Coordination of Freeway Ramp Metering and Arterial Traffic Signals

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ABSTRACT

The independent operation of freeway ramp meters and the adjacent arterial traffic signals often causes queue spillback on the freeway on-ramps and the surface street network, which prompts the activation of queue override and negates the benefit of ramp metering. A field test undertaken in this study at a real-world freeway corridor in San Jose, California shows that on-ramp queue override may reduce the freeway queue discharge flow by 5-10%. A control strategy for coordinating freeway ramp metering and arterial traffic signals was developed and evaluated in this study. The algorithm takes available on-ramp storage into account and dynamically adjusts the signal settings to prevent on-ramp queue spillback and mitigate unnecessary delay in the conflicting arterial directions. The proposed algorithm was tested through simulation of the selected test corridor. The simulation results show that the proposed strategy reduces the freeway and system-wide delay, at a modest penalty on adjacent arterial.

INTRODUCTION

Several efforts are underway for integrated corridor management (ICM) of facilities comprised of freeways and adjacent arterial streets (*1*). One of the main challenges toward an effective management of a travel corridor is the coordination of the various subsystems that it comprises, e.g., freeway ramp meters and traffic signals on the adjacent arterials. The objective of freeway on-ramp metering is to regulate the entry of vehicles to prevent congestion on the freeway mainline. Several ramp metering algorithms have been developed and implemented worldwide (*2*). Most of the operational ramp metering systems employ a "queue override" feature that is intended to prevent the on-ramp queue from obstructing traffic conditions along the adjacent surface streets. The override is triggered whenever a sensor placed at the entrance of the on-ramp detects a potential queue spillover of the on-ramp vehicles on the adjacent surface streets, and increases the metering rate to its maximum value, to empty the queue into the freeway. The queue override reduces the effectiveness of employed ramp metering systems during the time of highest traffic demand, when the ramp metering is most needed. Significant benefits can be realized by preventing the queue override. This can be accomplished by managing the on-ramp demands from the adjacent surface street with signal control strategies.

The objectives of the study described in this paper is to develop and test a control algorithm to manage the entry of vehicles on the on-ramp through signal timing changes at the intersections along adjacent arterial(s).

The rest of the paper is organized as follows: The next section presents an overview of recent research in the area of coordinating freeway ramp metering and arterial traffic signals. Next, the control algorithm is presented. The following section documents the application of the proposed strategy through simulation in a real-life freeway corridor. The final section summarizes the study findings and discusses the next steps in the ongoing research.

LITERATURE REVIEW

Existing research has focused on development of optimization algorithms and routing models for integrated control of freeway-arterial corridor system with emphasis on non-recurrent (incident related) congestion. Other approaches focus on control strategies for freeway interchanges to avoid off-ramp queue spillback, and algorithms that prevent overflow on metered ramps that adversely affect arterial operations under recurrent congestion. The Freeway-Arterial coordination handbook (*3*) provides information on interagency coordination, technological challenges and examples of freeway-arterial corridors that have implemented coordinated operation schemes, mostly on how local arterials can be coordinated with the freeway in the event of an incident. Representative approaches are presented in the following sections.

Coordination of Freeway On-ramp and Adjacent Arterial

Few studies have addressed the inefficient control of freeway ramp metering and the nearby arterial corridor facilitating freeway access in the day-to-day recurrent conditions, and no generalizable control strategies have been implemented.

Tian et al (*4*) developed an algorithm for diamond interchanges that reduces green durations for movements with on-ramp access to prevent on-ramp queue spillback, under the same cycle length. This approach may cause spillback of on-ramp demand onto the upstream arterial, especially under long cycle lengths, and temporary activation of queue override.

Recker et al (*5*) developed a system-wide optimization model for ramp metering and traffic signals from stochastic queuing theory, but the improvement observed after implementing the control strategy at a network of freeways and arterials was a result of using a more efficient ramp metering control, rather than coordination of ramp metering and traffic signals. Moreover, the proposed approach requires solving non-linear optimization in real time, which is computationally intensive and not feasible in most situations.

Other research efforts focused only on control of isolated signalized intersections at or adjacent to freeway on-ramps. For example, Li and Tao (*6*) proposed a signal optimization model for an arterial at an isolated freeway interchange using the cell transmission model but neglected ramp metering in their algorithm.

Recently, Su et al (*7*) developed a signal optimization model that takes the ramp meter rate and on-ramp queue length into account, for an isolated diamond interchange. A brief field test was conducted to show that coordination of freeway ramp metering and arterial traffic signals is technologically feasible and implementable in the real world. However, similar to the method by Tian et al (*4*), the proposed algorithm simply reallocated green times without changing the cycle length, therefore it provided unnecessarily long green durations for the conflicting movements and disregarded the potential queue spillback into the upstream arterial intersection. Furthermore, the impact of queue override was not considered.

