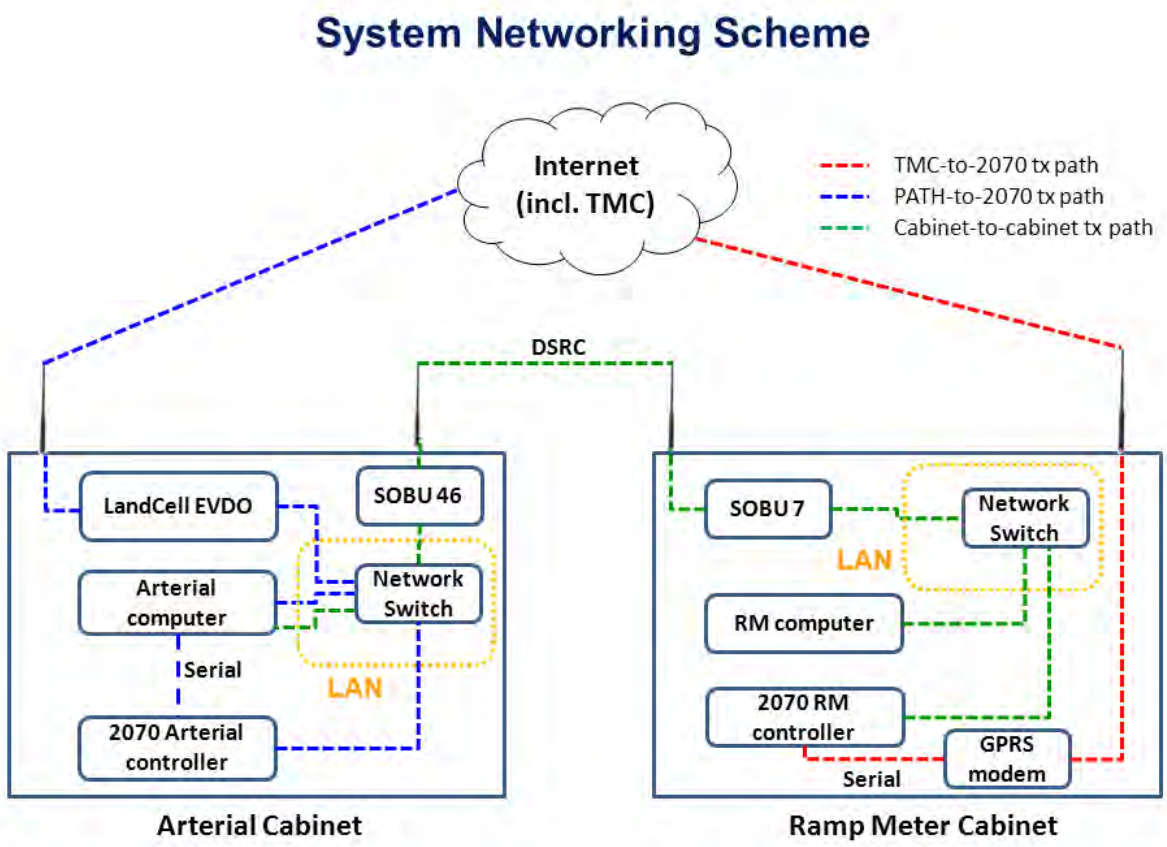


Figure 7-1. 2070 controllers are controlling both the arterial signals and ramp meter.

As shown in Figure 7-1, the arterial controller was running TSCP 2.17 and the ramp meter controller was running URMS 12.20. AB3418 was used to poll and control the arterial controller over a serial connection. URMS messages controlled the ramp meter over the LAN (Local Area Network). The TMC was capable to poll and control the ramp meter using TOS

(Traffic Operations Systems) via a GPRS modem with a serial connection to the ramp meter. The arterial computer, running PATH software, sent changed release rates to the ramp metering computer via port forwarding using the Savari On-Board (SOBU) wireless units. The arterial and ramp meter computers were communicating via the DSRC (Dedicated Short Range Communication) interface inside of the SOBU wireless units instead of over the internet. This connection was more reliable than the 3G connection with network latency eliminated. Security of communication over the 3G modem was ensured by allowing only SSH (Security Shell) connections from computers with one of two MAC addresses.

7.2 Hardware Development

Hardware for the coordinated signal and ramp meter control system comprised of two 332 cabinets, each containing a 2070 controller, a computer installed by PATH, a Savari On-Board Unit with LAN and DSRC interfaces, a network switch, and cabling (see Figure 7-1). The arterial cabinet contained a 3G modem for communicating with a host at PATH, and the ramp meter cabinet contains a GPRS modem with a serial interface for communicating with the Caltrans District 4 ramp meter center. Each of these components will be described below.

7.2.1 Arterial Cabinet Components

Arterial 2070 controller

The arterial 2070 controller was running TSCP 2.17. It had an Ethernet port and three serial ports, one of which (COM1) was used for communicating to the PATH computer. This port was transmitting AB3418(E) messages to and from the PATH computer. There was also an Ethernet port used for debugging, upgrading, and maintenance, but not for AB3418 messaging.

PATH arterial computer (AC)

The PATH arterial computer (AC) was a mini-ATX system with a Jetway NF9E-Q977 motherboard running a 3.4 Ghz Intel i5-3570 quad processor. It was running the Linux 3.2.0-48 operating system, with an Ubuntu 12.04 distribution. It had two Ethernet ports. One was used when the computer is running at PATH, and the other at the test site. It had two serial ports. One was connected to the arterial 2070. It also has 6 USB ports, two of which were used for

keyboard and mouse. It was running PATH software for communication between the arterial controller and the ramp meter computer via the SOBU wireless units. It was also running the control algorithm that determines the maximum green time for the right turn onto the SR87 entrance ramp and metering rate for the SOV (Single Occupancy Vehicle) lanes of the entrance ramp. The HOV (High Occupancy Vehicle) lane metering rate was always the maximum lane rate [900 veh/hr/lane].

3G modem

The 3G modem was a LandCell 882 Evolution, Data-Optimized (EVDO) modem.

DSRC Radio

PATH used two radios transmitting in the Dedicated Short Range Communications (DSRC) band. Since the DSRC band was currently not used for consumer wireless communication, it would be less likely to have security problems. The radios used were Savari On-Board (SOBU) Units, which have DSRC, 802.11, and LAN interfaces. The 802.11 interface was disabled. Only the DSRC and LAN interfaces were used.

Network switch

The two network switches used for the in-cabinet LANs were Black Box USB-powered switches.

7.2.2 Ramp meter cabinet components

Ramp meter 2070 controller

The ramp meter 2070 controller was running URMS 12.20. It had an Ethernet port and three serial ports, one of which was used by Caltrans District 4 Ramp Meter Field Office in San Jose to monitor and control the ramp meter remotely using TOS messages. PATH used logical port 2 of the Ethernet port for monitoring and controlling the ramp meter with URMS messages. Potential conflicts between PATH and Caltrans control messages ware resolved with the prioritization scheme developed at Caltrans Headquarters. Caltrans had a higher priority than PATH. Therefore, a control command from Caltrans would supersede one from PATH.

PATH ramp meter computer (RMC)

The PATH ramp meter computer was identical to the arterial computer described above. It was running software for monitoring and controlling the ramp meter and transmitting data to, and receiving metering rates from, the arterial computer.

7.3 Software Development

The overall software structure and data flow are depicted as in Figure 7-2.

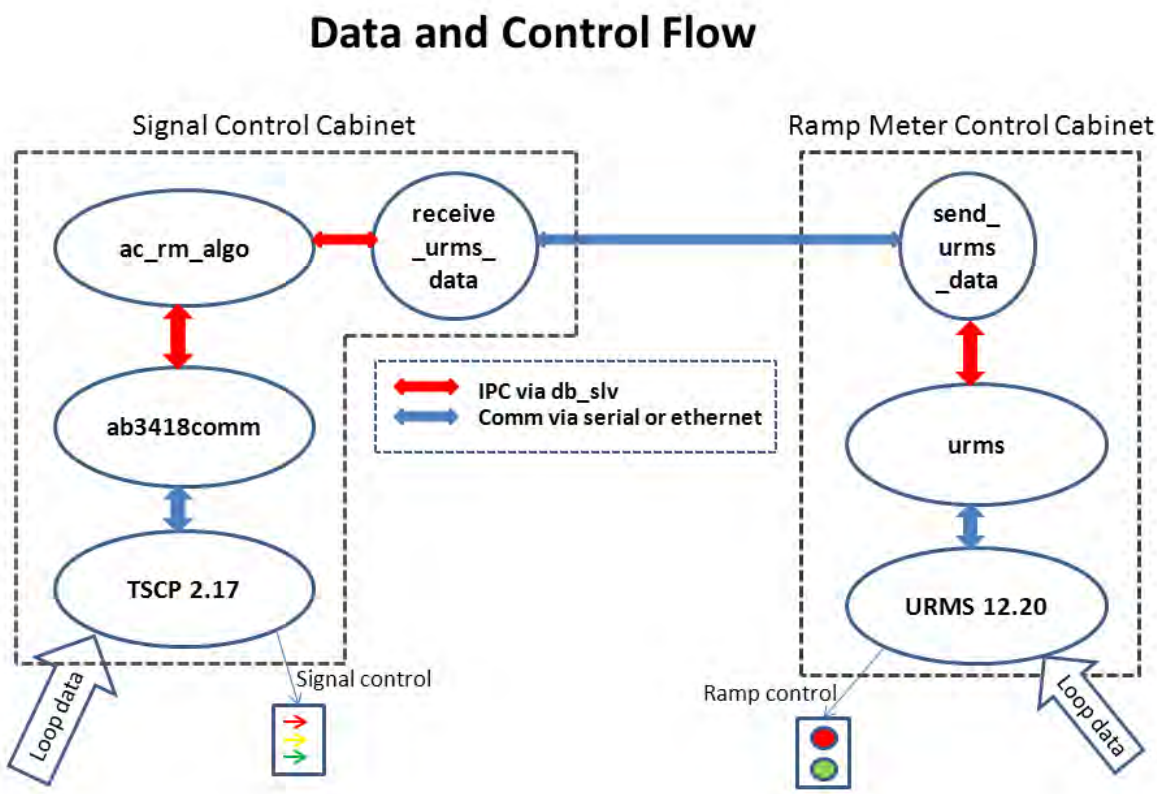


Figure 7-2. Software structure: data and control flow

7.3.1 Summary of Data and Control Flow

The control algorithm, *ac_rm_algo*, received loop data from the arterial traffic signal controller via its application TSCP. TSCP was polled by AB3418comm via serial port. AB3418comm then wrote the data to the publish/subscribe database *db_slv*. *ac_rm_algo* then

periodically polled *db_slv* for this data. In a similar fashion, *ac_rm_algo* received loop data from the ramp metering controller via its application URMS. URMS was polled by the PATH interfacing program URMS via the Ethernet LAN connection. URMS then wrote the data to *db_slv*. The difference here was that the ramp meter data must be sent wirelessly (via DSRC) from the ramp meter cabinet to the arterial cabinet. This was done using the two programs *send_urms_data* and *receive_urms_data*. (Despite their names, both programs were bidirectional. i.e., each program both sending and receiving data from the other program). When AB3418comm wrote ramp metering data to *db_slv*, this action triggered *send_urms_data* to read the data from *db_slv* and transmitted it through the DSRC-connected SOBUs to *receive_urms_data*. Upon reception of the ramp meter data, *receive_urms_data* wrote it to *db_slv*.

The maximum green time for phase 3 was generated by *ac_rm_algo* and written to *db_slv*. That action triggered AB3418comm to read the green time from *db_slv* and send it via AB3418(E) to TSCP, which controlled the overlap associated with phase 3. A new metering rate was also generated by *ac_rm_algo* and written to *db_slv*. This action triggered *receive_urms_data* to transmit the metering rate via DSRC to *send_urms_data*, running on RM computer. *send_urms_data* wrote the metering rate to *db_slv*, which triggered *urms* to read the metering rate and sent it to URMS via the LAN. URMS set the metering rate of the ramp meter lights.

Chapter 8. Progressive Implementation and Field Test

For success of field test, the project team had proposed a progressive system implementation and field test procedure before any action (Appendix 6) through extensive discussion with the project panel and Caltrans District 4 engineers.

8.1 Overlap Change in Phase Assignment

At the beginning of field test, the overlap of EB RT into freeway SR-87 SB with both Phase 6 and Phase 7 were changed to overlap with Phase 6 and Phase 3 as discussed in Chapter 5. Accordingly, all the loop assignments were changed.

8.2 Safety Concern

Caltrans District 4 Intersection Traffic Signal engineers requested that the UCB team to detect the gap between platoons in PATH control process or to retrieve the original Gap Detection from 2070 Controller, and the maximum green should be extended if the gap between two platoons was less than a specified threshold. The estimation should be similar to that by the default control system.

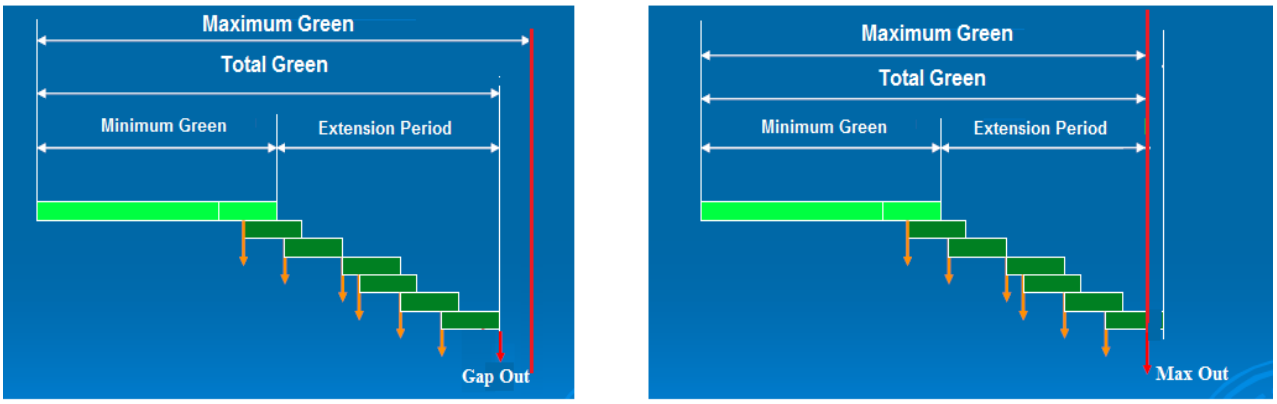
After careful investigation of the Gap Out detection and activation logistics, we found out that: (a) PATH program could detect gap out using a count timer based on the *preset gap* (*passage gap*); (b) since the *maximum green* of a phase PATH controller was allowed to change through AB3418(E) could only be conducted before the cycle started; and it could not be executed once traffic control was already in that phase. Therefore, even if PATH control could detect the Gap correctly, it could not activate the green extension in AB3418(E) level.

The underneath Actuated Traffic Control program was still running with all the operation logistics unchanged. The effect of maximum green on the Gap Out was the same as that of the default (original) maximum green:

- if the green extension was within the maximum green the Gap Out took effect as in Figure 8-1(a);
- if the green extension was so long that it exceeded the maximum green, then Max Out would take effect as in Figure 8-1(b), which was similar to the default situation; however,

if the underneath Actuated Controller program was to extend the green further to avoid Max Out, it would not be affected by PATH control either.

Therefore, we concluded that there was no safety issue with the proposed control and coordination strategy with PATH computer through AB3418(E) protocol.



(a) Gap Out Before Max Out

(b) Max Out before Gap Out

Figure 8-1. Traffic Signal Control: Gap Out and Max Out

8.3 Practical Field Test

For smooth transition between signal timing strategies, two transition timing modules were developed: one was from the field timing strategy to the proposed timing strategy; and the other was in the reversed direction. In case of any problem, the controllers were to fall back to the default one.

Details can be found in the Appendix 6. The practical tests were conducted exactly as planned.

