Issues Affecting the Performance of an Adaptive Traffic Control System in Oversaturated Conditions

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ABSTRACT
This paper identifies three broad issues that may negatively affect the performance of an adaptive traffic control system (ATCS) operating a coordinated arterial when oversaturated conditions arise on at least one intersection approach. First of the three issues is under-allocating green time to the critical (oversaturated) approach at the bottleneck intersection. Second, more green time may be given to the peak (critical) direction than necessary at intersections upstream of the bottleneck, and offsets that favor progression in the critical direction may be inappropriately used when the active bottleneck counters any benefits associated with green waves in the peak direction. Finally, offsets at intersections downstream of the bottleneck may be inefficiently set, resulting in additional delays for traffic departing the bottleneck and creating the potential for queue spillbacks to the bottleneck itself. Possible remedial actions involve reallocating green time to the critical approach until residual queues form on conflicting approaches (Issue 1), reducing the green time at signals upstream of the bottleneck in the peak direction so that their capacities are equivalent to the capacity of the bottleneck (Issue 2), and manually designing an offset plan that gives priority to traffic departing the bottleneck and protects the full green bandwidth for this traffic (Issue 3). These problems are then validated and analyzed on a five-mile adaptively controlled segment (using the LA-ATCS system) of Pacific Coast Highway in Los Angeles using field data from March–June 2013.
INTRODUCTION

Adaptive Traffic Control Systems (ATCSs) are becoming an increasingly popular tool among agencies wishing to address congestion on their street networks and major signalized corridors. Although literature has shown them to be effective at improving a wide range of performance metrics across a variety of undersaturated environments, results have been mixed in terms of handling oversaturated conditions. This paper will identify several issues that can degrade performance of ATCSs when oversaturated conditions arise, and will explore how these issues manifest themselves in a real-world adaptive system (LA-ATCS) implementation on Pacific Coast Highway (PCH) in northwestern Los Angeles. These issues include:

1. Inefficiently setting splits at the active bottleneck intersection.
2. Inefficiently setting splits and offsets at intersections upstream of the bottleneck.
3. Improperly setting offsets at intersections downstream of the bottleneck.

We begin by examining the gaps in current literature on the performance of ATCSs in oversaturated environments, to motivate our current work. We then give an overview of the PCH study site and data, and proceed to investigate each of the three issues identified above. For each issue, we provide a detailed description and an analysis of its occurrence on the PCH corridor. We end with a discussion of our results, their implications, and potential extensions of this work.

LITERATURE REVIEW

Although several analyses of adaptive systems already exist in literature, many are based on theoretical exercises and simulations rather than real-world data (1, 2, 3), and those that incorporate field implementations generally report broad performance measures without attempting to examine the mechanisms—particularly with respect to the handling of oversaturated conditions—that reduce the effectiveness of the adaptive systems apart from inadequate detection and agency-imposed constraints (4, 5, 6, 7, 8, 9, 10, 11).

In a recent NCHRP report on the state of practice for adaptive systems worldwide, the authors stated that 33% of ATCS users have found adaptive systems to be counterproductive in oversaturated traffic conditions, though it was beyond the scope of the report to examine the causal mechanisms underlying this (12). The authors also stated that 59% of ATCS users feel that adaptive systems reduce the duration of oversaturated conditions, although this may be attributed to an ATCS’s better handling of traffic in the time leading up to oversaturated conditions (which may delay the onset of oversaturation), rather than the system’s performance once oversaturation occurs.

The need for better ATCS operation when oversaturated conditions occur has been identified by other authors as well (1, 8), and although some possible solutions have been proposed (1, 5), additional research is still needed to examine how effectively they address the issues identified in this paper once implemented in the field.

FIELD DATA SOURCE

To illustrate each of the potential ATCS issues we have identified with respect to oversaturated conditions, we will be using field data from PCH in Los Angeles. This state highway is one of the primary traffic corridors linking the greater LA area with Malibu, Oxnard, and Ventura. The study segment begins at the connection to Interstate 10 in Santa Monica and ends at the Malibu city limit, with Topanga Canyon Blvd and California Incline serving as its boundary intersections (see Figure 1). On this 5-mile stretch, PCH has two to three lanes in each direction and average
daytime volumes (i.e., 6 AM to 8 PM) of 34,000 vehicles northbound and 38,000 southbound. It is maintained and operated by Caltrans, which uses LADOT’s LA-ATCS system to manage it. There are nine signalized intersections on the study segment, all of which are adaptively controlled.