Freeway Traffic Diversion

A commonly recommended strategy for freeway/arterial coordination in ICM projects is the use of parallel arterial(s) as reliever route(s) to the freeway travelers whenever there is a capacity reducing incident on the freeway. In this situation, drivers may be instructed to divert on the parallel arterial(s) and return to the freeway past the incident location. The signal settings on the arterial are set to facilitate the movement of the diverted freeway travelers ("flush plans"). However, there is no empirical evidence yet on the effectiveness of such strategies, and there is no clear understanding of the issues involved in the development and implementation of these strategies.

Tian et al (*8*) proposed a traffic-responsive coordination strategy that extends the green times corresponding to the freeway off-ramps and parallel arterial and maximizes ramp meter rates of the downstream on-ramps based on real time queue detection on the freeway, and it was shown to be effective for freeway-arterial corridors with consecutive diamond interchanges. In addition, the work by Zhang et al (*9*) tested a similar approach at a corridor with various configurations of freeway interchanges. Other works in this area include an optimization-based coordination strategy that minimizes corridor level delay during incident diversion (*10*), an empirical study of the effect of dynamic traveler information on the amount of freeway traffic diverted and the corridor-wide performance (*11*), and a control strategy for diverting traffic from the freeway to the adjacent arterials with significant spare capacity, in the event of periodic freeway capacity reduction (*12*).

Off-ramp Bottleneck

Off-ramp bottlenecks typically are created because of inefficient signal timing at the downstream end of the freeway off-ramp, when it intersects the adjacent arterial. Several studies investigated the queue spillback of off-ramp freeway traffic onto the freeway mainline with emphasis on the bottleneck activation and congestion propagation (*13*). Recently, Yang et al (*14*, *15*) proposed a conditional signal priority scheme at the off-ramp intersection and arterial signal progression to quickly discharge the off-ramp queue and further reduce the impact of off-ramp spillback.

PROPOSED COORDINATION STRATEGY

The proposed control approach maintains the existing freeway ramp metering algorithm in practice and is not limited to any specific freeway ramp metering algorithm. For the adjacent arterial traffic signals, this approach recommends that the signal timing plans for arterials adjacent to freeway on-ramps should be developed similar to signal timings of over-saturated arterials. Recent research in this area (*16*) suggests that long cycle lengths and long green durations must be avoided, and instead, the cycle lengths and green durations should consider the on-ramp queue storage space and should be designed to avoid queue spillback.

Consider a freeway on-ramp and the adjacent signalized intersection with 3 phases (Figure 1). The on-ramp is metered with a rate $r(t)$ with queue storage capacity Q_r. In this example, signal phases 1 and 2 serve the traffic movements feeding the on-ramp, and the remaining phase does not have on-ramp access.