Ramp Meter Data

As presented before, RM rate was calculated using ALINIA method. This was tuned down a little since Caltrans District 4 RM engineer felt that it was a bit too high for the first week dry-run. The tuned RM rate data presented in Figure 8-2 include:

- Timestamp
- Current ramp meter rate: actual RM rate of metered lane 3 (blue)
- Calculated new ramp meter rate with ALINEA (red)

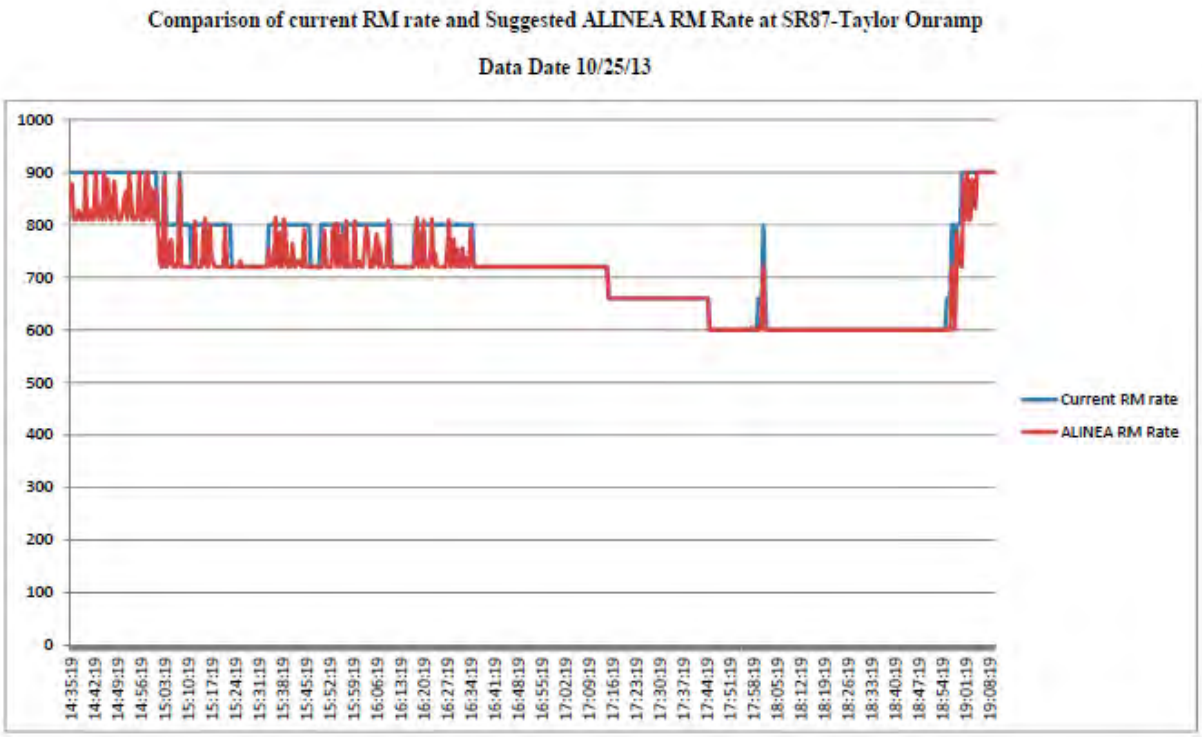


Figure 8-2. Dry Run RM Rate (vehicle/hour) Comparison

Dry Run Intersection Data

It is noted that the suggested control strategy only modulate the EB Right Turn (RT) green by changing the overlap from 6&7 to 6&3 (Figure 8-6), and to modulate the green time within specified max green for phase 3. All the other signals will NOT be changed and will keep the original scheme. The data collected in dry-run included entries

- time stamp
- new max green for phase 3
- new green for phase 3
- current actual green for phase 7
- left-turn occupancy during green period
- right-turn occupancy during green period
- release right-turn queue occasionally

Figure 8-3 indicates the green time difference for EB RT (to freeway) with overlap Phase 6&7 and overlap with Phase 6&3.

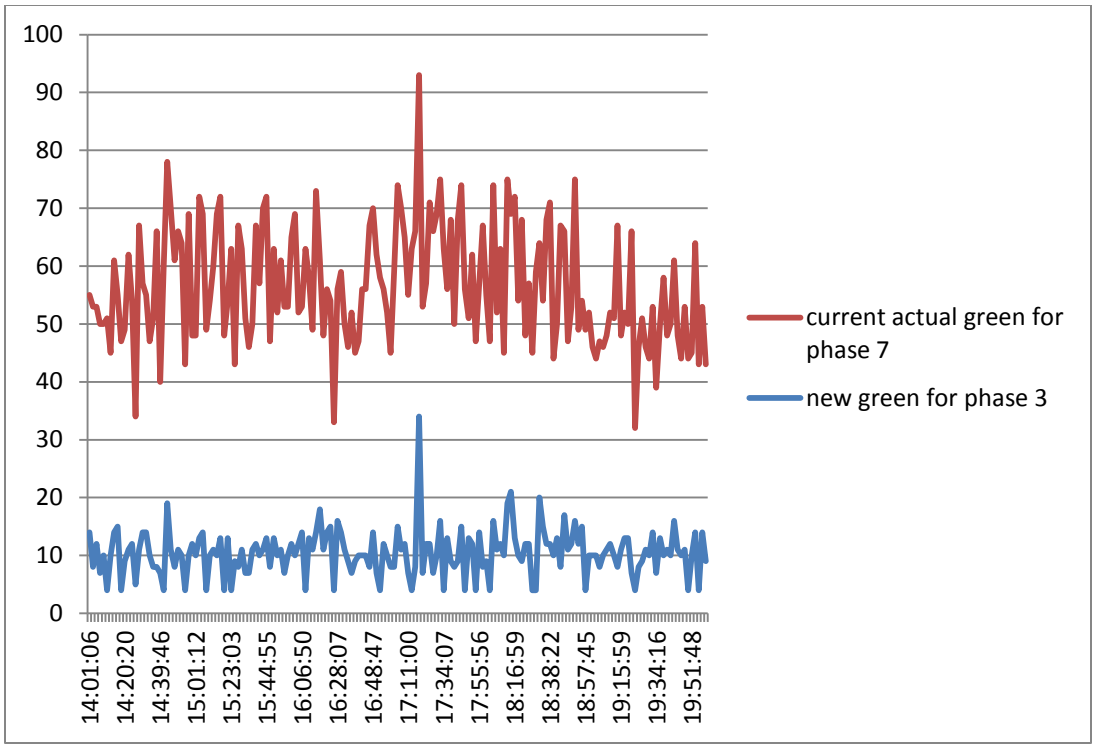


Figure 8-3. Dry Run Overlap Green Time Comparison: with Phase 7 (default) and with Phase 3 (proposed)

More detailed record of the tests can be found in Appendix 6.

8.5 Summary of Field Tests

The close cooperation between District 4 traffic engineers and UC Berkeley research team proved to be very effective to avoid any significant negative impact on traffic which could be very sensitive and could potentially cause problems to the motorists. The following are some major points which could be applied to the next phase of the project:

- Always use traffic signal tester for extensive hardware and software tests before field implementation
- Test system components to make sure they all work as specified before integration
- Test software for all parts to make sure they work as expected, are bug-free, and the control actuation works properly

- Conduct a dry-run for data collection and algorithm computation without control activation to make sure the new control signals are not significantly different from the field default signals to avoid any strange behaviors
- Adequately test all possible control scenarios to make sure the system behave as expected in all situations
- Adequately test all transitions between scenarios to make sure the transition are correct and smooth
- Never switch on control before everything is ready
- Traffic engineers should be present at the site at least for the first time for switching on
- Tightly monitor the system to avoid any unexpected behavior of the control systems during the test
- Acknowledge local traffic engineers about any actions to be taken to avoid any negative impact on local traffic
- Report and update any actions taken to the project panel in time and regularly

Chapter 9. Performance Analysis and Test Results

This chapter documents the test results and system performance analysis. Since the project involved one intersection, one entrance ramp, and a freeway section, the performance need to look at traffic changes for the three parts: intersection, entrance ramp and freeway mainline immediately upstream.

The intersection control signal changes for the test mainly affected EB RT (into the entrance ramp) (Figure 5-1) and WB LT (Phase 5 into the entrance ramp). All the other phases were not changed and not affected by the proposed control/coordination strategy. Besides, Phase 3 flow was very minor and its green time was increased somehow. Therefore, it was ignored in the system performance analysis. Intuitively, the new control strategy should improve WB (Phase 5) RT flow and decrease EB LT flow to some extent. Therefore, it is necessary to have a look at the net performance improvement. Due to limited sensor available, the project team used a method developed by other research before to determine the queue on EB RT and WB LT respectively using advance loop detector. From the estimated queue and flow, we calculated the Total Time Delay of those two movements for comparison.

9.1 Field Data Validation

Test dates of PATH controller at SR87 entrance ramp and Taylor Intersection were:

- PATH control on date: 10/29/13- 11/08/13
- PATH control off for data collection: 11/09/13 – 11/18/13; it is noted that the data for scenarios with PATH control off was collected after the test date, since Caltrans traffic engineers changed the 2070 traffic controller parameters on 10/29/13.

The effective data were compared (between green and red columns) (Table 9-1):

Table 9-1. Test Data Validation Record

PATH Control on date	PATH Control on date	PATH Control Off Date	Day of the Week	Comments
10/29	11/05	11/12	**Tue**	
10/30	11/06	11/13	**Wed**	
10/31	11/07	11/14	**Thu**	
11/01	11/08	11/15	**Fri**	
11/02		11/16	**Sat**	Weekend dropped
11/03		11/17	**Sun**	Weekend dropped
11/04		11/18	**Mon**	

(1) entries for Phase 5 LT count and occupancy when green

(2) entries for Phase 5 Stop-line count and occupancy when green

(3) phase 6 RT Advance loop count and occupancy when green

(4) phase 6 RT Stop-line count and occupancy when green

Oct 29 first day switching on data were dropped; data on 11/02 (Saturday) and 11/03 (Sunday) was dropped.

Traffic State Parameters

Since the control signals implemented in this project only included:

- Freeway RM rate
- Intersection (Figure 5-1):
    - Taylor EB right turn green time with overlap Phase 6 & 3
    - Taylor WB Phase 5 left turn green time is unchanged
    - The green times of all the other phases were unchanged
- Entrance ramp flow and queue were only affected by WB RT and EB LT.

Therefore, in performance analysis, only those two movements was considered in comparison. The following traffic state parameters was used for performance analysis:

- Freeway: vehicle count (flow) and occupancy of main lanes – individual lane and aggregation across lanes
- Intersection: vehicle count and green occupancy
    - at stop line
    - at advance loop
    - traffic signal of relevant phases (Phase 5, 6, and 3)

It is noted that, for intersection data, only occupancy of a movement when the corresponding traffic light was green was used, which meant that traffic of that movement was moving instead of stopped. The distance of advance loops to the stop line: Phase 5 WB LT – 141 [ft]; EB RT – 197 [ft] (Figure 9-1).

- Freeway mainline raw loop detector data were collected directly from the loop report instead of from the 2070 controller

- Intersection movement loop detector data and traffic signal timing data were collected
- Entrance ramp 30s aggregated traffic data were collected from the 2070 controller instead of raw data

Figure 9-1. Relevant detector locations; distance of advance loops to the stop line: WB LT – 141[ft]; EB RT – 197 [ft].

Performance Parameters

The following performance parameters have been adopted for performance analysis by comparison of data "before" and "after" PATH proposed control/coordination activated:

- Phase 5 LT accumulated flow at stop line
- Phase 5 LT accumulated flow at advance loop
- Phase 5 LT accumulated occupancy at advance loop
- EB RT advance loop accumulated flow
- EB RT advance loop accumulated occupancy

The following plots indicated the performance in those parameters.

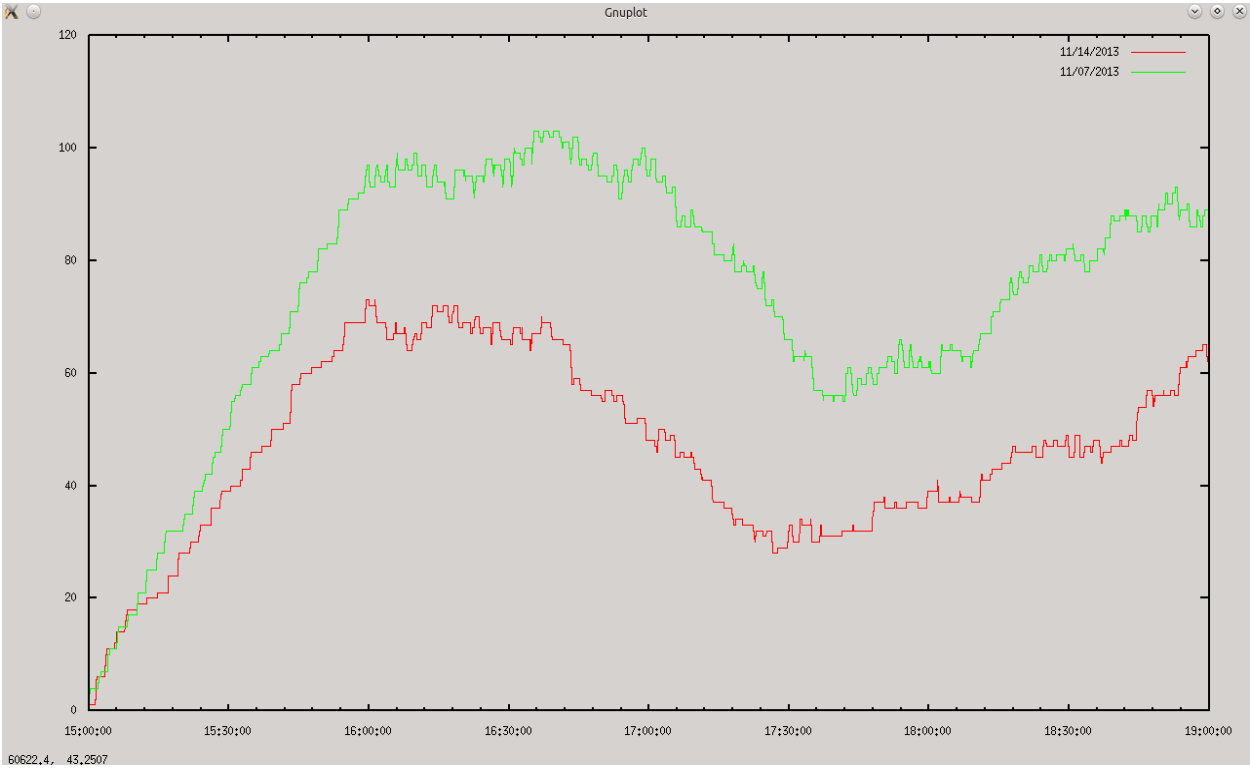


Figure 9-2. One day vehicle count comparison at stop-line detector of WB Phase 5 LT movement (2 lanes): Green – PATH control on; Red – PATH control off

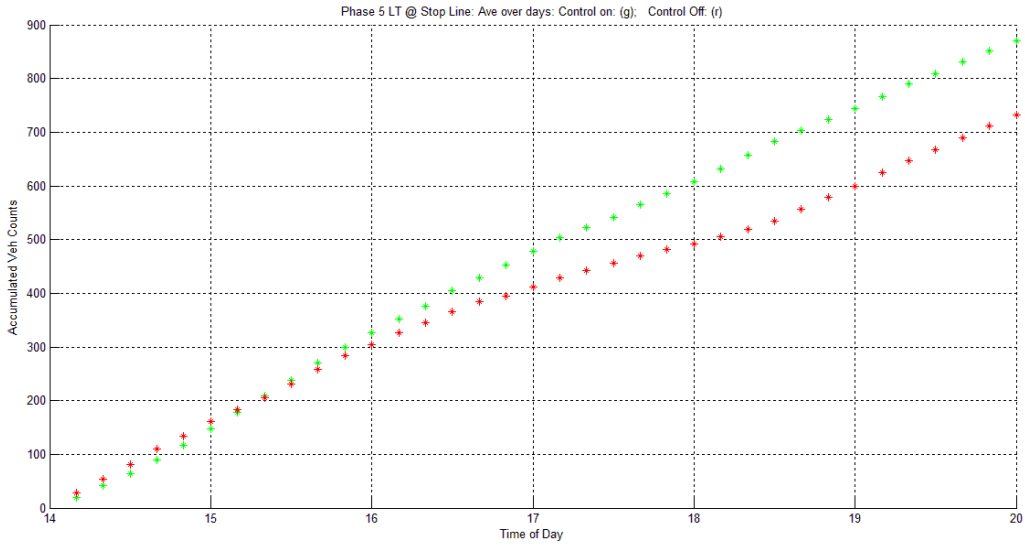


Figure 9-3. *Average cumulative vehicle count* comparison at stop-line detector of WB Phase 5 LT movement (2 lanes): Green – PATH control on; Red – PATH control off

Figure 9-2 indicates that vehicle count had a significant increase for one week day compared. Figure 9-3 shows averaged cumulative vehicle count at stop-line detector of WB Phase 5 LT movement (2 lanes). The merits for using accumulated value include:

- To observe intuitively the accumulated effect over time
- To avoid any difficulty for comparison caused by traffic count (flow) fluctuation

Figure 9-4 and Figure 9-5 show *average cumulative vehicle count* and *occupancy* at advance loop detector of WB Phase 5 LT movement (2 lanes). It is clear that, compared to the original control scheme, vehicle count increased and occupancy decreased which were very consistent.