The LA-ATCS system updates cycle lengths, splits, and offsets at each intersection once per cycle based on prevailing traffic conditions. Changes to each parameter are incremental and are based on detector data from each intersection, although the system has the ability to vary the size of these increments up to a certain threshold depending on how quickly traffic conditions are changing. Splits are based on traffic volumes and occupancies of each approach, offsets are based on minimizing the number of stops for the approach with the highest flows (with special priority given to coordinated directions), and a section-wide cycle length is based on the minimum time needed to keep all signals in a particular section operating below saturation. Loop detectors are required on all approaches to the major phases, and are ideally placed 200 to 300 feet in advance of the intersection to measure platoon arrival patterns (7).

In the case of PCH, the ATCS cycle times were constrained to 240 seconds during the AM and PM Peak, leaving only the splits and offsets available for adjustment at these times. There are stop bar detectors on all approaches at each intersection, with suitably placed green extension detectors on PCH and major cross-streets as well. For cross-streets, green extension was granted for vehicles crossing both upstream and stop bar detectors. This resulted in over-extension of cross-street green phases in some instances, but because this issue was present for both the “before” and “after” phases of the timing experiments and our conclusions are based on relative improvements, its presence is not expected to influence our findings. The base timing plans used as starting points for the adaptive optimizations were last updated within one year of the experiment.

Volume and occupancy data for each intersection are available in the form of 15-minute detector summaries, and travel time data are obtained using Bluetooth readers at five locations.
as shown in Figure 1. The Bluetooth units anonymously collect the unique identifiers of
discoverable Bluetooth devices within range (about 100 feet) every five seconds, which are
then used to estimate travel times. Signal timing parameters by cycle (splits, offsets, and cycle
lengths) are available for each intersection, and limited video data are also available at major
cross streets to monitor queue lengths.

Our analysis will focus on the PM Peak (2–8 PM) for typical weekdays (Tuesdays,
Wednesdays, and Thursdays) between March 5 and June 13, 2013. In the afternoon, the primary
bottleneck or critical intersection is Sunset Blvd, with northbound traffic being the heavier
oversaturated “critical” direction. Data were excluded in the cases of holidays and the weekdays
adjacent to them, major traffic incidents, and data quality or availability issues (e.g., days when
volume data were not collected due to field communication link failure). Additional data from
June 2012 will be used to supplement our analysis by enabling us to identify a suitable threshold
occupancy for evaluating when the Sunset Blvd approach is oversaturated.

ISSUE 1: INEFFICIENT SPLITS AT THE BOTTLENECK LOCATION

One feature of adaptive control systems is their ability to allocate green time proportionally to
each approach based on perceived demand obtained from detector readings. During oversaturated
conditions, however, the ATCS may incorrectly believe that the queues are still dissipating on all
approaches each cycle, and detector readings may suggest that green time utilization is equal on
all approaches when in fact it is not. This can happen if large gaps arise in discharging queues
as a result of (1) heavy vehicles and buses, (2) cars caught behind bicyclists and drivers making
parallel parking maneuvers, and (3) the split of mainline lanes of traffic into additional lanes
(turn pockets, auxiliary lanes, etc.) just upstream of the intersection. Longer loops at the stop bar
can address these issues to an extent, but may be impractical as extending the loop length may
also inhibit the ability to accurately measure occupancy.

In our analysis of LA-ATCS on PCH, we found that the adaptive system frequently gave
additional time to the cross-street at Sunset Blvd even after the startup queue cleared during
periods when persistent queues of 100 vehicles or more were present on the northbound PCH
approach. This may be because the adaptive system believed that the queues were clearing on
both approaches each cycle, based on the gap characteristics of PCH traffic and the widening
of PCH from two lanes to five (two turn pockets plus an auxiliary through lane) just before the
intersection. As a consequence, travelers on the mainline incurred large delays as crucial green
time was allocated instead to the side street at this critical bottleneck location.