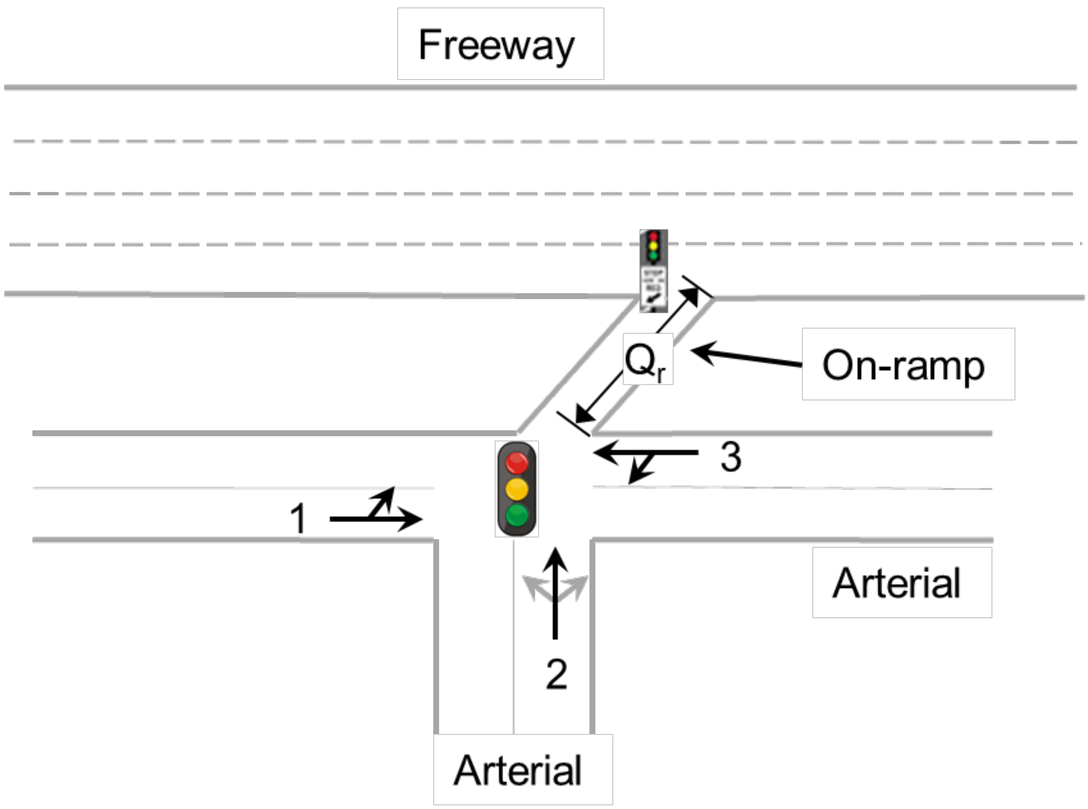

Figure 1 Example of a signalized intersection with on-ramp access.

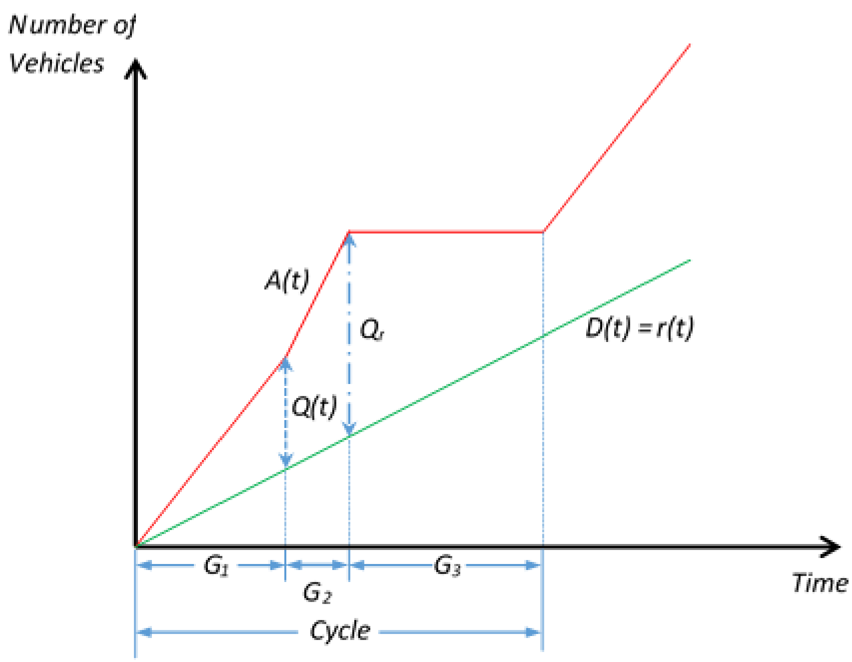

Figure 2 Queueing diagram of freeway on-ramp during a signal cycle.

The queuing diagram in Figure 2 illustrates the upstream arrival pattern, downstream departure rate, and the excess accumulation at the freeway on-ramp when ramp metering is active. When the vehicle arrivals *A(t)* from phases 1 and 2 of the upstream signalized intersection are greater than the discharge flow *D(t)*, then we have excess accumulation *Q(t)* on the on-ramp. When *Q(t)* exceeds the storage capacity Q_r , we have queue spillback that causes the activation of queue override.

Since the arrival rates (saturation flows) from phases 1 and 2 exceed the ramp metering rate, the corresponding phase green times must terminate before the excess accumulation reaches the on-ramp queue storage capacity. The remaining signal phase, which serves the intersection approach that does not feed the on-ramp, can be served earlier, and at that time the on-ramp queue dissipates. As a result, vehicles from phases 1 and 2 can enter the on-ramp in the next signal cycle.

Under this strategy phases 1 and 2 receive shorter green times which may cause spillback on the arterial, as it was reported in the literature (*4*, *7*). Such shortcoming can be remedied by maintaining the existing green distributions but using a shorter cycle length, as explained in the following sections.

