Increasing Freeway Capacity by Efficiently Timing its Nearby Arterial Traffic Signals

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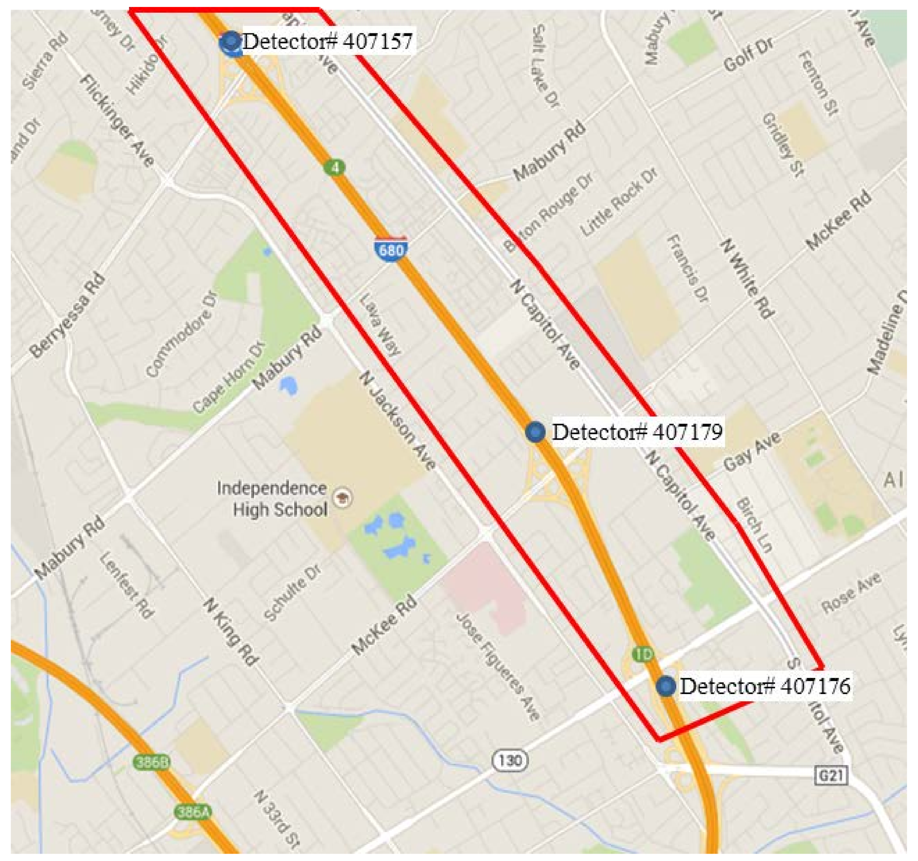
Introduction

Currently, freeway ramp metering and the adjacent traffic signals operate independently. The traffic signals respond to peak hour demand by employing long signal cycles to maximize intersection capacity. This leads to long green times and therefore large vehicle platoons entering the freeway on-ramps. As a result, metering the large influx of on-ramp traffic requires sufficient space to store queued vehicles. Unfortunately, land use constraints do not allow for longer on-ramps, and consequently lead to queue spillback prior to the long green time terminates. Due to the interference from queue spillback, vehicle movements completely stop during a portion of the green time, this causes reduction in the intersection capacity and severe delays. Most of the operational freeway ramp metering systems employ a “queue override” feature that is intended to prevent the on-ramp queue from obstructing traffic flow 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. This clears the on-ramp queue by temporarily turning off ramp metering. However, commonly employed metering is intended to maintain high capacity at freeway merge bottlenecks by restricting the flow of on-ramp traffic. Unfortunately, queue override reverses the intended benefit during the peak period, when the ramp metering is most needed. Therefore, it is important to control the arrival of arterial traffic to the freeway on-ramp. This would prevent on-ramp oversaturation and avoid queue override, thereby preserving the capacities of both the freeway bottleneck and the arterial intersection.