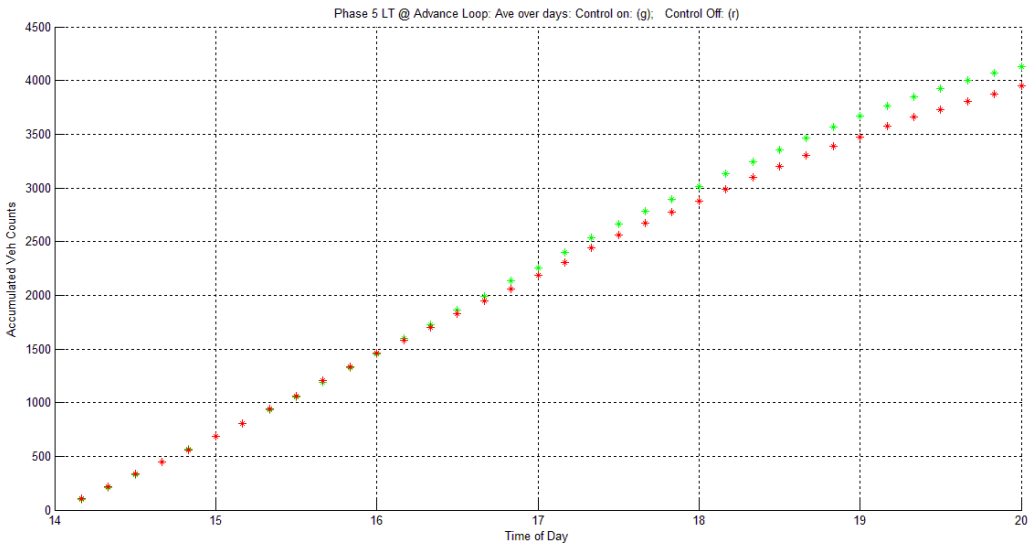


Figure 9-4. Average cumulative vehicle count comparison at advance loop detector of WB Phase 5 LT movement (2 lanes): Green – PATH control on; Red – PATH control off

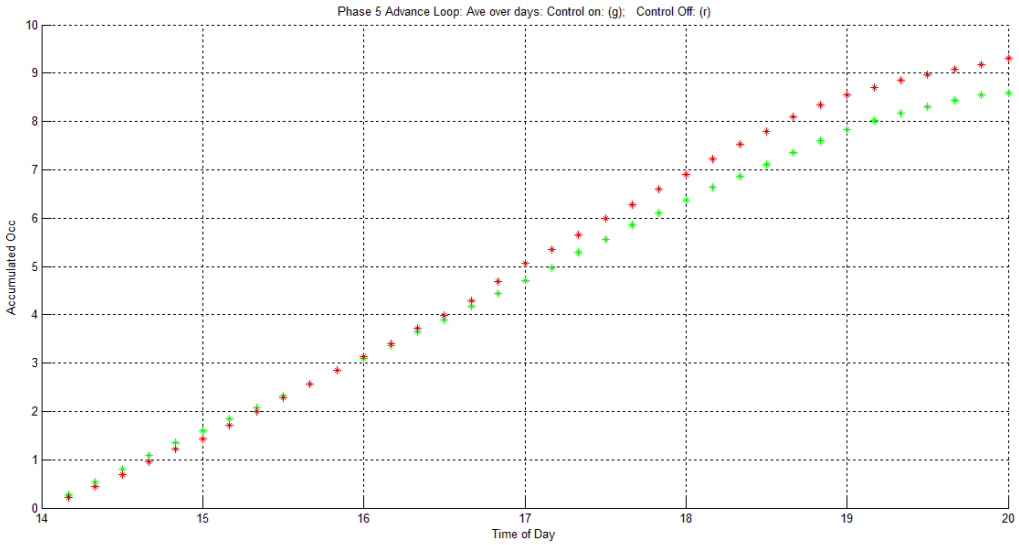


Figure 9-5. *Average cumulative occupancy* comparison at advance loop detector of WB Phase 5 LT movement (2 lanes): Green – PATH control on; Red – PATH control off

Figure 9-6 and Figure 9-7 show *average cumulative vehicle count* and *occupancy* at advance loop detector of EB RT movement. It can be observed that reduction of EB RT green time increased the queue somewhat as expected. It is therefore necessary to analyze the net benefit combining WB (Phase 5) LT and EB RT.

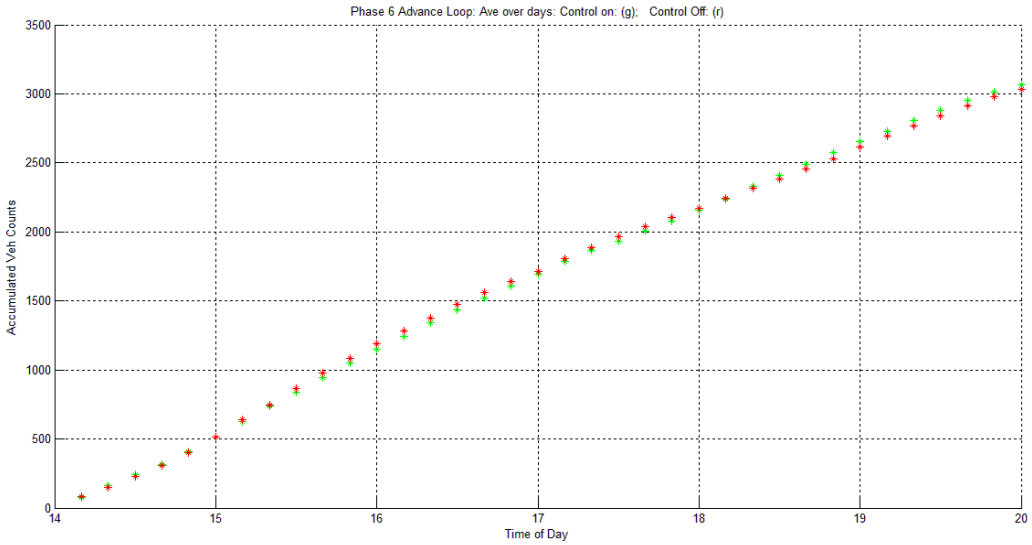


Figure 9-6. Average cumulative vehicle count comparison at advance loop detector of EB RT movement: Green – PATH control on; Red – PATH control off

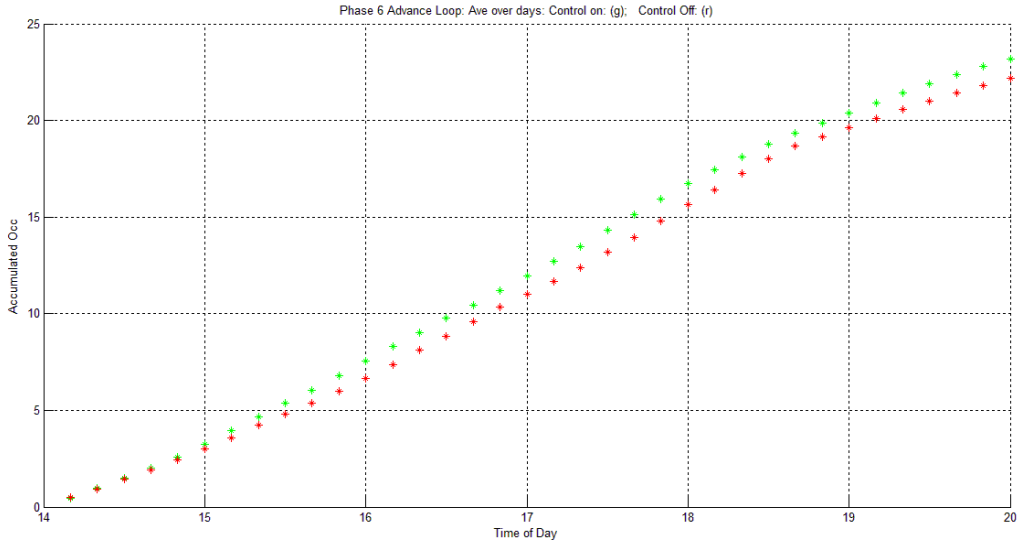


Figure 9-7. *Average cumulative occupancy* comparison at advance loop detector of EB RT movement: Green – PATH control on; Red – PATH control off

9.2 Performance Analysis

PATH intersection signal control suggested reducing green time of EB RT which was essentially to give more space at entrance ramp to WB LT in PM peak hours. As such, it is expected that EB RT queue could potentially increase while the queue of WB LT queue will

decrease. The question was: if there was any net benefit in some aspects in the overall system performance. To analyze it, the following two parameters were suggested.

- Net gain/loss of throughput of EB RT and WB LT over time
- Time delay savings at Taylor intersection

The former could be directly calculated based on the vehicle counts. To estimate the latter, we proposed the following approach. Firstly, we estimated the queue of the two movement based on a simple method developed in previous work [51], which assumed the location of loop detector and measured occupancy; secondly, the measured occupancy was converted into estimated density; thirdly, the density was integrated over time to provide delay due to queue bind the stop-line of the two movements; and finally, we compared the delays of the two movements to estimate the net benefit (of EB RT and WB LT).

As a traffic fundamental [52], it is well-known that for point measurement such as loop detector which provides vehicle count and occupancy, average vehicle density could be estimated as follows:

$$\begin{aligned} k &= a_o o \\ q &= k.v \end{aligned} \tag{9.1}$$

Where $o -$ occupancy (a point concept); $k -$ density (a section concept); and $a_o -$ is a constant parameter, $q -$ average flow of a movement; $v -$ average speed of a movement.

The work [51] suggested that the queue of a movement at an intersection be estimated as follows:

$$S_i = D_i + \frac{C \cdot L_q \cdot f_q\left(O_i - \bar{O}\right)}{h} \tag{9.2}$$

where,

$i -$ movement index of an intersection

S_i - Estimated queue length (feet) of movement *i*

O_i - Occupancy of movement *i* measured by detector

$\bar{O} -$ Occupancy threshold for the queue beyond the detector location

D_i - Distance of detector (feet) to stop line of movement *i*

C - Signal cycle length (seconds), common to all movements at an intersection

f_q – Queue growth adjustment factor, common to all movements at an intersection

L_q – Average vehicle spacing (feet) in queue, common to all movements at an intersection

h - Discharge headway (sec/vehicle), common to all movements at an intersection

Apply (9.1) to the two movements for "before" and "after scenarios", it is obtained that:

$$\begin{aligned} k_i^j &= a_o o_i^j \\ q_i^j &= k_i^j . v_0 \end{aligned} \tag{9.3}$$

$j \in \{bf, af\}$ representing the two scenarios with PATH control OFF (*before*) and ON (*after*). It was further assumed that the average speed when traffic light was green for the two movements were the same v_0, which was reasonable in practice since the posted speed were the same and they all approaching the same intersection.

The total number of vehicles N_i – stored behind the stop line for each cycle is:

$$N_i = S_i k_i = D_i k_i + \frac{k_i C \cdot L_q \cdot f_q \left(O_i - \bar{O}\right)}{h} = D_i \frac{q_i}{v_0} + \frac{q_i C \cdot L_q \cdot f_q \left(O_i - \bar{O}\right)}{h v_0} \tag{9.4}$$

It is noted that this simple transformation makes it possible to use the vehicle count data collected in the field test.

For PM peak hours, it was assumed that the queue would be beyond the detector location all the time which was reasonable statistically (on average) as observed. The following parameters values were used for performance evaluation

Table 9-2. Model parameters used for performance evaluation at Taylor intersection

Parameters	C	L_q	f_q	h	v_0	$\bar{O}$	(D_{WB}, D_{EB})
Value	130s	17	1.1	2.0	15mph	0.25	(141,196.8)

where (L_q, f_q) were obtained from [51]. All the others were determined from field traffic data for PM peak hours.

The time delay DT_i for a movement was the number of vehicles in the queue integrated over time during the PM peak hours:

$$DT_i = \int_{T_s}^{T_f} S_i k_i dt = \int_{T_s}^{T_f} \left(D_i \frac{q_i}{v_0} + \frac{q_i C \cdot L_q \cdot f_q\left(O_i - \bar{O}\right)}{h v_0} \right) dt$$
$$= \frac{1}{v_0} \int_{T_s}^{T_f} q_i \left(D_i + \frac{C \cdot L_q \cdot f_q\left(O_i - \bar{O}\right)}{h} \right) dt \tag{9.5}$$

Applying it to "*bf*" (before PATH control on) and "*af*" (after PATH control on) of both EB RT and WB LT, the percentage of delay changes with respect to the "before" situation was obtained:

$$GT_{total} = 100.\frac{DT_{EB}^{bf} + DT_{WB}^{bf} - (DT_{EB}^{af} + DT_{WB}^{af})}{DT_{EB}^{bf} + DT_{WB}^{bf}}\% \tag{9.6}$$

$GT_{total} > 0$ meaning delay decreasing, and $GT_{total} < 0$ meaning delay increasing.

9.3 Test Results

Performance analysis was conducted for the Taylor intersection, freeway entrance ramp and freeway mainline, which are presented respectively in the following:

9.3.1 Intersection Changes

Applying (9.5) and (9.6) to the average values for all the traffic data of PM peak hours for PATH control ON ("*af*") and OFF ("*bf*") days, it is observed that the delay changes.

Table 9-3. Intersection flow and time delay changes with respect to "before" scenario in different PM time periods

Time interval for evaluation	**4:00-6:00pm**	**4:00- 6:30pm**	**4:00-7:00pm**
Total Flow increased	6.98%	7.64%	8.18%
Time delay reduced	7.15%	5.24%	3.06%

It can be observed from Table 9-3 that flow changes at advance loop of WB (Phase 5) LT is about 7% on average. Net time delay reduction is also about 7% reduction considering both EB RT and WB LT together.

9.3.2. Entrance ramp Flow Changes

Table 9-4. Entrance ramp flow changes with respect to "before" scenario in different PM time periods

Time interval for evaluation	**4:00-6:00pm**	**4:00- 6:30pm**	**4:00-7:00pm**
Passage detector flow change (after meter)	0.73%	1.2%	1.8%
Queue detector flow change	11.01%	11.12%	11.28%

It can be observed from Table 9-4 that entrance ramp passage detector flow increased about 1% on average, which means more traffic injected into freeway from the entrance ramp. The 11% queue detector flow increase means better use of entrance ramp storage in PM peak hours since Phase 5 (with large demand) would have more space at the entrance ramp.

9.3.3. Freeway Mainline Flow Changes

If we sum up all lanes vehicle volumes and accumulate it over time and averaged over all the test days, the outcome is shown in Figure 9-8. It indicated that the accumulated flow for "*before*" and "*after*" were exactly the same on average. This means that the changed control strategy at intersection did not affect the traffic on freeway mainline. This make sense because RM rate used in PATH control was very similar to the default control RM rate as indicated in Figure 8-2. This also means that to improve freeway mainline flow, it is necessary to consider a larger system by coordinating multiple entrance ramps along a freeway corridor and corresponding intersections.

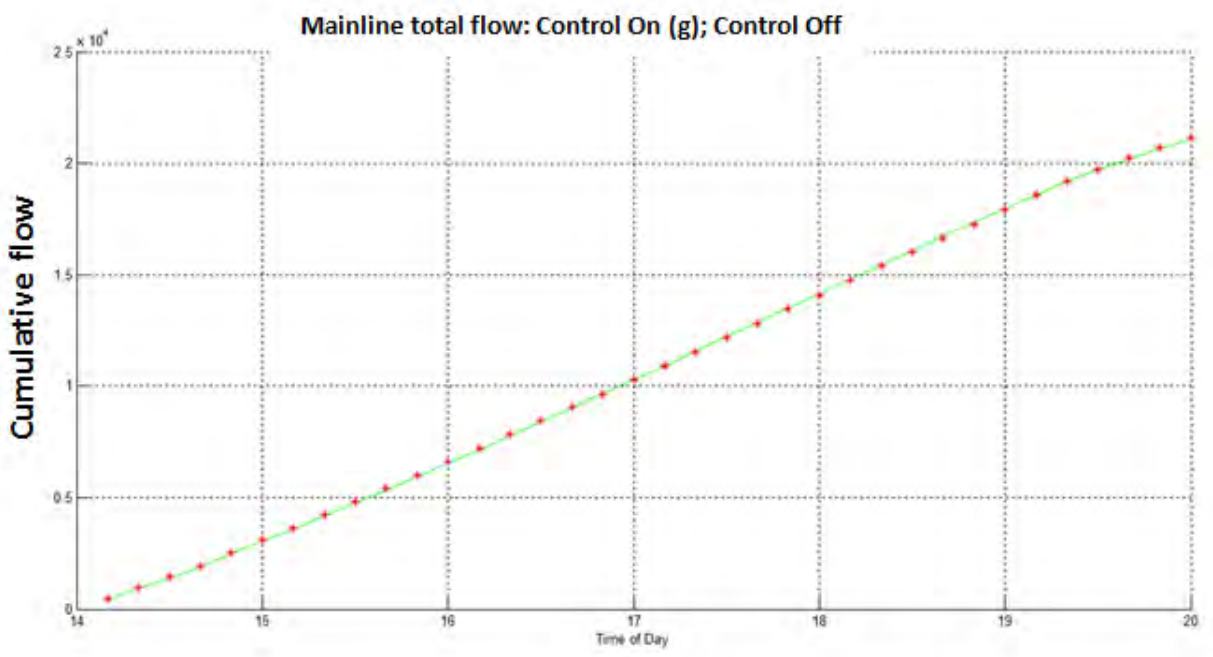


Figure 9-8. Cumulative flow comparison on freeway mainline immediate upstream

9.4 Summary of Performance Improvement

- Intersection
  - WB RT flow increased by 7% in PM peak hours
  - Total delay reduced by 7% in PM Peak
- Entrance ramp
  - Pass flow increased about 1%
  - Onramp entrance flow increased by 11% ➔ better use of entrance ramp storage in PM peak hours ➔ avoiding queue back up to intersection
- Freeway mainline upstream
  - End even, not affected in PM peak hours

Chapter 10. Concluding Remarks, Recommendations

10.1 Concluding Remarks

For better performance of overall traffic operation in a corridor, it is necessary to coordinate freeway RM and arterial intersection traffic signal control. The main idea is to optimally use the entrance ramp storage and to appropriately inject traffic into the freeway. This project has developed practical control and coordination strategy and implemented it at SR87-Taylor Street intersection in City of in San Jose. The test results have showed that this can be achieved to some extent even with one intersection and one freeway entrance ramp. The improvements are in several aspects: (a) important movement vehicle count increase and occupancy decrease; (b) Total Time Delay reduction at the intersection; and (c) improved use of the entrance ramp. However, the freeway mainline flow ended even on average. This means that, to improve freeway mainline traffic, it is necessary to coordinate all the important entrance ramps (with high demand) and relevant arterial intersections along a freeway corridor.