The mathematical expressions for this control strategy are described as follows. First, the excess accumulation of the on-ramp must be estimated. Using the ramp meter rate $r(t)$ that is updated each time step *t*, the on-ramp excess accumulation *Q(t)* at time step *t* can be determined based on the following process:

$$Q(0) = 0$$

$$Q(1) = Q(0) + A(1) - D(1)$$

$$\vdots$$

$$Q(t) = Q(t-1) + A(t) - D(t)$$

Where $A(t)$ is the number of arrivals at the on-ramp during time step t, and $D(t)$ is the number of departures from ramp meter during time step t. The arrivals and departures can be measured by the loop detectors at the upstream and downstream ends of the freeway on-ramp, respectively. The on-ramp excess accumulation should be updated at the end of every cycle in order to perform real time control.

Equation 1 is developed using the queuing diagram in Figure 2, to ensure that the green time for phase 1 and phase 2 must terminate at or before the excess accumulation reaches the maximum on-ramp queue storage capacity Q_r, therefore imposes an upper limit for the cycle length:

$$Q(t-1) + g_1 \cdot s_1 \cdot \beta_1 + g_2 \cdot s_2 \cdot \beta_2 - g_1 \cdot r(t) - g_2 \cdot r(t) \leq Q_r \quad (1)$$

where,

g_1: effective green time of phase 1
g_2: effective green time of phase 2
s_1: saturation flow of phase 1
s_2: saturation flow of phase 2
β_1: percentage of demand of phase 1 that access the on-ramp
β_2: percentage of demand of phase 2 that access the on-ramp
$Q(t-1)$: residual on-ramp queue from the previous cycle.
$r(t)$: ramp metering rate

The effective green times can be expressed as functions of cycle length (*17*). Thus, g_1 and g_2 are expressed as the following:

$$g_1 = \frac{y_1}{Y} \cdot (C - 4l) \quad (2)$$

$$g_2 = \frac{y_2}{Y} \cdot (C - 4l) \quad (3)$$

where,

y_1: ratio of arrival rate and saturation flow of phase 1
y_2: ratio of arrival rate and saturation flow of phase 2
Y: sum of y's of the cycle
C: cycle length (sec)
l: lost time of each phase (sec)

Substitute Equations 2 and 3 into Equation 1, Equation 1 can be expressed in terms of cycle length. Solving for cycle length in terms of the rest of the variables, the upper limit of cycle length is the following:

$$C \leq \frac{[Q_r - Q(t-1) + r(t) \cdot 2l] \cdot Y + 4l \cdot \left[\sum_{i=1,2} s_i \beta_i y_i - \sum_{i=1,2} r(t) y_i\right]}{\left[\sum_{i=1,2} s_i \beta_i y_i - \sum_{i=1,2} r(t) y_i\right]} \quad (4)$$

The upper limit of the cycle length must be updated at the end of every cycle in order to perform real time control that coordinates with freeway ramp metering.

The above selected cycle length does not provide for the maximum bandwidth of through traffic on the parallel arterial, which is appropriate for close to saturation arterial facilities that primarily provide access to multiple freeway on-ramps. The appropriate signal settings in this case, consist of shorter cycles and offsets that prevent long queues on the intersection approaches.

The proposed strategy is applicable to real-world multiphase signalized intersections by appropriately adjusting Equations 1 through 4. Also, the proposed strategy does not require any new surveillance technologies or infrastructural changes and can be accomplished using the existing infrastructure and detection capabilities. It only requires modification of signal and ramp meter controller settings (i.e. cycle length, queue override) and communication between the two controllers.

APPLICATION

The proposed control strategy was tested through simulation in a real-world test site. The study site was carefully selected, calibrated using field data, and modeled in microscopic simulation.

Site Selection

The test site was selected based on several criteria including i) size: the freeway segment and its parallel arterial should not be longer than 5 miles, and the parallel arterial should have no more than 5 major signalized intersections; ii) presence of active bottlenecks in the test section, iii) free-flow conditions at the study section boundaries, iii) functional loop detector system and iv) cooperation among jurisdictions managing the system.

A three mile section of northbound I-680 from Alum Rock Ave. to Berryessa Rd. and a section of Capitol Ave. arterial with 5 signalized intersections in the city of San Jose, California was selected as the study area (Figure 3). There are three recurrent bottlenecks on this stretch of I-680, located near the on-ramps from Berryessa Rd., McKee Rd., and Alum Rock Ave. At all three bottlenecks, the high on-ramp traffic demand from of the westbound direction of Berryessa Rd., McKee Rd., or Alum Rock Ave., along with high on-ramp demand from the northbound direction of Capitol Ave., result in high volumes of merging traffic onto the northbound freeway mainline during the morning peak (typically 7:30-9:30 AM). This results into excessive queues at the on-ramps that activate the queue override feature for 30 minutes to one hour of the peak period (typically 7:30-8:00 or 8:30 AM).