To demonstrate this, we will describe a method to identify when residual queues have
formed on Sunset Blvd (i.e., the side-street), followed by a method for identifying when the
northbound mainline bottleneck is active at Sunset Blvd. We then demonstrate that the ATCS
is inefficiently allocating green time at the bottleneck intersection by showing that reallocating
some cycle time away from the side street to PCH increases the capacity of the bottleneck (on
PCH) without resulting in longer queues on the side-street.

When is there a persistent (residual) queue on the cross-street at the bottleneck
intersection?

We begin by showing that the Sunset Blvd approach is receiving more green time than necessary,
by confirming that long queues are not forming on the side street even when there are large
queues on the mainline. To accomplish this, we use occupancy data from the Sunset Blvd
FIGURE 2  Occupancy distributions at Sunset Blvd (left turns) comparing (a) relationship between residual queues and occupancy using data from 2012, and (b) relationship between phase duration and occupancy using data from 2013.
approach and check for periods when it exceeds a certain threshold. If this threshold is never crossed, we may reasonably conclude that the approach never has a long persistent queue and is not oversaturated. Determining this threshold can be difficult, however, because occupancies will naturally be higher for side-streets whose green time is a lower fraction of the cycle time. The proper threshold will therefore be intersection-specific (and timing-plan specific).

Using video footage of the queues on Sunset Blvd for June 7, 12, 13, and 14, 2012, we investigated the relationship between occupancies and residual queues on this approach. In the four days of queue length footage, there were no cycles out of the 516 where a residual queue of more than 7 or 8 vehicles was observed behind the stop bar in any lane, and only three cycles where a short residual queue of 7-8 vehicles in one lane was seen. The 15-minute occupancy data for periods with and without these short residual queues are plotted in Figure 2a, which implies 40% as a suitable conservative threshold for identifying when residual queues start to form.

Given the limited cases of queue formation in our data for Sunset Blvd, we also conducted a similar analysis of Topanga Canyon Blvd to supplement our results from Sunset Blvd. Unlike Sunset Blvd, however, long residual queues were frequently observed, and in this case we were able to partition the data from 1189 cycles into well-defined “No Queue” or “Residual Queue” categories. The “No Queue” category captured those 15-minute periods where visible residual queues were not observed the majority of the time and were less than 10 vehicles when present (215 periods total). In contrast, the “Residual Queue” category reflected 15-minute periods where visible residual queues exceeded 10 vehicles the entire time (52 periods total). Any 15-minute periods that did not qualify for either of these groups were considered indeterminate or transition periods, and were excluded (27 total).

From the occupancy distributions for Topanga Canyon Blvd, we find that 100% of the measured occupancies exceeded 0.40 when a residual queue was present, whereas only 9 out of the 215 measured occupancies exceeded 0.40 when a residual queue was not present. This suggests a threshold occupancy of about 40%, just as we obtained from the data for Sunset Blvd. Because the average green time per cycle for Topanga Canyon Blvd throughout the day is 35 seconds, whereas the average at Sunset Blvd is 27 seconds, and given that cycle length is kept the same between the two intersections, it is reasonable to expect the threshold occupancy at Sunset Blvd to be higher than the 40% threshold observed at Topanga Canyon Blvd. Thus, using a threshold occupancy of 40% is a conservative criterion to identify oversaturated conditions at Sunset Blvd.

We also note that side-street occupancy data were taken only from the left turn lanes, as these were the only lanes that were subject to oversaturation during the day.

When is there a persistent queue on the mainline at the bottleneck intersection?