10.2 Recommendations

Based on the experience gained and lesson learned, we propose the following recommendations:

- To develop a good site selection criteria, one must take into account all the critical factors (size, complication of road geometry, institutional issues, traffic situation, sensors, and controllers);
- To collect enough detailed data for site selection and to analyze rigorously the traffic situation in the finest details such as entrance ramp queue and intersection movement queue and flow;
- To engage Caltrans and local traffic engineers (technical personnel) as early as possible since they know the technical details of the system;
- To understand the original system in details to the lowest level:
    - traffic controller types of freeway (URMS or TOS) and arterial (TOD, actuated, adaptive, proactive, etc; overlap of movements, detector assignment with respect to movement/phase)

    - interface capabilities through AB3418(E) as communication protocol
    - operating systems of the controller
    - data passing media
    - centralized or non-centralized
- To investigate the sensor location, type, health condition, data reporting channel and rate, and measurement accuracy;
- To find out as early as possible what is allowed to do to the system by the jurisdiction since this will determine the control/coordination strategies to be implemented;
- To collect very detailed system data for modeling which needs to consider the locations of practical sensors; temporary sensor locations for this data collection needs to match practical sensor locations of the system;
- To budget enough funding for sensor purchase and installation since most current traffic systems do not have enough sensors detections or they might be at wrong location or did not work as expected;
- To model the system in microscopic simulation as close as possible, which requires extensive work on model calibration; the original control and coordination strategies (if applicable) need to be modelled as well;
- ConOps development needs to be iteratively conducted almost throughout the life of the project since its higher level is used for planning, middle level will be used for system interface and integration, and lower level will be used for control and coordination of the two subsystems - freeway and arterial(s);
- To be well-prepared to respond to system security questions: this might be a concern to Caltrans and local transportation agencies;
- Minimum sensor detection and data requirement:
    - Queue detection (advance loop) at intersection pockets of major movements involved;
    - Stop-line detection for major movement involved
    - All traffic signals of an intersection
    - Entrance ramp detector at ramp meter and queue detector (85% location at entrance ramp upstream)
- Data resolution: 30[s] or higher update rate is desirable.

10.3 Future Work

Based on the experience gained and lessons learned in this project, the following are proposed main work to be done in the next phase of the project to achieve system-wide performance improvements:

- To consider a freeway corridor with relevant arterial(s)
- Coordinated ramp metering (developed in another project)
- Coordinated arterial intersection signal control
- For both freeway RM and arterial intersections
  - Centralized data systems
  - Centralized signal control
  - PATH computer interface with TMC computer
- Systematic coordination of the two subsystems
- Secured communication between two PATH computers running a special Operating System to avoid virus

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Appendix 1: Site Selection Considerations: SR87 / West Taylor

The road geometry of the section of SR87 near West Taylor Street with traffic detector IDs is shown in Figure A1-1

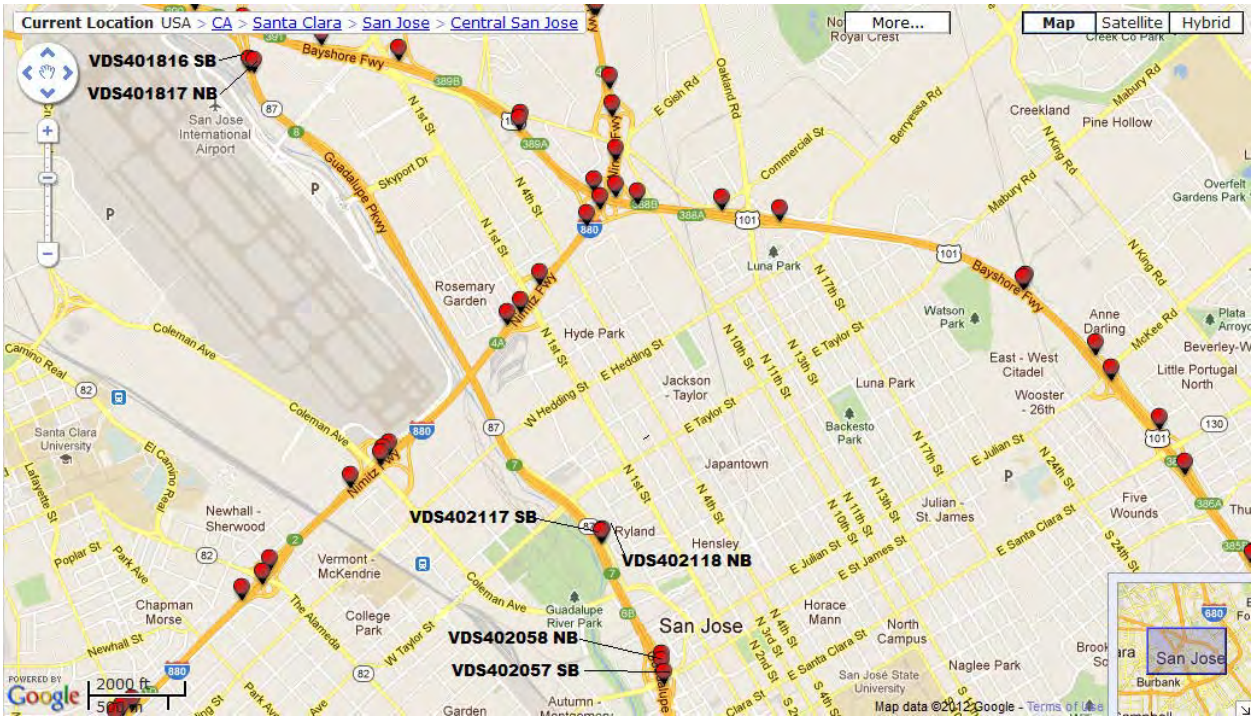

Figure A1-1. Road geometry and sensor locations near SR87-Taylor; there is no sensor available upstream of Taylor for SB.

A. South Bound

Traffic data are listed for Monday (05/02/2011) through Friday (05/06/2011). For each day, data plots were listed from downstream to upstream. There is a PM peak recurrent bottleneck there. The difficulty is that there is no enough sensor data around that intersection to support the study. The only detector stations are VDS #402057 and VDS #402117.

Sensor Locations: VDS402117 is right at the upstream of entrance ramp for SB; NB VDS is at the SB sensor location which may not be suitable to control, and there is no other sensor for NB until 2.7 miles further downstream. i.e. it does not support NB traffic management yet.

Observation Results:

Traffic situation (Figure A1-2): traffic has regular speed drop in the PM peak hours (16:00-19:00pm) at SR87-Taylor St (VDS #402117; PM=6.7); this location is a discharging bottleneck since further downstream has more lanes. The road geometry here is ideal for a simple implementation.

Downstream about 0.6 mile: Some slight traffic congestion downstream (VDS #402057) in the afternoon occasionally, but not persistent at SR87-Jullian SB; this station location has more lanes than at Taylor.

Upstream about 2.7 miles (VDS #401816; PM=9.04): Traffic upstream almost does not have congestion.

Data quality: the data are available now for (VDS #402117 SR87-Taylor) and (VDS #402057 _SR87-Jullian), with some occasional data missing.

Table A1-1. Demand of SB from entrance ramp every 2 hour for PM Peak

Prefi	PM	Leg	Dir	Description	Date	Day	15-16		16-17		17-18		18-19	
	6.724	N	S	SB ON FROM TAYLOR STREET	6/30/2006	THU	**1587**	**C**	**1745**	**C**	**2117**	**C**	**1321**	**C**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/29/2006	WED	**1593**	**A**	**1749**	**A**	**2108**	**A**	**1371**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/28/2006	TUE	**1693**	**A**	**1994**	**A**	**2041**	**A**	**1226**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/27/2006	MON	**1621**	**A**	**1702**	**A**	**2081**	**A**	**1159**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/26/2006	SUN	**741**	**A**	**803**	**A**	**628**	**A**	**607**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/25/2006	SAT	**881**	**A**	**872**	**A**	**713**	**A**	**718**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/24/2006	FRI	**1665**	**A**	**1617**	**A**	**2164**	**A**	**1276**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/23/2006	THU	**1587**	**A**	**1745**	**A**	**2117**	**A**	**1321**	**A**
	6.724	N	S	SB ON FROM TAYLOR STREET	6/22/2006	WED	**1518**	**A**	**1855**	**A**	**1977**	**A**	**1384**	**A**

SB from entrance ramp average flow on workdays 4:00 – 7:00 pm is 1718veh/hr/lane;

Exit ramp flow data is not available.

Analysis:

It can be observed from Table A1-1 that the feeding from Taylor Street in PM Peak hours is significant. Its upstream entrance ramp (about 1 mile) is from Skyport – the traffic directly from SJC airport, might have some impact on the mainline flow (**no traffic data**). But airport traffic is likely to be even out during the day instead of significant in the peak hours. Therefore, we may infer that the flow drop in PM hours is likely to be caused by entrance ramp traffic from Taylor Street.

There is no direct interchange between I-880 and SR87. The traffic from I-880 to SR87 has to enter from Taylor Street entrance ramp through Coleman Ave. This traffic flow has been counted in Table A1-1.

Its downstream entrance ramp at Julian St does not have speed drop for most of the times. ➔ the speed drop is not caused by traffic jam back-propagation.

Ramp geometry: Both Taylor entrance ramp and exit ramp have 2 lanes which can accommodate the demand flow. The SB entrance ramp is about 700 feet long with 2 lanes (one is HOV) merging into 1 before ramp meter. The ramp storage capacity is reasonable.

This means that SR87-Taylor is almost isolated from traffic from upstream and downstream: its congestion may be mainly caused by local traffic from entrance ramp. This makes it an ideal simple site for the coordination of freeway ramp metering and feeding intersection traffic signal control.

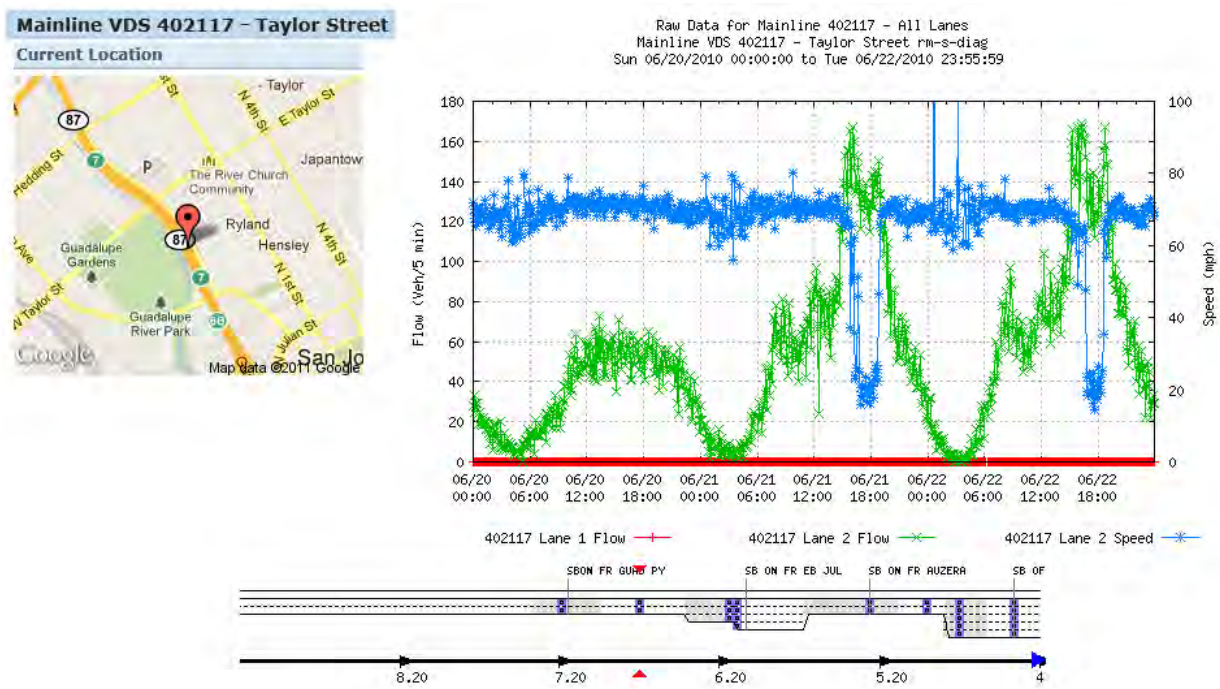

Figure A1-2. Traffic 5min flow and speed at VDS 402117, SR87 SB at Taylor; 06/20-06/22

B. North Bound

Based on PeMS data in August, it seems that AP peak have regular speed drop for NB.

Table A1-2. Demand of SB from entrance ramp every 2 hour for PM Peak

Dist	Cnty	Rte	Prefi	PM	Leg	Dir	Description	Date	Day	7-8	8-9	9-10
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/24/2006	FRI	**1498 A**	**1725 A**	**1318 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/23/2006	THU	**1537 A**	**1808 A**	**1318 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/22/2006	WED	**1601 A**	**1823 A**	**1296 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/21/2006	TUE	**1552 A**	**1766 A**	**1350 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/20/2006	MON	**1542 A**	**1784 A**	**1270 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/19/2006	SUN	**315 A**	**392 A**	**581 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/18/2006	SAT	**476 A**	**609 A**	**838 A**
4	SCL	87		6.649	F	N	NB OFF TO TAYLOR STREET	6/17/2006	FRI	**1515 A**	**1613 A**	**1306 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/16/2006	THU	**256 A**	**270 A**	**273 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/15/2006	WED	**270 A**	**268 A**	**284 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/14/2006	TUE	**254 A**	**261 A**	**315 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/13/2006	MON	**221 A**	**263 A**	**282 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/12/2006	SUN	**42 A**	**87 A**	**115 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/11/2006	SAT	**100 A**	**111 A**	**133 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/10/2006	FRI	**213 A**	**265 A**	**299 A**
4	SCL	87		7.09	N	N	NB ON FROM TAYLOR STREET	6/9/2006	THU	**225 A**	**262 A**	**295 A**

For NB: average (7:00~10:00am on workdays) entrance ramp flow: 266 veh/hr; exit ramp flow: 1535 veh/hr

Appendix 2. Site Selection Consideration: I-280/Saratoga Ave

A2-1. Introduction

For selecting a proper site to conduct the field implementation and test on the coordination of arterial traffic signal control and freeway ramp metering, traffic demand data from entrance ramp of Saratoga Avenue on 11/17/2009 from San Jose Transportation has been taken into account. For freeway traffic, PeMS data of I-280 in both directions at stations near Saratoga Avenue on the same day have been downloaded and analyzed.

Number of Lanes for Entrance ramp and Storage Capacity

This is a hybrid "diamond-parclo" (partial cloverleaf) interchange (Figure A2-1). The storage capacity of Southbound is about 68 vehicles (2 lanes, 220m), and Northbound is about 104 vehicles (2 lanes, 335m).

Jurisdictions

Saratoga Avenue and adjacent local streets are under the jurisdiction of the City of San Jose, and the freeway is under the jurisdiction of Caltrans.

Traffic Situation of Freeway and Arterials

To confirm the traffic pattern, PeMS data I-280 NB and SB in the week of 09/20/2010 have been considered.