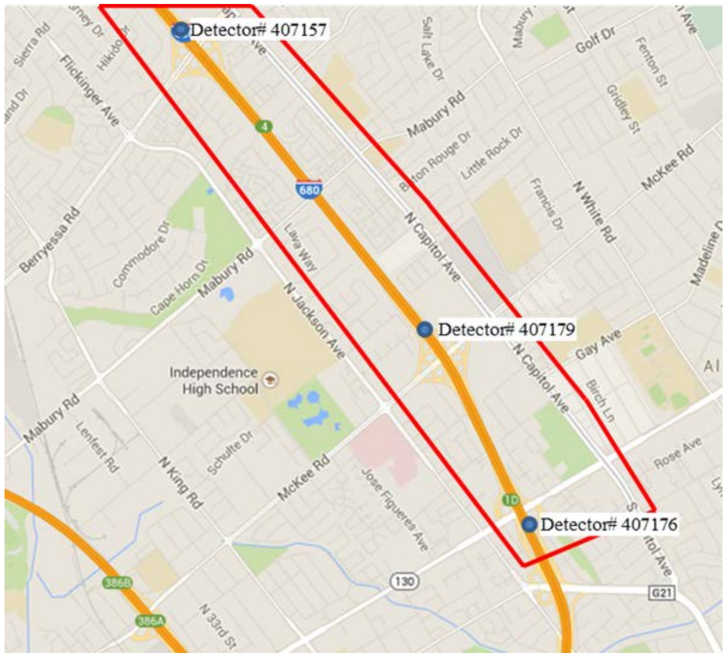

Figure 3 Study site: I-680-Capitol Ave and mainline detector locations.

Model Application and Calibration

The site was modeled using the AIMSUN microscopic simulation model (*18*) based on the field data on road geometry, lane configurations, and speed limits of the freeway and the arterial at the selected site. The simulation model covered three miles of northbound I-680, the on-ramps and off-ramps at Alum Rock Ave., McKee Rd., and Berryessa Rd., the parallel arterial Capitol Ave., and 5 major signalized intersections. All of the on-ramps are metered using the local traffic responsive demand-capacity approach, i.e., the metering rates are determined based on the occupancy of the upstream detector at each on-ramp. Ramp metering algorithm and rates were obtained from Caltrans District 4 and modeled in AIMSUN via a specially written API (Application Programming Interface). The signalized intersections of this corridor operate with time of day (TOD) coordinated actuated timing plans. The existing cycle lengths are in the range of 130 to 160 seconds, and the signal timing plan provides progression to the heavier northbound direction. The signal timing plans were provided by the city of San Jose.

Freeway and arterial demand data obtained from 7:30 AM to 9:30 AM of Wednesday, September 23, 2015 were used for the inputs in demand and turning percentages. For the freeway, 5-minute interval loop detector data for flow were obtained from the PeMS system (*19*) and used as the demand input at the most upstream location of the simulation network and as the turning percentages at the mainline-off-ramp splits. Traffic flows on the arterial were obtained from video recordings. Video cameras were placed at the signalized intersections and arterial-on-ramp splits. Turning movement flows were recorded every 5 minutes, and they were used as the demand input at the entry points of the corridor (i.e., southbound Capitol Avenue north of Berrryessa Rd.) and as turning percentages at the signalized intersections and the arterial-on-ramp splits.

The model was calibrated to existing conditions prior to the evaluation of the proposed control strategy. Twenty replications of each simulation model runs with different random number seeds were made. The 5 minute predicted flows and speeds at selected locations on the freeway mainline were compared with field measurements to assess the accuracy of the simulation model in representing observed conditions. The GEH criterion was used to assess the agreement of simulated predictions and field measured flows (*20*). The GEH statistic is computed as:

$$GEH(k) = \sqrt{\frac{2[M(k) - C(k)]^2}{M(k) + C(k)}} \tag{5}$$

where,

$M(k)$: simulated flow during the *k*-th time interval (veh/hour)
$C(k)$: flow measured in the field during the *k*-th time interval (veh/hour)

A satisfactory calibration requires that the predicted freeway flow satisfies the condition GEH < 5 for at least 85% of all 5-minute time intervals. For arterial flows, the GEH < 5 criterion must be satisfied for at least 85% of all 5-minute time intervals, for each turning movement of the major intersections. For speed, the relative root mean squared error (RRMSE) of the simulated speed values is required to be 15% or lower, on average of all detectors.