Before we can evaluate whether the ATCS is choosing inefficient splits for the mainline while the northbound bottleneck is active at Sunset Blvd, we must first identify when the bottleneck is active each day. For this, we rely on detector data from the northbound PCH detectors at Bay Club Drive—a low-volume cross-street 2850 feet south of Sunset Blvd. Assuming a jam density of 180 veh/mi/lane, we find that approximately 100 vehicles/lane can be stored between Bay Club Drive and Sunset Blvd. Assuming a saturation headway of 2 seconds, this is enough storage to provide queue discharge for approximately 200 seconds of green time. Given that the through phase for the northbound mainline at Sunset Blvd has a 99th percentile duration of 191 seconds, we can reasonably conclude that any northbound queue spillover from Sunset Blvd to Bay Club Drive is in place.
Drive implies that a persistent queue is present at Sunset Blvd (i.e., the northbound mainline queue at Sunset Blvd will not completely clear in the next cycle).

Using occupancy and flow time-series data, we can evaluate when the northbound queue at Sunset Blvd has spilled back to Bay Club Drive. Because the average red-time for northbound PCH at Bay Club Drive is less than 10% of the entire cycle, the detectors on the mainline behave similarly to freeway detectors, meaning that we can estimate when queue spillover occurs at Bay Club Drive by looking for large increases in occupancy without an accompanying increase in flow. During these periods, we reasonably conclude that the northbound approach at Sunset Blvd is oversaturated. Thus, it is during these periods that the northbound mainline needs as much green time as possible at the bottleneck, without unduly penalizing traffic on competing movements.

From a data set of 16 days, we identified 9 with a well-defined period of oversaturation at Sunset Blvd based on occupancy and flow data at Bay Club Drive. After excluding 4 days for which the LA-ATCS splits data were not available, we were left with 5 days of usable data. When examining the real-time adaptive splits given to the Sunset Blvd side-street when the northbound bottleneck at Sunset Blvd was active on each of these days, we obtained an average of 30.2 seconds.

Confirming that the cross-street splits were too long at the bottleneck intersection

As part of a timing experiment conducted on the PCH study corridor in May and June 2013, a maximum green time of 24 seconds was imposed on the Sunset Blvd side-street split. As part of the same experiment, the cycle time was reduced from 240 to 230 seconds, such that the equivalent green time constraint under the original cycle length would have been a limit of approximately 25 seconds. Despite this reduction in effective green time by 16%, there was no increase in the occupancy measurements on the cross-street, as Figure 2b shows. In fact, the frequency of occupancies exceeding 40% dropped from 6.8% before the green time reduction to 4.5% after it. This indicates that the ATCS was giving more green time to the side-street than necessary to accommodate all its demand, meaning that it was inefficiently setting splits when considering that the mainline was experiencing long residual queues during these times. In fact, it is probable that even more green time could be reallocated from Sunset Blvd to PCH than the 5 seconds we experimented with before significant residual queues begin forming on the side-street.

Comparing volume data for the days with and without the 24-second limit on the Sunset Blvd split, we find that there was no drop in demand for the days when the split was constrained, with a two-tailed Student’s t-test yielding a p-value of 0.85. Thus, our results cannot be attributed to a drop in volume.

We therefore conclude that the adaptive system gives far more time than appropriate (30.2 seconds on average) to the Sunset Blvd side-street when the northbound bottleneck is active, whereas a split of less than 25 seconds was found to be sufficient to accommodate the side-street demands. Reducing the split for Sunset Blvd would increase capacity of the mainline at this critical location during those crucial periods when the northbound bottleneck is active. Even larger capacity increases could be achieved if the side-street split were reduced to the point where non-trivial residual queues began to form (i.e., queues longer than 1-2 vehicles), which may not be unreasonable given the presence of long queues on the mainline.
ISSUE 2: INEFFICIENT SPLITS & OFFSETS UPSTREAM OF THE BOTTLENECK

When a corridor-oriented adaptive system does not have the ability to determine which intersection is the critical bottleneck location, it can result in sub-optimal allocation of green time at locations upstream of the bottleneck.