According to the information from the City of San Jose and Caltrans District 4, the traffic for the site is very heavy in both AM peak and PM peak hours. For AM peak hours, entrance ramp traffic has significant delay (spillback into arterial) on Saratoga Avenue to get onto I-280 Southbound– with a queue sometimes as long as one mile. It is noted that the entrance ramp is not metered in AM peak hours. To a lesser degree, delay (spillback into arterial) also occurs for I-280 Northbound entrance ramp which is metered in AM peak hours. Based on PeMS data analysis, I-280 NB near Saratoga Ave. is usually heavily congested in AM peak hours, but it is nearly saturated in PM peak hours most of the time; on the contrary, I-280 SB near Saratoga

Ave. is usually heavily congested in PM peak hours, but it is nearly saturated in AM peak hours most of the time.

For PM peak hours, traffic delay is heavy on the freeway and getting off I-280 Northbound onto Saratoga Avenue are also very difficult for both Northbound and Southbound. The traffic spills back into freeway from both exit ramps and has an effect on freeway traffic in both directions. Heavy freeway traffic also delays arterial traffic onto the freeway in both directions.

Figure A2-1. Road geometry with 3 intersection traffic controller and 2 entrance ramp meters;

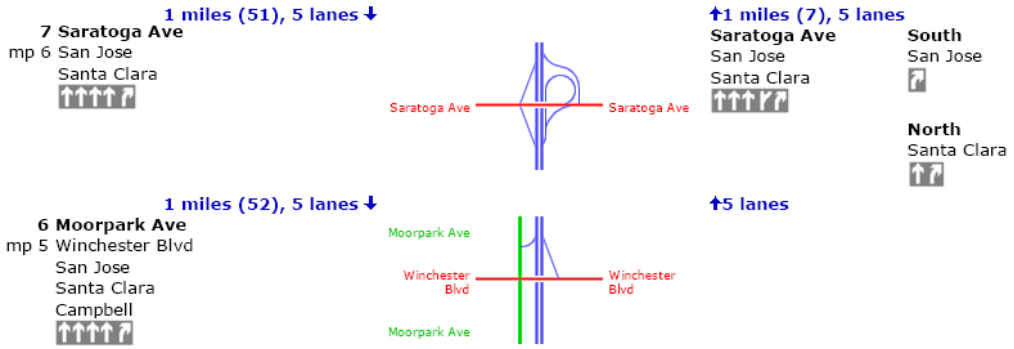

Figure A2-2. Road geometry near Saratoga

Road geometry:

Saratoga: entrance ramp and exit ramp of two directions to/from I-280;

San Tomas Expy: No entrance ramp and exit ramp to/from I-280;

S. Winchester Blvd: Entrance ramp to NB only; Exit ramp from SB only;

Moorpark Ave. is a parallel arterial to I-280

A2-2. I-280 NB Traffic near Saratoga Ave on 11/17/09

This section introduces the typical traffic pattern of I-280 NB. Although only one day flow-speed have been presented here, the traffic pattern observed is repeatable for other work days as indicated in the appendix where a week data of flow, occupancy and speed have been presented.

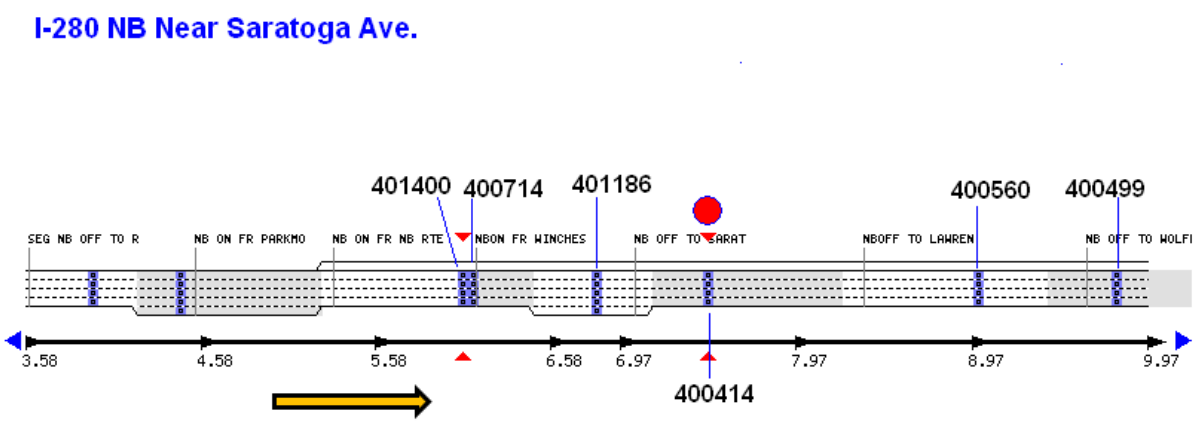

Figure A2-3. Lane Map and Loop ID near Saratoga entrance ramp and traffic direction

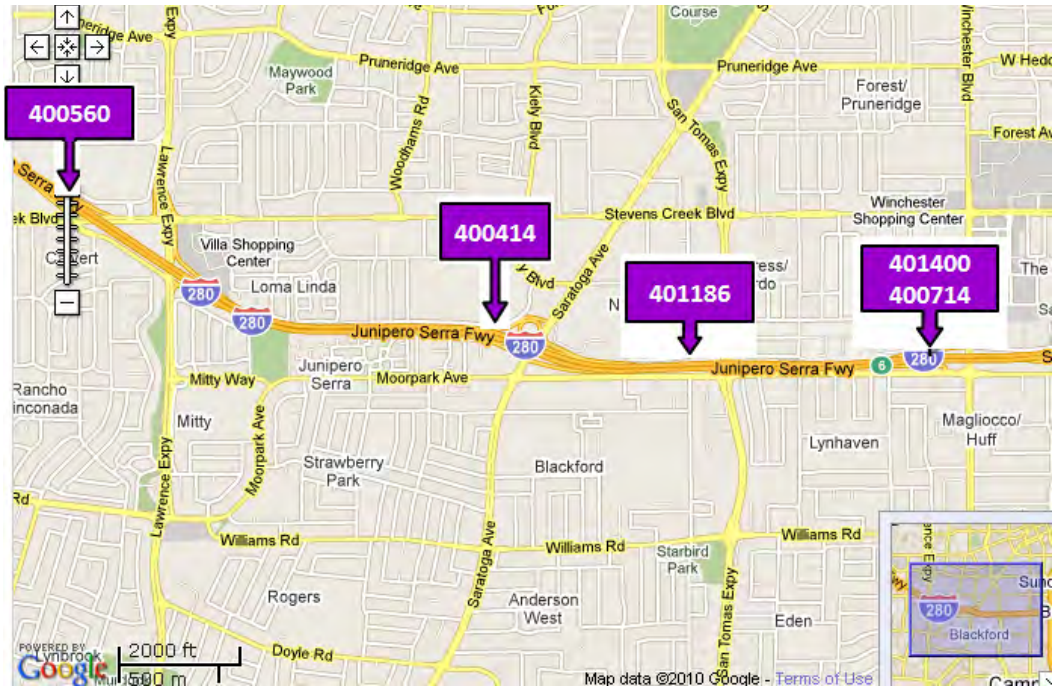

Figure A2-4. Map with Loop ID & Locations, I-280 NB near Saratoga Ave.

PeMS data showed that for I-280 NB traffic near Saratoga Avenue, AM peak traffic is pretty heavily congested. The congestion is even observed from the further downstream station 400560. The system is NOT isolated, which means that it is very difficult to use the NB AM Peak traffic for the Phase I study. Besides, PM traffic for NB did not have congestion, which is not interested to the project.

This is further confirmed by a whole week 5min flow-occupancy and speed. Figures A2-5 and A2-6 are used as examples. Besides, the loop data quality at stations 400414 and 40056 has good quality as shown in the figures. This is very important to support the study of the coordination between arterial traffic signal control and freeway ramp metering.

A2-3. 280 SB Traffic near Saratoga Avenue

This section presents the I-280 SB traffic analysis at the stations near the Saratoga Avenue. Unfortunately, the raw data in PeMS is not available for 2009 anymore. Therefore, traffic data in this year has to be used. Besides, the detector station near Saratoga Avenue behaved very badly, i.e. the data quality is not good.

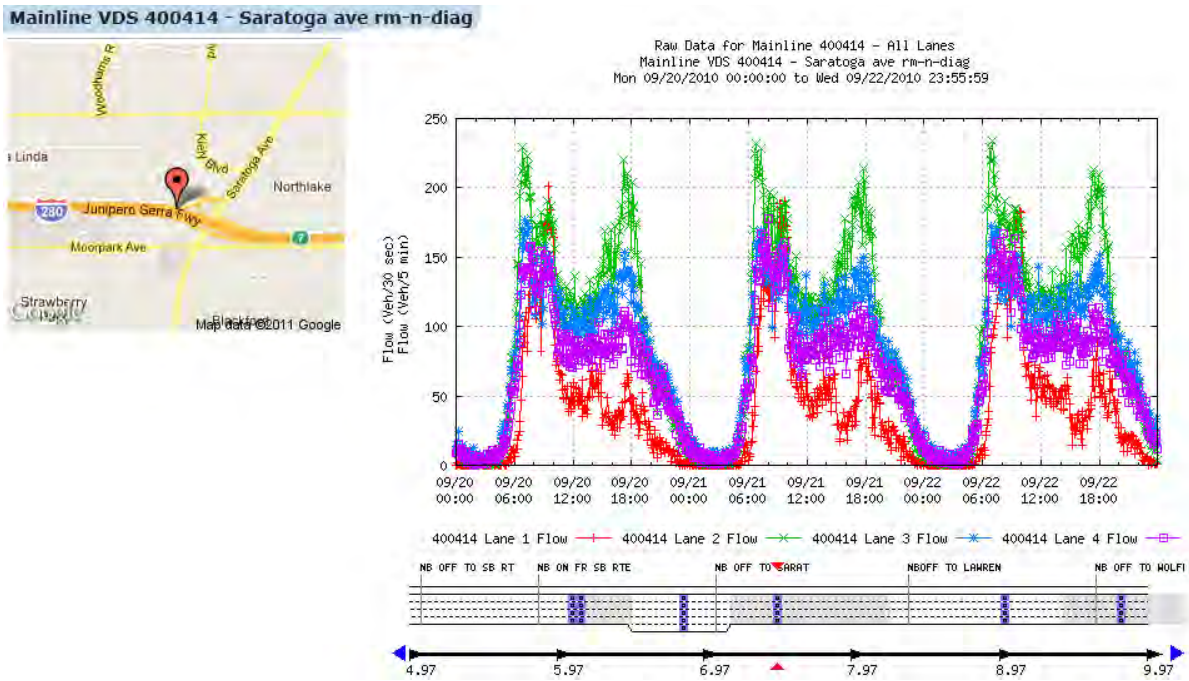

Figure A2-5. 5min Flow at 400414, 09/20~09/22, 2010

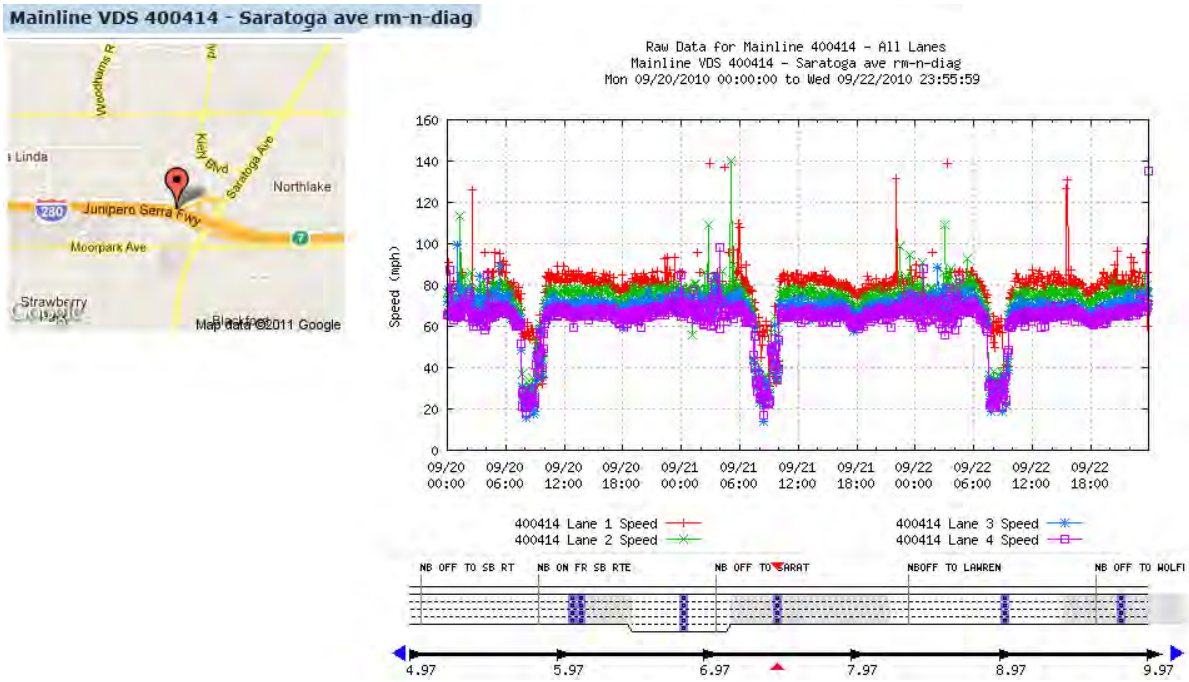

Figure A2-6. Speed at 400414, 09/20~09/22, 2010

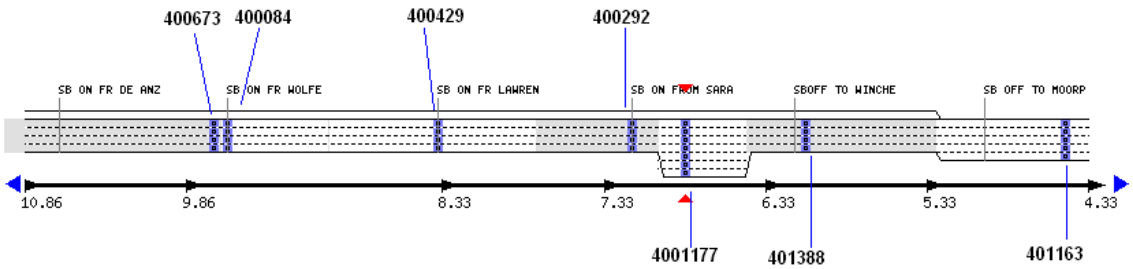

Figure A2-7. Lane Map and Loop Detector Station Locations for I-280 SB near Saratoga Ave.

PeMS data analysis showed that, for I-280 SB near Saratoga, AM peak traffic was reasonably mild but PM Peak traffic is very heavy. The congestion happens recurrently which was caused by a bottleneck downstream of Saratoga Avenue entrance ramp. From the PeMS lane sketch, it can be observed that the 7 lane drops to 4 lanes downstream of Saratoga entrance ramp. The capacity downstream is a serious limit to the traffic upstream including the mainline and entrance ramp flow from Saratoga Avenue. With current road geometry, only use the control strategy of coordination of freeway ramp metering and arterial traffic control cannot improve the system performance. To improve the traffic flow, some other Active Traffic Management strategies must be adopted jointly along the whole corridor.

Data quality: PeMS data showed that the quality of data for SB at stations near Saratoga were very bad currently. In fact, the data has been bad since earlier this year. Therefore, SB should be excluded from the site selection list for this study since data quality is very critical for the study.

Further Analysis (08/27/11): There is a possible storage area at St-401177 with 6 lanes (but PeMS only provides 4 lanes data before– lane flow is well-below 100*12=1200, PeMS now provides 6 lanes data). Saratoga entrance ramp is upstream of the potential storage area. There are 4 lanes close to Saratoga entrance ramp. The downstream of the potential storage area has 4 lanes and is an active bottleneck – from St. 401388.

Checked data on 08/24/11, 08/25/11, 08/26/11 for those stations:

401163: no data, but it did not have data before 08/06/10

401388: no data, but it had data until 08/06/10, not from 08/10/10

401177: there was speed drop at PM peak (16:00-19:00pm) but not significant flow drop

400292: (immediate downstream of Saratoga entrance ramp) there was speed drop at PM peak but not significant flow drop

400429: there was speed drop at PM peak but not significant flow drop

If there is not significant flow drop, it is difficult to justify using Saratoga SB as a test site;

Now the PeMS plot is not as good as it was before based on the observation of the data on 11/17/2009 of 401388.

From the new plot on 08/27/11: speed drop leads to some flow drop between 16:00-19:00pm.