Table 1 summarizes the calibration results for the three detectors along the three mile stretch of Northbound I-680, as well as the 5-minute turning movement flows of the major arterial intersections. On the average, the simulated flows on the freeway and the arterial intersections satisfy the calibration criterion. Also the RRMSE of the simulated speeds at all freeway detector locations satisfy the criteria. Figure 4 shows a comparison of the field measured and simulated speeds at the most upstream bottleneck (Alum Rock Ave. on-ramp).

Table 1 Calibration of freeway and arterial flows.

Freeway: 5-min flows of I-680 Northbound					
Detector Location	Target	Cases	Cases Met	% Met	Target Met?
Alum Rock Ave. on-ramp (loop)	GEH < 5 for > 85% of *k*	24	24	100.00%	Yes
McKee Rd. on-ramp	GEH < 5 for > 85% of *k*	24	24	100.00%	Yes
Berryessa Rd. on-ramp	GEH < 5 for > 85% of *k*	24	23	95.83%	Yes
Overall	GEH < 5 for > 85% of *k*	72	71	98.61%	Yes
Arterial: 5-min flows of major intersections—all movements					
Capitol Ave. & Alum Rock Ave.	GEH < 5 for > 85% of *k*	192	191	99.48%	Yes
Capitol Ave. & Berryessa Rd.	GEH < 5 for > 85% of *k*	240	240	100.00%	Yes
Capitol Ave. & Mabury Rd.	GEH < 5 for > 85% of *k*	192	192	100.00%	Yes
Capitol Ave. & McKee Rd.	GEH < 5 for > 85% of *k*	240	235	97.92%	Yes
Alum Rock Ave. & I-680 off-ramp	GEH < 5 for > 85% of *k*	144	143	99.31%	Yes
Arterial: Overall	GEH < 5 for > 85% of *k*	1008	1001	99.31%	Yes

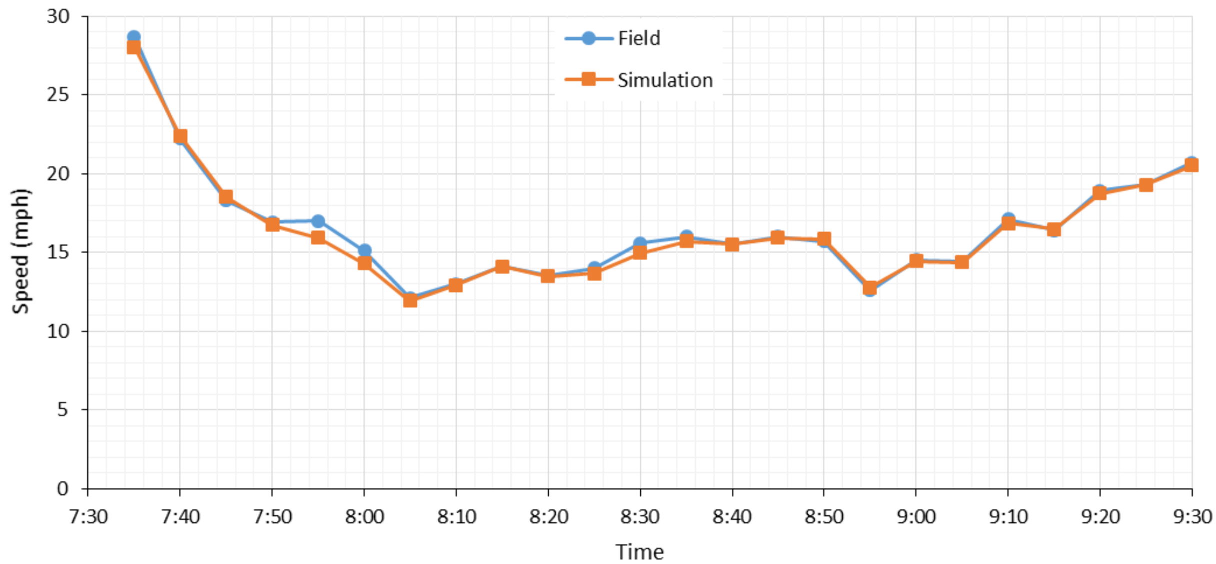

Figure 4 Field observed and simulated speeds near Alum Rock Ave. on-ramp.

Simulation Results

Twenty replications were conducted using the existing independent control and the proposed coordinated control during the two hour morning peak. The results are summarized in Table 2.