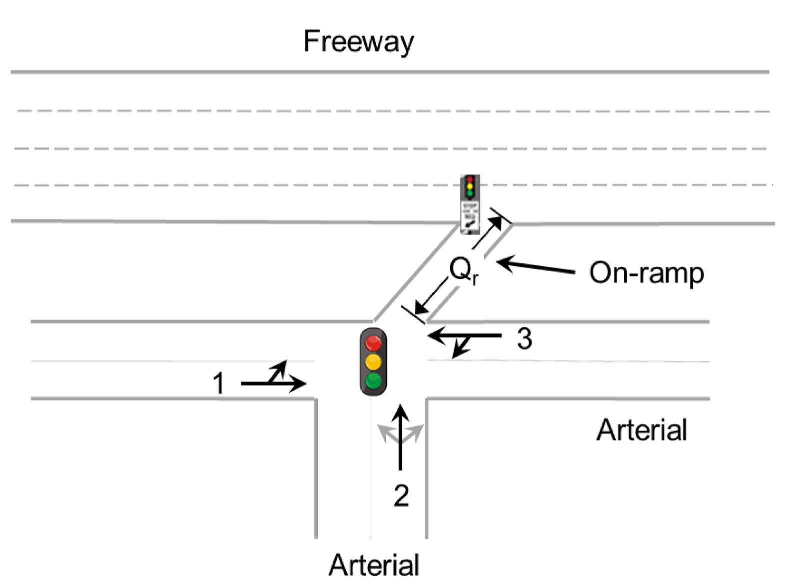
Case Study: I-680/Capitol Ave. Corridor

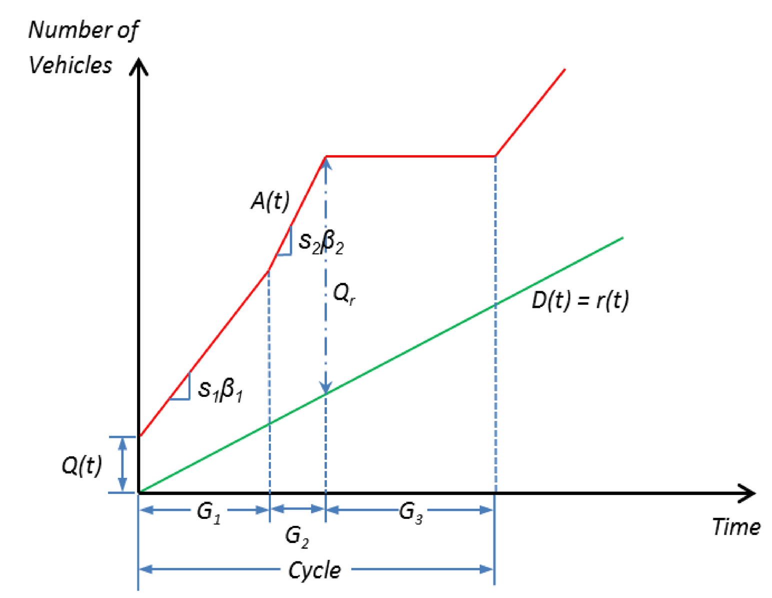
- Calibrated Aimsun micro-simulation using real world data from the morning peak (7:00 AM – 9:30 AM)
- 3 mile section from the Alum Rock Ave. interchange to the Berryessa Rd. interchange San Jose, CA
- 4 on-ramps and 3 off-ramps.
- High on-ramp demand is the main cause of the observed bottlenecks



Proposed Signal Control Strategy

- Readily implementable at most freeway-arterial interchanges
- Maintains existing ramp metering algorithms
- Reduces long cycle lengths
- Consider the example below
  - On-ramp is metered with a rate $r(t)$ and has queue storage capacity Q_r
  - On-ramp access for phase 1 and 2





Queuing Diagram of on-ramp:

- Phases 1 and 2 terminate when on-ramp excess accumulation reaches Q_r
- Phase 3 initiates early to allow for dissipation of on-ramp queue
- Maintains the same green distribution

Estimation of excess accumulation:

$$Q(0) = 0$$
$$Q(1) = Q(0) + A(1) - D(1)$$
$$Q(2) = Q(1) + A(2) - D(2)$$
$$\vdots$$
$$Q(t) = Q(t-1) + A(t) - D(t)$$

Mathematical expression:

$$Q(t-1) + g_1 \cdot s_1 \cdot \beta_1 + g_2 \cdot s_2 \cdot \beta_2 - g_1 \cdot r(t) - g_2 \cdot r(t) - 2l \cdot r(t) \leq Q_r$$

Substitute green time equations expressed in terms of cycle length:

$$g_1 = \frac{y_1}{Y} \cdot (C - 3l)$$
$$g_2 = \frac{y_2}{Y} \cdot (C - 3l)$$

Cycle length limit:

$$C \leq \frac{[Q_r - Q(t-1) + r(t) \cdot 2l] \cdot Y + 3l \cdot [\sum_{i=1,2} s_i\beta_i y_i - \sum_{i=1,2} r(t) y_i]}{[\sum_{i=1,2} s_i\beta_i y_i - \sum_{i=1,2} r(t) y_i]}$$

- May introduce more lost time but prevents spillback
  - Maintains saturation flow during green phases
- Avoids maximum bandwidth of through traffic
- Applicable to real-world multiphase signalized intersections
- Suitable for exiting ramp metering and signal controllers

Simulation Results

	Before		After		% 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	833.41	43104.13	740.64	44792.95	-11.13%	3.92%
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		47.33		-1.43%	
Alum Rock EB	37.27		37.82		1.47%	
McKee WB	56.76		52.34		-7.79%	
McKee EB	28.92		16.51		-42.91%	
Berryessa WB	47.27		39.26		-16.73%	
Berryessa EB	50.50		37.55		-34.48%	
Total System						
	Total Delay (veh-hr)		Total Delay (veh-hr)		Change in Total Delay	
Freeway & Arterial	2881.37		2727.19		-5.65%	

Concluding Remarks and Next Steps

Nearby arterial traffic signals can help avoid queue spillback at freeway on-ramps if the signal control systems were integrated with those of the freeway ramp metering and if the traffic signals were timed effectively based on the current ramp metering rate and on-ramp queue lengths. We recommend reducing the arterial signal cycle length and maintaining the same green time distribution such that only a short platoon feeds the adjacent freeway on-ramp every cycle. This can prevent queue spillback and subsequently avoid queue override by sending on-ramp bound traffic in smaller but more frequent platoons, without imposing significant penalties. This approach also increase the intersection capacity by avoiding wasted green caused by queue spillback.

A section of the I-680 Northbound freeway with Capitol Ave. as the parallel arterial in the city of San Jose, California was selected as the test site to evaluate the proposed signal control. The simulation results of the AM peak show the proposed signal control strategy eliminated the queue spillback on the metered on-ramps reduced the freeway, arterial, and system-wide delay, at a modest penalty for on-ramp bound traffic.

Acknowledgment

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