It is observed from traffic data analysis that, for SB at Saratoga:

(1) There is a regular (all workdays) significant speed drop at VDS 400292 in PM peak but not in AM peak;

(2) This happens to its downstream Station VDS 401177

A2-4. Hourly Demand from Saratoga Avenue on 11/17/09

Based on the data provided by San Jose Transportation, the demands to I-280 SB and NB from Saratoga Avenue for a typical day (11/17/2009, Tuesday) are as follows:

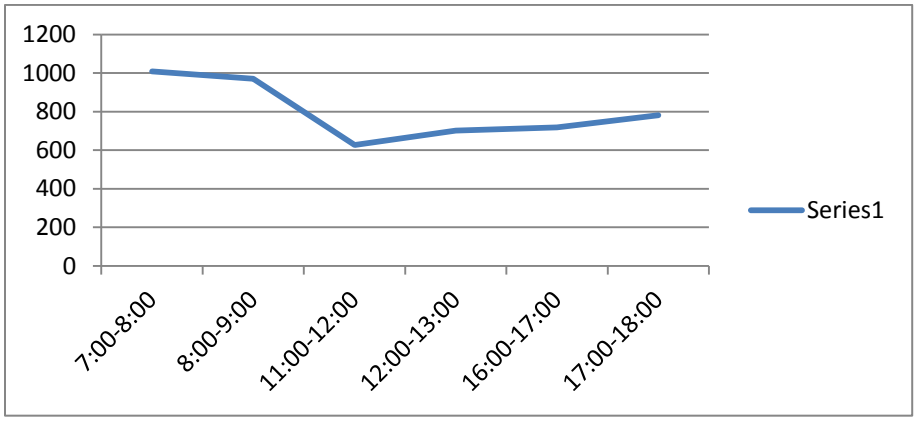

Figure A2-8. Saratoga Ave to I-280 NB Entrance ramp Demand on 11/17/2009 Tuesday

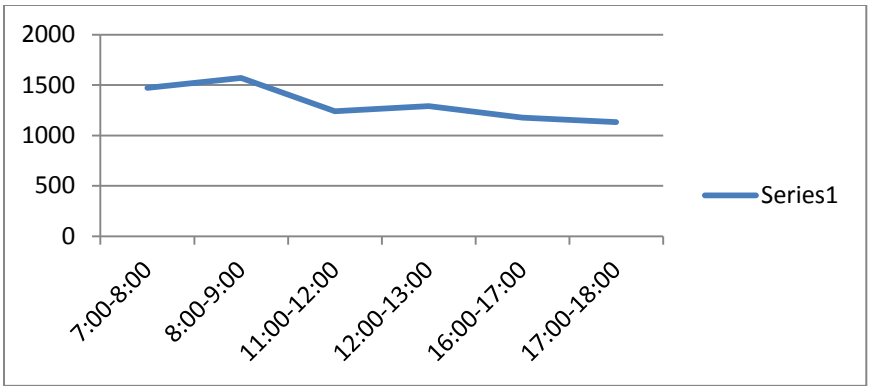

Figure A2-9. Saratoga Ave to I-280 SB Entrance ramp Demand on 11/17/2009 Tuesday

A2-5. Preliminary Recommendations

Based on the factors of traffic, demand from entrance ramp, and the Scope of Work of the project, it is recommended to consider using Saratoga Avenue NB PM Peak traffic as a case study in the first phase. The reason for doing so is that some speed drops have been observed downstream of the Saratoga Avenue entrance ramp, which indicates some minor congestion. Besides, the demand to I-280 NB entrance ramp from Saratoga Avenue in PM Peak hours are mild. Such minor congestion might be caused by the joint effect of mainline flow and entrance ramp flow which could be improved through the coordination of Ramp Metering and Saratoga Ave intersection traffic signal control.

I-280 SB PM Peak traffic and NB AM peak traffic are usually very heavily congested with high entrance ramp demand, which cannot be improved simply through the coordination of Ramp Metering and arterial traffic signal control. Particularly, there is recurrent bottleneck downstream of the Saratoga entrance ramp with lane reduction from 7 to 4 which severely limits the capacity. Some other Active Traffic Management measures have to be jointly used for improving the traffic flow in peak hours.

Appendix 3. Site Selection Considerations: I-280 / Lawrence

The road geometry of the section of I280 Near Lawrence Expy with traffic detector ID is shown in Figure A3-1. It is upstream of Saratoga Ave.

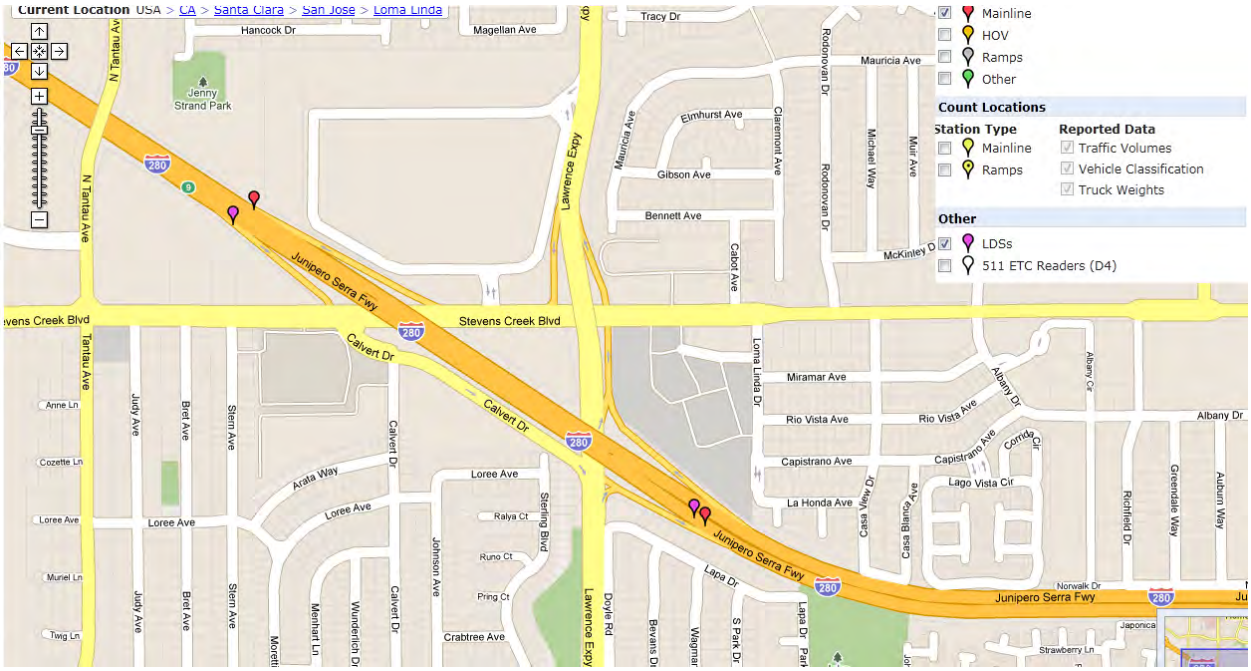

Figure A3-1. SB from Lawrence Expy to I-280

Traffic data are listed for Tuesday (05/03/2011) as a representative (Figure A3-2, A3-3). There are some moderate traffic drops in the morning, but it is not very heavy.

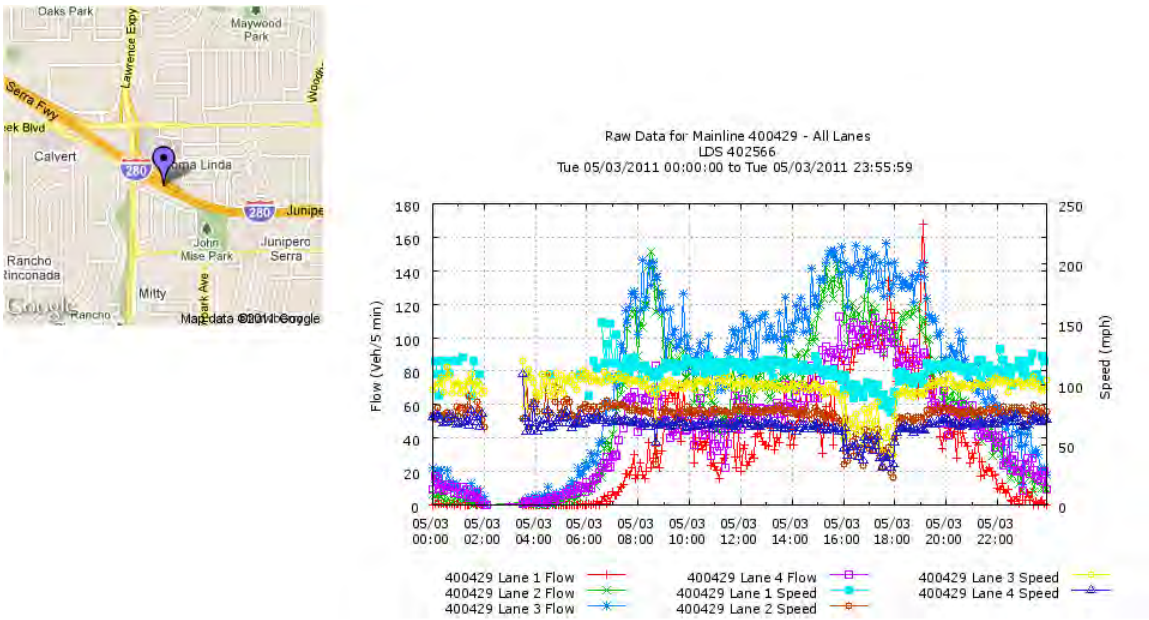

Figure A3-2. Raw flow and speed data on at LDS 402566 05/03/2011(Tuesday)

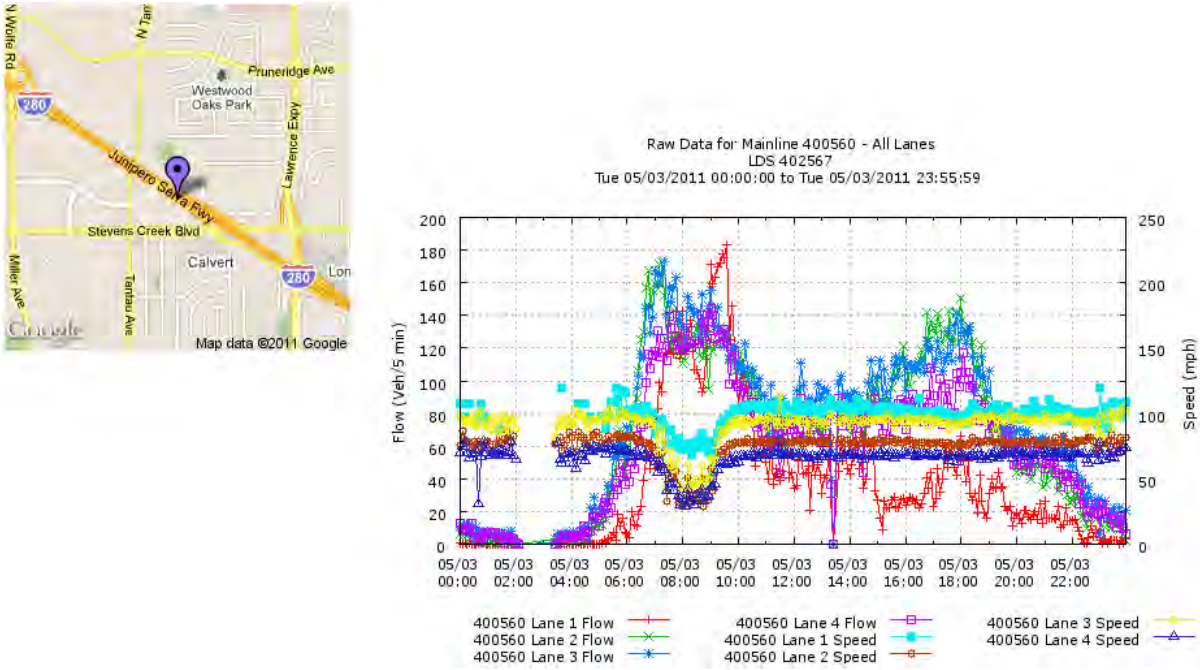

Figure A3-3. Raw flow and speed data on at LDS 402567 05/03/2011(Tuesday)

Appendix 4. Site Selection Considerations: SR101 Corridor from Mathilda Ave to De La Cruz (Trimble Road)

The corridor from Mathilda Ave to Trimble Road on SR101 is about 5.3 miles. The related arterial is Central Expressway. It intersects with both Great America Pkwy and Lawrence Express Way. Traffic detector IDs are shown in Figure A4- 1.

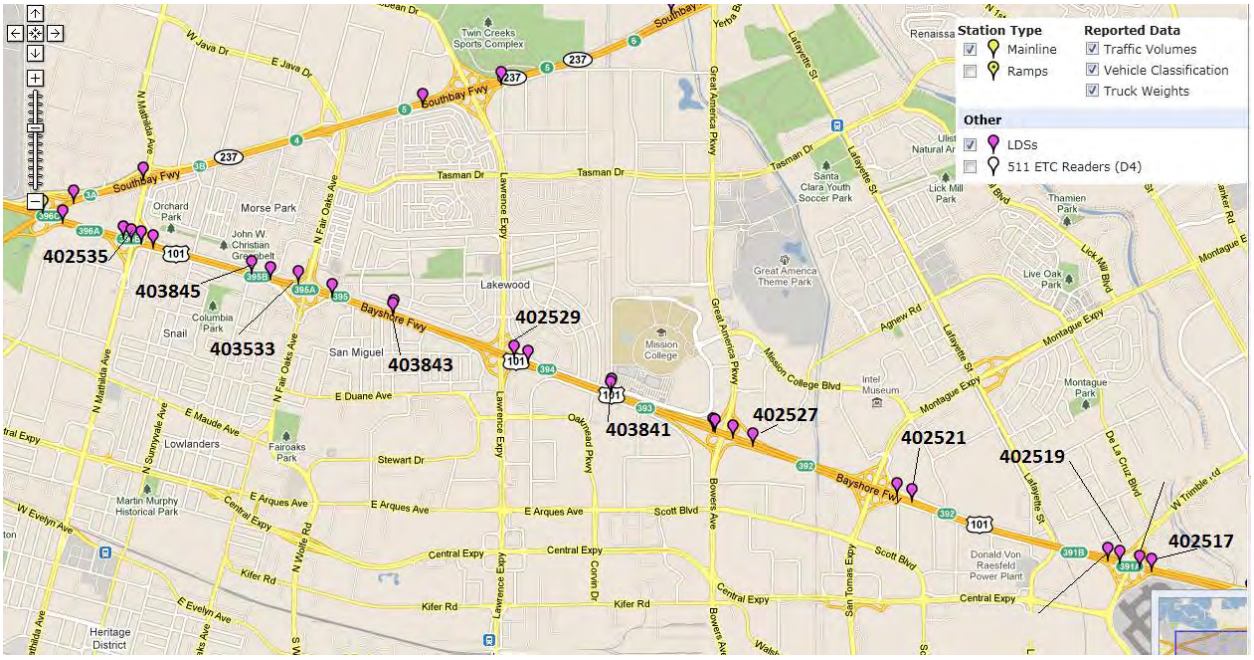

Figure A4-1. Corridor from Mathelida Ave to W. Trimble Road

The data from most detector stations seem reasonable except the station #403841 near Mission College. Its flow and speed estimations in PM peak are questionable. Traffic data are listed for Tuesday (05/03/2011) as a representative (at Loop Station #402521) to the most upstream station (#402535).

Traffic data along the stretch shows that the intersection of SR101 with Trimble Rd is the major recurrent bottleneck along the corridor. Traffic upstream of Lawrence Express Way is almost free flow. A combined strategy would be necessary to maximize the bottleneck flow (equivalent to minimizing the Total Travel Time):

- Reducing the feeding to Trimble Road junction through diverging traffic from E. Arques Ave and Scott Blvd, which could be realized through integrated arterial intersection traffic signal control;

- Integrated traffic signal control of other minor road along the corridor;
- Using storage capacity of upstream of Lawrence Expressway through diverging traffic from Central Express Way;

This means that the problem at this site cannot be solved simply by a local coordination of ramp metering and feeding intersection signal control. It needs a corridor wide system consideration with combined Active Traffic Management Strategies. Besides, the jurisdiction is not within San Jose City limit. Therefore, a new institutional issue needs to be sorted out for feasibility.

It is recommended that this site be considered as test site for Active Traffic Management strategy in a long run.