When the critical bottleneck becomes oversaturated, the mainline splits at each intersection upstream would ideally be adjusted to reflect the capacity constraint at the bottleneck, since any additional green time given to the mainline in the critical direction at these locations results in no travel time benefit to the extra vehicles served (assuming no major trip ends exist between the upstream intersection and the bottleneck). When an adaptive system adjusts splits without awareness of whether the heaviest approach is feeding an active bottleneck farther downstream, the result is an over-allocation of time to the critical direction when the extra time is of no benefit to those drivers. Without a downward adjustment to the green time for the critical mainline direction, the bottleneck queue could eventually spill back past upstream intersections, further worsening delays as vehicles begin to block intersections and obstruct side-street traffic. Queue spillover at upstream intersections can also encourage the adaptive system to give more green time to the mainline at those locations (as vehicles sit on the stop bar detectors during the green phase, raising occupancy measurements for that approach and encouraging the algorithm to give it even more green time), when such a decision would not increase the productivity of the oversaturated direction and would increase delays for all conflicting movements.

Instead, more efficient operation of the intersections upstream of the critical intersection would involve reducing the mainline splits for the critical direction to the minimum needed to avoid starving the bottleneck downstream, and giving the time balance to conflicting movements such as side streets or opposing left turns. The mainline offsets could also be adjusted to accommodate platoon progression in the opposite non-critical direction (i.e., heading away from the bottleneck), since the presence of a residual queue at the bottleneck implies that progression has already broken down for the peak direction. To maintain efficient operation, these split and offset adjustments at upstream intersections would be reversed once the residual queue at the critical intersection begins to dissipate.

The following analysis of adaptive control on PCH at a major intersection upstream of the Sunset Blvd bottleneck shows that the offset remained unchanged regardless of whether the bottleneck was active, and that the northbound split was increased rather than decreased after the bottleneck became active. Both of these findings indicate that the ATCS is operating this intersection inefficiently when the downstream bottleneck is active.

Confirming that the northbound PCH split is too long at an intersection upstream of the bottleneck

To explore how the LA-ATCS system responds at upstream intersections when the northbound bottleneck at Sunset Blvd becomes active, we examine the splits and offsets for northbound PCH at Temescal Canyon Rd (see Table 1 and Figure 1). From this data, we find that the average northbound PCH split at Temescal Canyon Rd was 170 seconds when the bottleneck at Sunset Blvd was active, whereas it was only 163 seconds in the hour leading up to activation. In every case, cycle length remained unchanged at 240 seconds.

These findings indicate that 163 seconds of green time for northbound PCH at Temescal Canyon Rd is more than enough to avoid starving the downstream bottleneck at Sunset Blvd, and
**TABLE 1 Offsets and Northbound Through Splits for PCH at Temescal Canyon Rd (sec)**