- **Freeway mainline**: The proposed control strategy eliminated the activation of the queue override which improved the freeway operating conditions. The total delay on the freeway mainline was reduced by 17.9%, and the throughput (expressed in vehicles miles of travel VMT) was improved by 1.3%. There is also small improvement in freeway capacity, as evident in small increase in total distance travelled shown in Table 2, thus the proposed control did not simply redistribute delay from the freeway mainline to the on-ramp. However, the microscopic simulation relies on assumptions in driving behavior that may not represent the real world conditions, thus the real world freeway capacity improvement may be higher than the improvement shown in Table 3 if queue override was not activated.

- **Arterial:** The delay increased in the northbound direction of the parallel arterial, which serves significant demand for on-ramp access, because it no longer benefits from queue override that disabled the more restrictive ramp metering in the existing control. However, the southbound direction of the parallel arterial remained mostly unaffected, due to the low demand for on-ramp access (a 3% increase). On the cross streets, delays were reduced because the shorter cycle lengths mitigated the long delays imposed on the cross streets. There were significant delay reductions at McKee Rd. and Berryessa Rd. but almost none at Alum Rock Ave. This is because there is sufficient space for on-ramp queue storage near the Alum Rock Ave. so the signal timing remained the same. The queue storage space were limited at the McKee Rd. and Berryessa Rd. on-ramps therefore the cycle lengths were reduced at the corresponding signalized intersections, which reduced the average delay on those cross streets and improved the level of service (LOS) on two intersection approaches. The westbound directions of the cross streets benefited much less than the eastbound directions because there is significant on-ramp demand in the westbound direction that no longer benefit from queue override after the new control is implemented.

- **Total system:** The proposed control strategy reduced the system-wide delay by more than 7%.

Table 2 Performance of proposed control strategy.

	Before Coordination		**After Coordination**		**% Difference**	
Freeway Mainline						
	Total Delay (veh-hr)	Total Distance Traveled (veh-mile)	Total Delay (veh-hr)	Total Distance Traveled (veh-mile)	Change in Total Delay	Change in Total Distance Traveled
I-680 NB	799.06	37295.75	655.81	37788.13	-17.93%	1.30%
Arterial						
Average Delay on Main Parallel Arterial (min/veh)						
Capitol Ave NB	8.63		10.51		21.84%	
Capitol Ave SB	5.72		5.91		3.33%	
Average Delay of Cross Street (sec/veh)						
Alum Rock WB	48.05 (D)*		47.33 (D)*		-1.43%	
Alum Rock EB	37.27 (D) *		37.82 (D)*		1.47%	
McKee WB	56.76 (E)*		52.34 (D)*		-7.79%	
McKee EB	28.92 (C)*		16.51 (B)*		-42.91%	
Berryessa WB	47.27 (D)*		39.26 (D)*		-16.73%	
Berryessa EB	50.50 (D)*		37.55 (D)*		-34.48%	
Total System						
	Total Delay (veh-hr)		Total Delay (veh-hr)		Change in Total Delay	
Freeway & Arterial	2847.02		2642.36		-7.19%	

*(Level of Service)

Field Study

A field study has been conducted at one of the active bottlenecks at the selected site to field measure the changes in discharge rate (capacity) due to de-activation of queue override (*21*). Data were collected over ten weekdays. Figure 5 shows cumulative vehicle count curves for the AM peak on Thursday, May 12, 2016. The curves represent i) the mainline and on-ramp arrivals upstream of the bottleneck, and ii) the virtual departures downstream of the on-ramp merge. The cumulative count $V(t)$ is shown in oblique scale in order to make the excess accumulation (vertical displacement) and flow (slope) more noticeable by visual inspection. The oblique coordinate transformation of $V(t)$ is described by the following:

$$V(t) - q_0(t - t_0)$$

where,

q_0: specified reference value of flow
t_0: specified reference value of initial time

As shown in Figure 5, the freeway bottleneck outflow remained fairly high (9054 vph) during the time interval $t = 7{:}15$ and $t = 7{:}34$, and overlapping $V(t)$ curves indicates free-flow condition. However, queue override was activated because of on-ramp queue spillback from $t = 7{:}34$ to $t = 8{:}04$, and this reduced the freeway bottleneck discharge rate to 8176 vph (a reduction of 9.70% compared to the 9054 vph queue discharge prior to queue override). Preliminary results from the data analysis of the other test days indicate that avoiding queue override improves freeway capacity by 5 to 10% (*21*).