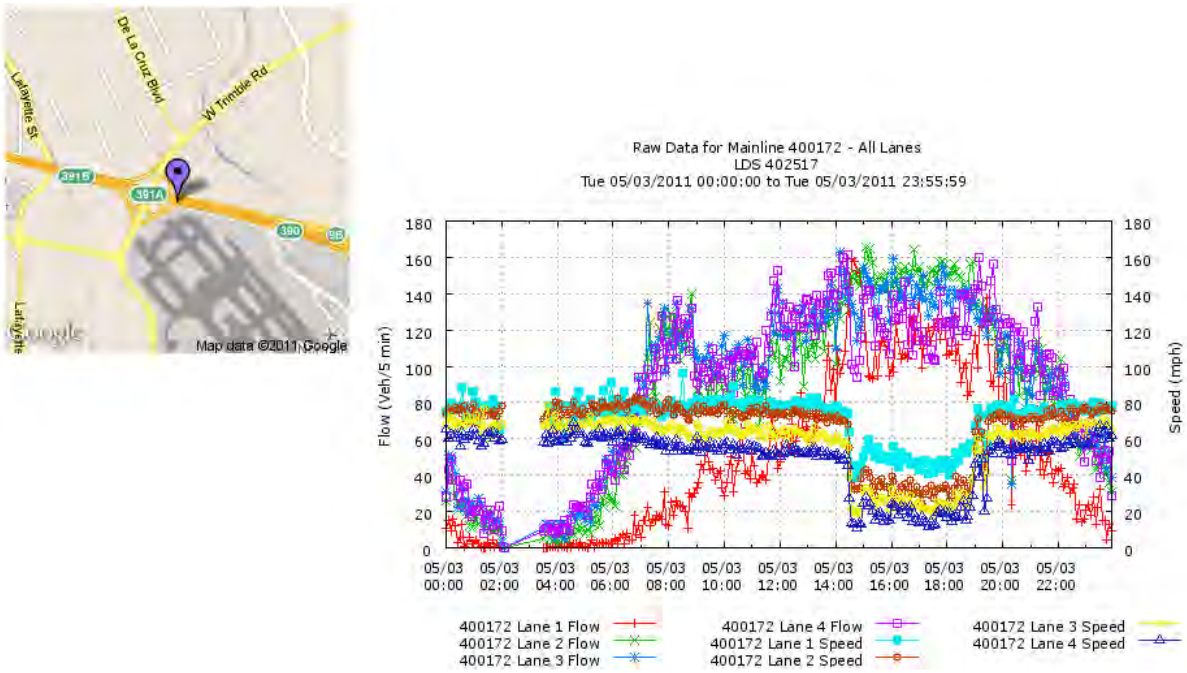

Figure A4- 2. Five [min] vehicle count at LDS # 402517 on 05/03/2011

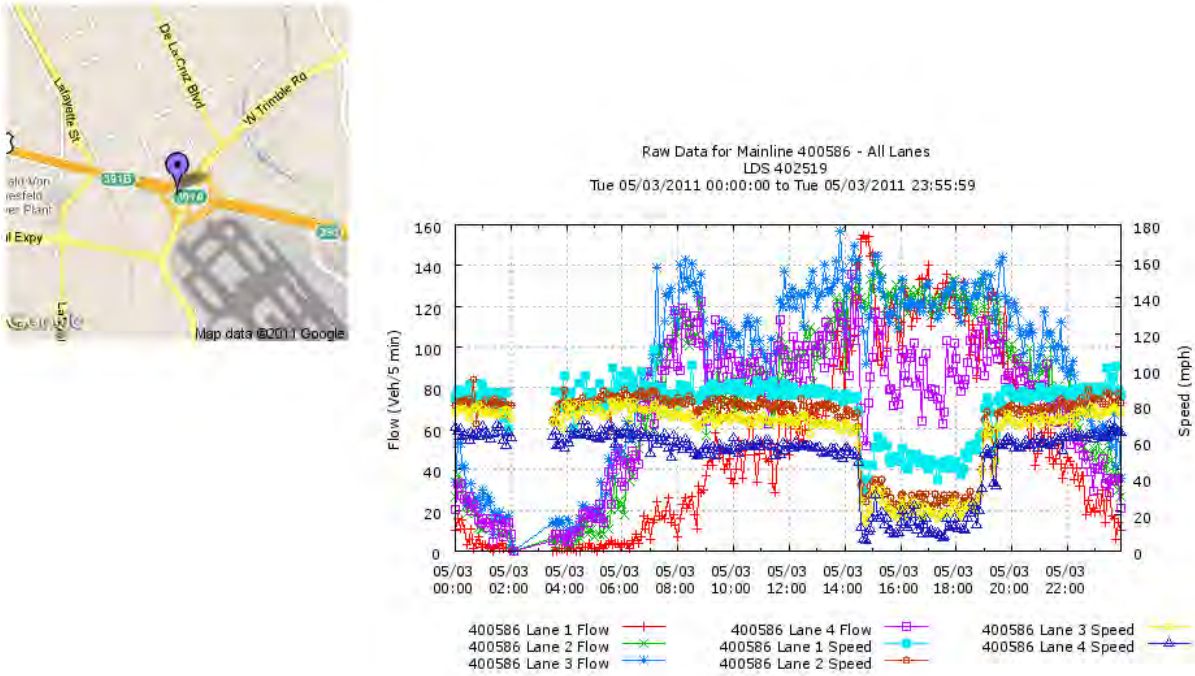

Figure A4-3. Five [min] speed at Station # 402517 on 05/03/2011

Appendix 5. Site Selection Considerations: SR85-Camden Ave

The road geometry of the section of SR85-Camden with traffic detector ID is shown in Figure A5- 1. Both SB and NB data have been looked at.

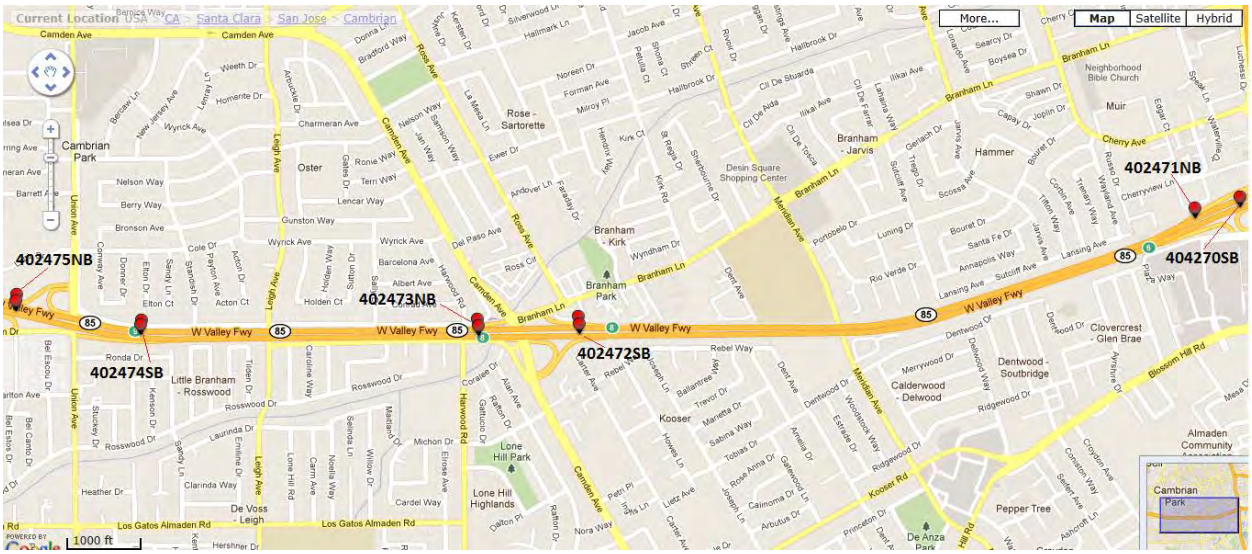

Figure A5-1. Road Geometry and VDS Locations for SR85-Camden

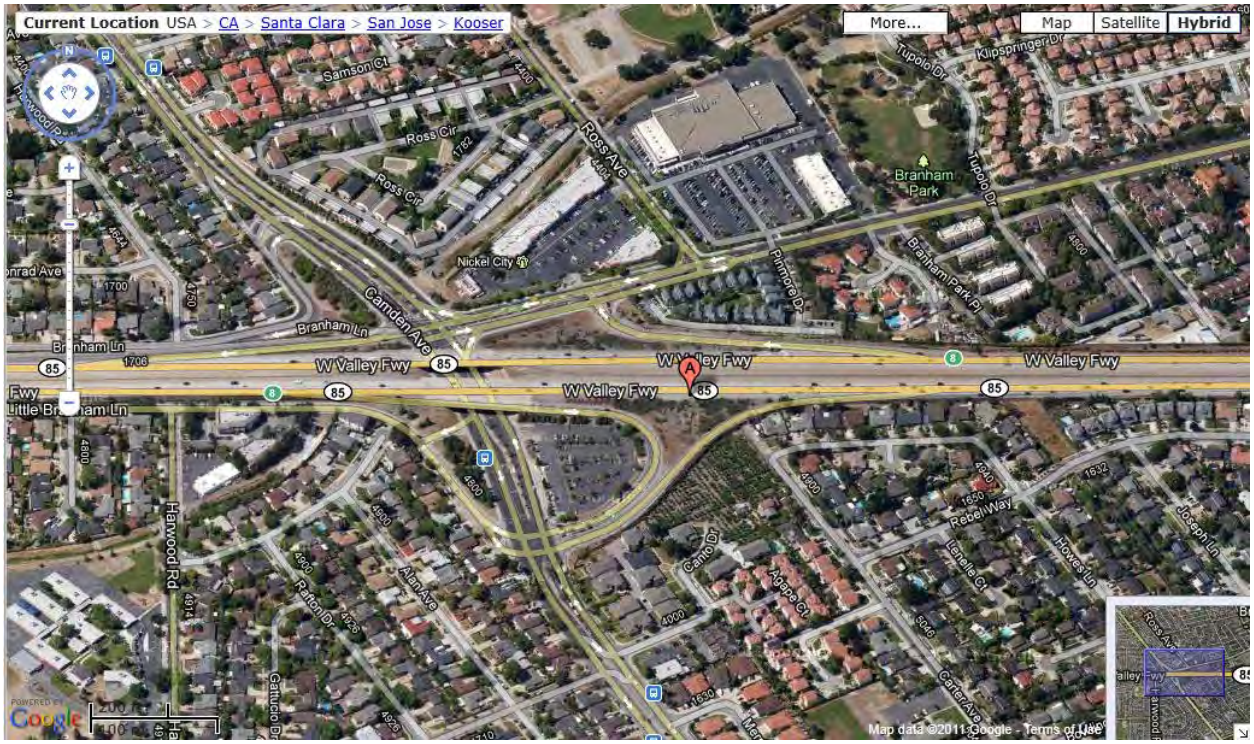

Figure A5-2. Road geometry for connection between SR85 and Camden

Figure A5-3. Three Intersections in the vicinity of Camden

South Bound Traffic Analysis

For traffic to SB of SR85: since Branham Ln traffic has to go through Camden, using Camden traffic counts should be OK;

Table A5-1. Traffic counts on 09/21/2010 from San Jose Transportation

#	Intersection	Peak	Peak Hour	NB			EB			SB			
				L	T	R	L	T	R	L	T	R	L
219	85/CAMDEN (S)	AM	AM 7:45-8:45	25	1396	279	152	129	8	196	423	2	371
219	85/CAMDEN (S)	PM	PM 5:00-6:00	16	833	235	148	179	32	431	1139	1	451
675	85/BRANHAM	AM	AM 7:45-8:45	262	11	78	22	495	0	0	0	52	0
675	85/BRANHAM	PM	PM 5:00-6:00	538	28	198	62	912	0	0	0	107	0
674	85/CAMDEN (N)	AM	AM 7:45-8:45	381	982	401	0	0	0	140	485	225	426
674	85/CAMDEN (N)	PM	PM 5:00-6:00	570	418	638	0	0	0	248	1101	56	594

In the above Table A5-1, only those traffic counts of those movement marked in red is related to entrance ramp flow towards SR85 SB or NB.

Table A5-2. Traffic to SB of SR85 from Camden Intersection (SB) in Peak Hours

09/21/2010 (Tue)	AM: 7:45-8:45	604
09/21/2010 (Tue)	PM: 5:00-6:00	845

SR85 SB traffic: Traffic data analysis indicated that there was no congestion back-propagation from downstream to Camden. Therefore, SB at SR85-Camden is isolated.

North Bound Traffic Analysis

For traffic to NB of SR85: Branham Ln through traffic goes to SR85 NB.

Table A5-3. Traffic to NB of SR85 from Camden Intersection (NB) in Peak Hours

09/21/2010 (Tue)	AM: 7:45-8:45	1024
09/21/2010 (Tue)	PM: 5:00-6:00	969

After observing the traffic in two directions of the newly downloaded data and previous data, it seems that:

Traffic congestion happens (speed drop) regularly on workdays in AM peak hours for loop VDS 402472 (SB) and 402473 (NB)

Traffic congestion happens (speed drop) regularly on workdays in PM peak hours for loop LDS: 402474 (SB) and 402475 (NB)

The following plots (Figures A5-4 and A5-5) show the regular behavior of freeway traffic.

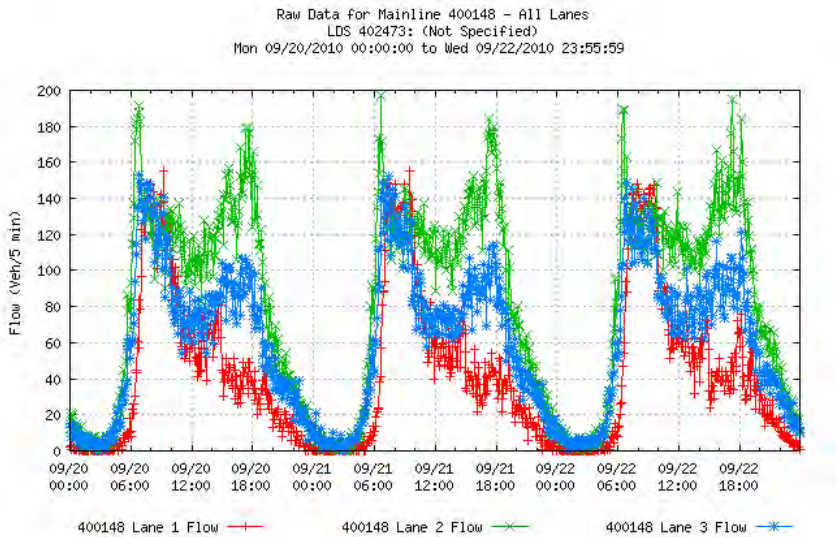

Figure A5-4. NB Speed, just before entrance ramp of Camden, 3 days

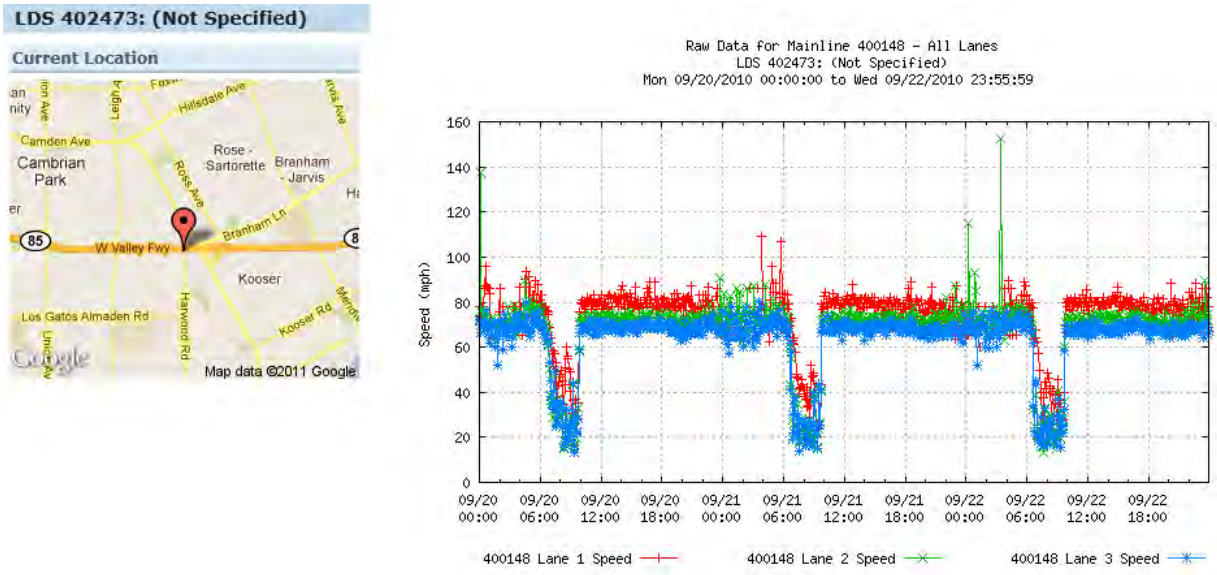

Figure A5-5. NB Speed, just before entrance ramp of Camden, 3 days, AM peak speed drop

Table A5-4. Traffic observation for both direction of SR85 at Camden

Date/VDS	402472 SB (D)		402473 NB (U)		402474 SB (U)	402475 NB (D)	Comment
09/21/10	AM	PM	AM	PM	AM	PM	Intersection data available
09/20/10-10/02/10	No	PM	AM		AM	PM	
05/02/11-05/08/11	No		medium		AM	PM	
Congestion	No	Light, or no	Regular Medium	No	Medium congestion	Medium congestion	
Data health	No data sometimes for the same time period of several days; almost no congestion		No data sometimes for several days at the same time; confirmed some AM		No data sometimes for several days at the same time; confirmed some AM peak congestion		

Entrance ramp demands are higher for both AM & PM peak traffic in NB. SB has light traffic in both AM and PM peak hours, but this could not explain the odd behavior. For NB, 402475 is further downstream than 402473. If it is congested in PM hours, it is likely that traffic will back propagate to 402473 and cause its speed drop, but this never happened. The same case for SB.