<table>
<thead>
<tr>
<th>15-Min Period Start</th>
<th>3-13-13</th>
<th>3-20-13</th>
<th>3-26-13</th>
<th>5-1-13</th>
<th>5-2-13</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Split</td>
<td>Offset</td>
<td>Split</td>
<td>Offset</td>
<td>Split</td>
</tr>
<tr>
<td>2:00 PM</td>
<td>N/A</td>
<td>N/A</td>
<td>180</td>
<td>160</td>
<td>156</td>
</tr>
<tr>
<td>2:15 PM</td>
<td>N/A</td>
<td>N/A</td>
<td>168</td>
<td>160</td>
<td>162</td>
</tr>
<tr>
<td>2:30 PM</td>
<td>N/A</td>
<td>N/A</td>
<td>173</td>
<td>160</td>
<td>160</td>
</tr>
<tr>
<td>2:45 PM</td>
<td>N/A</td>
<td>N/A</td>
<td>171</td>
<td>160</td>
<td>157</td>
</tr>
<tr>
<td>3:00 PM</td>
<td>162</td>
<td>160</td>
<td>169</td>
<td>160</td>
<td>156</td>
</tr>
<tr>
<td>3:15 PM</td>
<td>149</td>
<td>160</td>
<td>144</td>
<td>160</td>
<td>156</td>
</tr>
<tr>
<td>3:30 PM</td>
<td>148</td>
<td>160</td>
<td>148</td>
<td>160</td>
<td>168</td>
</tr>
<tr>
<td>3:45 PM</td>
<td>154</td>
<td>160</td>
<td>166</td>
<td>160</td>
<td>159</td>
</tr>
<tr>
<td>4:00 PM</td>
<td>155</td>
<td>160</td>
<td>160</td>
<td>160</td>
<td>161*</td>
</tr>
<tr>
<td>4:15 PM</td>
<td>156</td>
<td>160</td>
<td>174</td>
<td>160</td>
<td>163*</td>
</tr>
<tr>
<td>4:30 PM</td>
<td>170*</td>
<td>160*</td>
<td>167*</td>
<td>160*</td>
<td>174*</td>
</tr>
<tr>
<td>4:45 PM</td>
<td>166*</td>
<td>160*</td>
<td>170*</td>
<td>160*</td>
<td>171*</td>
</tr>
<tr>
<td>5:00 PM</td>
<td>172*</td>
<td>160*</td>
<td>168*</td>
<td>160*</td>
<td>163*</td>
</tr>
<tr>
<td>5:15 PM</td>
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<td>160*</td>
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<td>160*</td>
<td>175*</td>
</tr>
<tr>
<td>5:30 PM</td>
<td>150*</td>
<td>160*</td>
<td>164*</td>
<td>160*</td>
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</tr>
<tr>
<td>5:45 PM</td>
<td>166*</td>
<td>160*</td>
<td>166*</td>
<td>160*</td>
<td>176*</td>
</tr>
<tr>
<td>6:00 PM</td>
<td>161*</td>
<td>160*</td>
<td>152*</td>
<td>160*</td>
<td>176*</td>
</tr>
<tr>
<td>6:15 PM</td>
<td>172*</td>
<td>160*</td>
<td>165*</td>
<td>160*</td>
<td>184*</td>
</tr>
<tr>
<td>6:30 PM</td>
<td>170*</td>
<td>160*</td>
<td>175*</td>
<td>160*</td>
<td>179*</td>
</tr>
<tr>
<td>6:45 PM</td>
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<td>160*</td>
<td>166*</td>
<td>160*</td>
<td>180*</td>
</tr>
<tr>
<td>7:00 PM</td>
<td>173*</td>
<td>160*</td>
<td>174</td>
<td>160</td>
<td>180*</td>
</tr>
<tr>
<td>7:15 PM</td>
<td>179</td>
<td>160</td>
<td>169</td>
<td>160</td>
<td>190*</td>
</tr>
</tbody>
</table>

Average for the period a persistent queue is present at the Sunset Bl bottleneck, and for the hour prior.

<table>
<thead>
<tr>
<th>Prior Hour</th>
<th>153</th>
<th>160</th>
<th>162</th>
<th>160</th>
<th>160</th>
<th>160</th>
<th>169</th>
<th>230</th>
<th>172</th>
<th>230</th>
</tr>
</thead>
<tbody>
<tr>
<td>During</td>
<td>166</td>
<td>160</td>
<td>165</td>
<td>160</td>
<td>174</td>
<td>160</td>
<td>171</td>
<td>230</td>
<td>172</td>
<td>230</td>
</tr>
</tbody>
</table>

*A persistent queue was present on the northbound mainline at Sunset Blvd during this 15-minute period.

N/A = LA-ATCS split and offset data not available during these periods.
that the ATCS is inappropriately exceeding this threshold while the downstream bottleneck is active. This inefficient split for northbound PCH at Temescal Canyon Rd does not improve travel times on the northbound side, encourages queue spillover at additional intersections upstream of the bottleneck at Sunset Blvd, and adds to delays on conflicting movements that could instead be taking advantage of this extra time (e.g., southbound PCH left turns, side-street movements). Given that 163 seconds was enough to allow a residual queue to develop at Sunset Blvd, the optimal amount of green time for the northbound approach at Temescal Canyon Rd would be even lower than this as long as the bottleneck at Sunset Blvd is active, assuming again that there are no major northbound trip ends between Temescal Canyon Rd and Sunset Blvd (and that no more time can be allocated to the critical direction at the Sunset Blvd bottleneck).