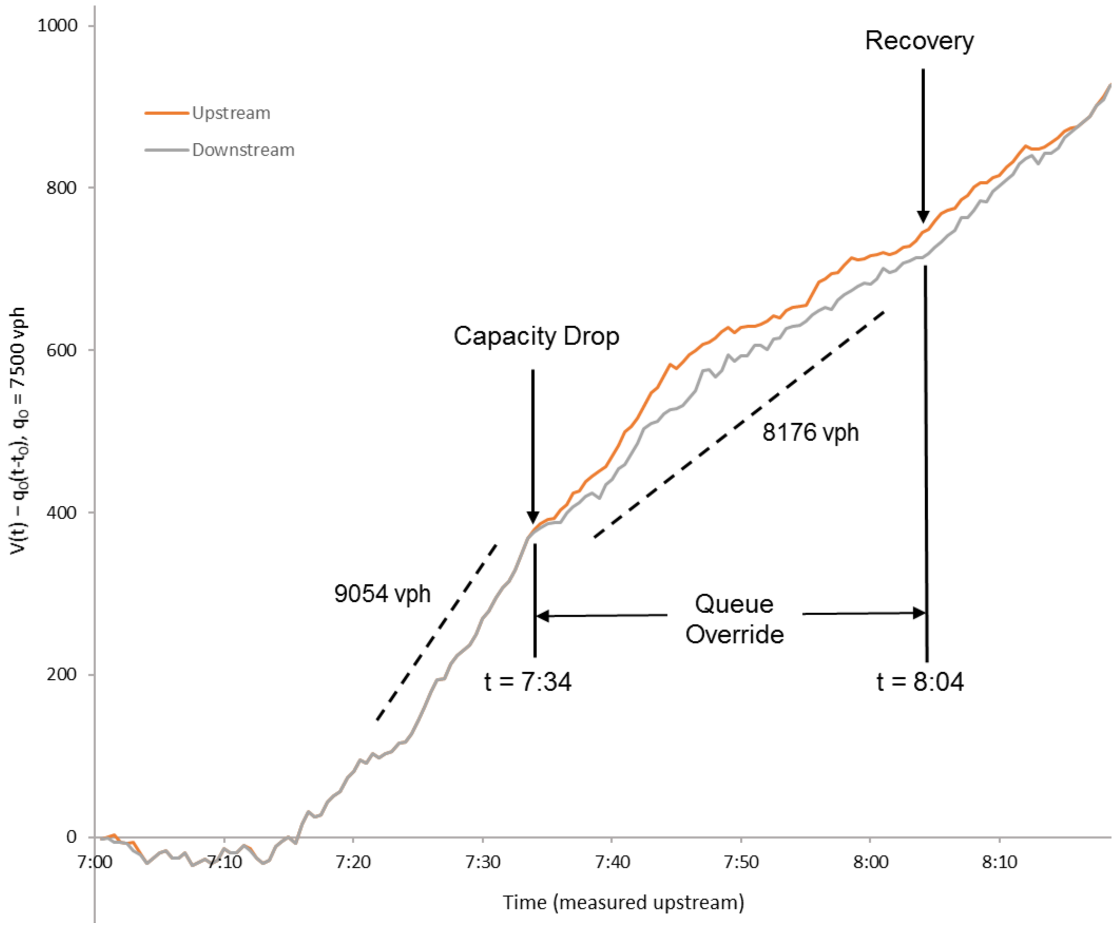

Figure 5 Cumulative vehicle counts (oblique scale) of May 12, 2016 (Thursday).

CONCLUSIONS

This study developed and evaluated a control algorithm for coordinating freeway ramp metering and arterial traffic signals. Improvements were achieved by managing the entry of vehicles onto the on-ramp through signal timing modifications at the arterial intersections nearby the freeway.

The proposed strategy was evaluated through simulation on a real-file freeway corridor in San Jose, California. The simulation results show the proposed coordination strategy eliminated the queue spillback on the metered on-ramps that activate the queue override. This resulted in 17.9% reduction on freeway delay. Supplemental field studies indicate that the proposed strategy may improve the freeway capacity by 5 to 10% percent. The delay on the parallel arterial was increased on the approaches feeding the on-ramps but decreased on the rest of signalized approaches.

The proposed algorithm is simple and readily implementable at most freeway corridors with metered on-ramps and adjacent arterials primarily used to facilitate freeway access. The proposed approach is not limited to any specific freeway ramp metering algorithm. For the adjacent arterial traffic signals, the algorithm addresses the existing signal timing plan's flaw of disregarding downstream queue storage space through incremental adjustments of cycle length and signal coordination.

Ongoing research consists of data analysis of the recently completed study on the effects of queue override on freeway capacity. The next step in the ongoing research is the field testing of the proposed strategy at the selected test site, and sensitivity analysis of the proposed strategy on a wide range of traffic demands and design characteristics of freeway arterial corridors.

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