In summary, from current traffic data, SB did not have heavy traffic. NB has some AM peak congestion at LDS 4024723, which is isolated from its downstream entrance ramp. This could be a simple candidate. But the data system needs detection and may need repairing. Sensor distance is long: data at two consecutive stations do not show close relevance.

After field traffic observation on 10/24/11 AM peak: both Camden and Union had AM peak congestion. The conclusion is that:

402573_Camden is correct;

402474_Union: supposed to be SB, but it is actually NB;

402475_Union: supposed to be NB, but it is actually SB;

Therefore, 402474_Union and 402475_Union have been assigned to the opposite direction, which should be corrected.

Therefore, the site selection must be conducted through field traffic observations instead of just based on PeMS data.

Appendix 6. Progressive Field Test Plan

A6.1 Intersection Traffic Signal Timing Field Test Plan

The following *progressive test procedure* was proposed for signal timing at Taylor intersection:

Step 1: Interface of PATH computer with the 2070 controller will be conducted after controller change.

Step 2: Traffic data of all the detectors and signal timing (green yellow, red, "gap out", "max out" and "force off" of all phases, and all red time) will be retrieved, recorded and analyzed; it will be sent to relevant signal operation engineer for review;

Step 3: To make sure that traffic data processing module can estimate traffic state parameters robustly even in case of detector and or data error, and it generate all the required information;

Step 4: To run the proposed control on PATH computer strategy without activation in parallel with the original "Actuated Signal Timing" and record all the data;

Step 5: To compare those two signal timing for each phase to see how different they are, and if the differences are within reasonable threshold; this will be conducted for some non-peak as well PM peak hours; this procedure will continue for 2~3 weeks to make sure signal timing strategy running on PATH computer are reasonable and reliable. Otherwise, it will be corrected, modified or refined until it is satisfactory;

Step 6: To test transition modules to make sure the transition between the two signal timing strategies can be executed smoothly;

Step 7: To activate signal timing from PATH computer through AB3418(E) in non-peak hours prior to the PM peak hours for 1~2 days to make sure it generates reasonable signal timing;

Step 8: To activate signal timing from PATH computer through AB3418(E) from non-peak hours prior to the PM peak hours and continue into PM peak hour for 15 min and then fall back to default signal timing; to conduct data analysis to make sure the control strategy will not generate negative impact; continue this process for a week; if there is any problem, the PATH signal timing module will be changed and refined accordingly to resolve the problem;

Step 9: To extend the test period to the whole PM peak hours (4:30~6:00pm) gradually in 1~2 weeks with

- closely monitoring the traffic data
- closely monitoring signal timing; if there is any problem, fall back to the default control
- fine tuning the signal timing strategy to improve performance

Step 10: To test the control strategy for 1~2 weeks before overall system integration (with ramp metering)

Project team will be on scene during the testing period. In case of any problem, controller will fall back to the default one.

A6.2 Ramp Metering Field Test Plan

In case of any operational issues, the control strategy were to automatically fall back to the default ramp meter control. Then the test was followed by an integrated system test (involving both RM and Taylor intersection signal timing). Two transition modules were developed between the original RM control and PATH implemented RM control. Those transition controls were used for smooth transition between the two whenever PATH computer control starts and ends. RM rate change limit were added to PATH RM control to guarantee that the RM rate generated on PATH computer will not be too different from that generated from the original RM control. The following *progressive test procedure* was proposed:

Step 1: After interface being established with Caltrans District 4 TMC (Traffic Management Center) or at the entrance ramp with the ramp meter controller, real-time freeway traffic data and RM rate will be collected and analyzed; data will be sent to freeway operation engineer for review;

Step 2. Make sure that data process module for traffic state parameter (occupancy, flow and time-mean speed) estimation run correctly;

Step 3: Run PATH RM control without activation in parallel with District 4 original RM control and save data for analysis to make sure that the RM rate generated from PATH computer is reasonable;

Step 4: Run the two transition modules without activation to make sure transition can be done smoothly;

Step 5: Start to activate PATH RM control for a short time period (15~30min) before heavily congested PM peak hours;

Step 6: Gradually extend PATH RM control into the whole PM peak hours in 1~2 weeks;

Step 7: Test PATH RM strategy in PM peak hours for one week before system integration (with intersection signal timing);

Step 8: Tune the control strategy if necessary, which may take a week;

A6.3 System Integration Field Test Plan

Step 1: after successful tests of both intersection signal timing and freeway RM, the overall system will be integrated for preliminary test at the beginning of PM peak hours for 2~3 days; if there is any problem, the overall system will be modified and tuned;

Step 2: gradually extend the test period for the integrated system into PM peak hours for a week;

Step 3: test the integrated system and tune the overall control if necessary in 1~2 weeks;

Step 4: systematic test of the integrated system for 2~3 weeks and collect data for performance evaluation;

Project team and freeway and intersection traffic operation engineers will be on scene for all the tests. In case there is any problem, the controllers will fall back to the default ones.

A6.4 Practical Field Test Procedure Record

Practical test procedure followed the proposed test plan as was presented to the project panel before. The objective to effectively avoid any negative impact on traffic operation was successfully achieved. The practical test procedures are listed below as a record:

09/23 – 10/07: PATH team finalized control code and both PATH computers

10/07- 10/11: PATH team installed code on PATH computers in the two cabinet – one at Taylor intersection and one at Taylor entrance ramp, and make dry-runs: NO control was activated; all the data were saved to files; (accomplished)

10/14 – 10/18: Test of Ramp Metering code with a 2070 controller in District 4 RM Field Office in San Jose with Caltrans District 4 Ramp Metering Field; field installation kept as they were; PATH used a laptop to do so; field dry run continued in parallel;

PATH team modified control code only in PATH computer; all the hardware and software problem were resolved

10/14 – 10/18: PATH team presented processed dry run data to all the panel for comments; the data included the comparison between: (a) default RM rate and suggested RM rate; (b) Default Green Times of Phase 5 & 6, and suggested Green Times for them under the modulation of Phase 3;

10/21 – 10/28: PATH team made demos to both intersection and RM engineers in District 4 for actuation of control signals on field 2070 controllers;

10/29: First day trial for PATH control activated from 2:30~3:00pm for one hour on 10/29/13 both Ramp Meter and Intersection Traffic Signal Control engineers were on the scene; they helped to switch the overlap including loop detector assignment from Phase 7 to Phase 3. The two control systems, i.e. freeway RM and Taylor intersection, and their coordination started at 3:00pm smoothly and worked as expected afterwards. Just based on our intuitive observation, switch overlap from 6&7 to 6&3 for the Right Turn to freeway did provide more space on the entrance ramp to Phase 5 Left Turn (LT) to some extent. The Phase 5 LT dumped traffic faster than what we had observed before. Phase 6 RT (Right Turn) queue length was acceptable;

10/30 – 11/ 08 Formal Tests were conducted with the overall system running for 9 days. PATH team was at the site on 10/30, 10/31, and 11/01. On 10/30/13, PATH team collected video data and also observed AM peak traffic to make sure the test would not have significant negative impact in the morning hours since the coordination/control strategy were developed for PM peak hours. The observation showed that the operation in AM peak hours were also fine. After that, PATH team tightly monitored the behavior of the controller remotely by watching the phase 3 green time at the intersection and RM rate of the entrance ramp through network data with update rate every second.

11/08 (Fri) PATH project team deactivated the control systems of the PATH computers in both intersection and RM control cabinets and kept the system in dry-run status: only collected data with actuation of control.

11/09-11/18 PATH team conducted one more week data collection for data analysis.

11/19 (**Tue**) PATH team removed all the hardware in the two control cabinets including computers and wireless modems etc. The test was completed.

Appendix 7 Caltrans Advisory Group Charter

Caltrans Technical Advisory Group (TAG) Charter For Coordinated Ramp/Arterial Signal Control Project (Phase 1)

1. Background

In current traffic operating practice, traffic control at freeway on-ramps and arterial intersections are operated independently. Such a situation may significantly reduce performance on both roadways. It is recognized that for highly efficient and reliable traffic flow over the entire traffic network, it may be necessary to coordinate the traffic between roads of different levels due to the strong dynamic interaction between them.

Arterial intersection traffic control maximizes flow by progressively coordinating traffic signals over a series of intersections. Conversely, freeway on-ramp traffic control maximizes mainline flow by restricting traffic from entering the mainline if the total demand (upstream mainline flow + expected on-ramp flow) approaches or exceeds the capacity of the downstream mainline section. Another conflict is that arterial intersection traffic control groups vehicles into platoons, while freeway on-ramp metering tends to break these platoons into individual vehicles – usually one vehicle per green. If an onramp is subjected to serious storage limit, either through high arterial demand or low on-ramp discharge, traffic may spill back from the on-ramp into the arterial. Balance these two to achieve maximum flow or minimum Total Travel Time for the overall system is the critical issue.

2. Project Objectives

The objectives of studying the coordination between freeway ramp metering and arterial traffic signal control are (1) to identify when coordination is necessary; (2) to develop coordination strategies, (3) to identify any technical hurdles in integration of the two systems for coordination (ramp metering and intersection traffic signal control), (4) to resolve the conflict of interests between freeway traffic control and arterial traffic control; (5) to optimize the control variables such as metering rate and green/cycle length, off-set, priority assignment etc. to minimize the Total Time Spent (TTS) in the system involved; and (6) to fully use real-time traffic data from freeway and arterial to estimate/predict the traffic state parameters for updating the model and the controllers.

3. Expected Outcomes

The expected outcome for this project are: (1) to develop control and coordination strategies through simulation which includes developing/selecting a practical coordination strategy for integrating both freeway ramp metering and arterial intersections traffic signal control; and (2) to conduct a preliminarily small scale field implementation of the coordination strategy for the selected site.

4. Caltrans Technical Advisory Group Roles & Responsibilities

The Caltrans Technical Advisory Group (TAG) members are involved in the entire project and their expected roles and responsibilities are as follows:

1. Determine the Scope of Work. (This work was completed in 2010)
2. Attend a Kick-off meeting for the project after the contract is awarded. (This was completed on 10/6/2011)

3. Attend project meetings.
4. Assist the PATH research team in selecting the appropriate site for Proof of Concept analysis.
5. Assist the PATH research team in collecting needed data for the selected site.
6. Provide expert knowledge of ramp metering and signal control system to assist the PATH research team during the course of the project.
7. Review and comment on documents related to the project, and attend the final presentation.
8. Agree to the terms and conditions of the attached Technical Agreement.

5. Team Members

The following staff will be the core members of the Caltrans TAG for this project:

Member Name	Organization	E-Mail Address	Phone Number
Zhongren Wang	Caltrans/HQ Traffic Operations	zhongren.wang@dot.ca.gov	916-654-6133
David J Wells	Caltrans/HQ Traffic Operations	david.j.wells@dot.ca.gov	916-653-1342
Ted Lombardi	Caltrans/HQ Traffic Operations	ted.lombardi@dot.ca.gov	916-653-8993
Alan chow	Caltrans/D04/Traffic Sys.	alan.chow@dot.ca.gov	510-286 4577
Lester Lee	Caltrans/D04/Traffic Sys.	lester.s.lee@dot.ca.gov	510-286 4528
Sean Coughlin	Caltrans/D04/Elec. Sys.	sean.coughlin@dot.ca.gov	510-286 4804
Lily Lim-Tsao	City of San Jose Dept. of Transportation	lily.lim-tsao@sanjoseca.gov	408-975-3269
Xiao-Yun Lu	UC Berkeley/PATH	xylu@path.berkeley.edu	510- 665-3644
Alexander Skabardonis	UC Berkeley/PATH	skabardonis@ce.berkeley.edu	510-642-9166
Fred Yazdan	Caltrans/HQ DRI	fred.yazdan@dot.ca.gov	949-936-3462
Paul Mazdiyasni	Caltrans/HQ DRI	paul.mazdiyasni@dot.ca.gov	949-936-3496

6. Small Scale Field Operational Test Technical Agreement

Due to the complex nature of the coordination activities between ramps and signals, and the fact that some minor adjustments to the field elements at the selected sites, such as signal timing changes, and ramp metering rate changes etc., may be needed for a successful filed operational test, the attached Technical Agreement must be agreed to among the stakeholders.

FIELD OPERATIONAL TEST TECHNICAL AGREEMENT

This document sets forth the terms of the Field Operational Test Technical Agreement (FOT-TA) among the stakeholders of the Coordinated Ramp Metering/Arterial Signal Control project. The stakeholders are: Caltrans District 4 Traffic Operations, City of San Jose Traffic Department, Caltrans HQ Traffic Operations, and Caltrans HQ Division of Research & Innovation (DRI).

GENERAL TERMS & CONDITIONS

The project stakeholders (named above) agree to the following terms and conditions:

Caltrans District 4:

- Provide expert knowledge of District 4 ramp metering and signal control system to assist the PATH research team during the course of the FOT;
- Provide on-site supervision during the small scale FOT;
- Allow UC Berkley/PATH researchers access to real-time traffic data required for ramp metering control;
- Allow UC Berkley/PATH researchers to interface with the ramp metering Controller with a laptop computer to modify the rate in real-time, under fully controlled and supervised session;
- Assist in monitor the progress of the project and approve all the major actions to be taken and materials developed during the course of the project.

City of San Jose Department of Transportation:

- Provide expert knowledge of City's arterial signal control system to assist the PATH research team during the course of the FOT;
- Provide on-site support during the small scale FOT;
- Allow UC Berkley/PATH researchers access to real-time traffic data required for arterial intersection traffic signal control;
- Allow UC Berkley/PATH researchers to interface with arterial signal controller with a laptop computer to modify a few traffic control parameters such as off-set, cycle length, and green time distribution, under fully controlled and supervised session.
- Assist in monitoring the progress of the project and review of all the major actions to be taken and materials developed during the course of the project.

UC Berkley/PATH Research Team:

- Report the progress of the project and document all the finding including successful results, hurdles to overcome, lesson learned, algorithm developed, and software developed.
- Work closely with staff from Caltrans HQ Traffic Ops, District 4, and City of San Jose to plan and implement the small scale FOT;
- Make sure the original signal control parameters are not disturbed, particularly in peak hours;
- Ensure to keep the original controller parameters intact and to avoid any impacts to its operation, in case if the arterial signal control has already been coordinated (e.g. based on time-of-day offset);

- Ensure the traffic control that is developed will not touch any safety critical logistics in the original signal or ramp meter controller.

Caltrans HQ Traffic Operations:

- Provide expert knowledge of overall Caltrans ramp metering and signal control strategies;
- Assist in monitoring the progress of the project and approve all the major actions to be taken and materials developed during the course of the project.

HQ DRI:

- Assist in monitoring the progress of the project and approve all the major actions to be taken and materials developed during the course of the project;
- Ensure the resources identified by the contract are available to be used by the project team.
- Manage the research contract.

POTENTIAL RISKS AND LIABILITIES

In order to minimize the potential risks in conducting the FOT, it is intended to develop a traffic control algorithm in parallel with the original Adaptive Traffic Control System (ATCS) running on UC Berkley/PATH computer without disturbing the original arterial signal control parameters. And at the same time allow the UC Berkley/PATH computer to obtain real-time data from the control cabinet. In particular, it will include the following aspects;

(1) The output of the control algorithm is a set of parameters such as off-set, cycle length, green time distribution among all the phases. The original controller will run as it is and it will pick up the provided parameters from a database or a file dedicated to the FOT traffic control. Particularly, the safety critical control logics built in the signal controller will not be touched at all. Therefore, there will be no safety concerns and liability issues in this respect. It is suggested to work with the original control software provider to make it work this way;

(2) To minimize the impact on local community, the test will start from non-peak hours to avoid any disturbance of the traffic controller for original peak hour operation. Then it will gradually test for some limited peak hours interval for evaluation.

(3) Anything to be tested will be fully discussed with the project panel to make sure it would not affect traffic operation, and it will be supervised by the project panel.

DURATION OF MOU

This FOT-TA will go into effect after all stakeholders approve and sign off on it, and will remain in effect for the duration of the project ending when the contract with UC Berkley/PATH is expired, currently set for 12/31/2012. Any party may terminate this FOT-TA by mutual consent of all stakeholders. However, it can only be extended if the contract end date has officially been extended through Caltrans Contract Amendment process.

SIGNATURES:

Date 5/15/12
Alan Chow
Office Chief, Caltrans District 4 Traffic Systems

Date 5/31/12
Lily Lim-Tsao
Division Manager, Department of Transportation, City of San Jose

Date 5/16/12
Alex Skabardonis
Principal Investigator, UC Berkley/PATH

Date 5/16/12
Zhongren Wang
Branch Chief of Ramp Metering Systems, Caltrans Division of Traffic Operations

Date 5/14/12
Fred Yazdan
Contract Manager, Caltrans Division of Research & Innovation