**Confirming that the PCH offsets are not being optimally set at an intersection upstream of the bottleneck**

From Table 1, we also observe that the offsets remained unchanged throughout the entire PM Peak period in every case, regardless of whether the Sunset Blvd bottleneck was active or not. Based on this finding, we conclude that the adaptive system is not intelligently switching between an offset plan (i.e., a set of offsets for the signals on PCH) that favors the critical northbound direction when the bottleneck is inactive, and an offset plan that accommodates the opposite southbound direction when the northbound bottleneck is active. Instead, the adaptive algorithm seems to use the same algorithm to compute offsets regardless of whether the bottleneck is active. As stated earlier, the southbound (non-peak) direction should be given priority if any only if the bottleneck is active on the critical northbound side. The net effect is unnecessary delays to southbound traffic whenever the Sunset Blvd northbound approach is oversaturated, or unnecessary delays to northbound traffic if the LA-ATCS offsets are already being selected to favor the non-critical southbound direction (an unlikely, but possible, scenario).

**ISSUE 3: IMPROPER OFFSETS DOWNSTREAM OF THE BOTTLENECK**

In addition to the problems we have already seen at the bottleneck intersection and those locations upstream of it, a third issue can occur for intersections downstream of the bottleneck when the adaptive system fails to properly identify the bottleneck intersection. Specifically, if the offsets are not set appropriately (i.e., if they are set according to the adaptive system’s default algorithm without consideration for the fact that one direction is handling departing traffic from an upstream bottleneck intersection), platoons departing from the critical bottleneck may incur additional, unnecessary delays as they get stopped at red signals farther downstream (i.e., the adaptive system does not give priority to the departing bottleneck traffic when computing offsets). Even more critical, though, is the possibility of a shock wave from such an interruption propagating back to the critical intersection while its green through phase is still active, thereby reducing the capacity of the bottleneck by preventing vehicles from proceeding through the intersection (despite the green signal) until the shock wave passes.

In this third analysis of PCH, we use time-space diagrams to demonstrate that the ATCS is choosing inefficient offsets for the downstream intersections, and follow up with travel time data to confirm that an alternate offset pattern would reduce delays. We begin by examining the LA-ATCS offset data for Sunset Blvd and the next three signals farther downstream (see Figure 1). Although the offsets at Porto Marina Way, Coastline Dr, and Topanga Canyon Blvd were generally consistent across all days of data, the offset at Sunset was found to alternate between
one of two vastly different values as shown in Figures 3a and 3b. For the offsets plotted in Figure 3a, which occurred 57% of the time, the northbound platoon from Sunset gets disrupted by the red signal at each downstream intersection, adding delay to the majority of vehicles in the northbound stream. The shaded portion of Figure 3a indicates the amount of delay imposed on all but the first 26 seconds of the northbound platoon (i.e., all platoon vehicles in the shaded region and to the right of it are delayed) departing Sunset Blvd due to inefficient offset selection at the downstream intersections. The spacing of the intersections in Figure 3 is based on free flow speeds of 45 mph, which reflect the mainline speed limit.

The offset pattern of Figure 3a also has the potential to reduce the capacity of the northbound bottleneck at Sunset Blvd. With these offsets, the northbound green phase at Porto Marina Way terminates 120 seconds before it does at Sunset Blvd. Given a spacing of 1550 feet between Porto Marina Way and Sunset Blvd, if the reverse-propagating shock wave were to move at a speed of 9 mph or faster, it would reach Sunset Blvd while the through phase is still active. The result would be a reduction in bottleneck capacity, as northbound vehicles would be prevented from passing through the intersection until the shock passes.

Figure 3b illustrates the alternate offset pattern selected by the adaptive system 43% of the time, which is unchanged from Figure 3a aside from the offset at Sunset Blvd. Note that with the offsets of Figure 3b, there are still large delays due to the poor offset choice at Topanga Canyon Blvd, but there is no longer a risk of shock wave propagation from Porto Marina Way back to Sunset Blvd (and consequently no risk of capacity reduction at the critical intersection), making this a better choice than the offsets shown in Figure 3a.

Confirming that the PCH offsets are not being optimally set at intersections downstream of the bottleneck
As part of a timing experiment conducted on the PCH study corridor in May and June 2013, we implemented a different set of offsets at the four intersections on PCH from Sunset Blvd to Topanga Canyon Blvd in an attempt to demonstrate that the ATCS offsets are not optimal (although they may represent local optima). The new offsets we used for the experiment were designed to minimize disruption of the northbound platoon departing Sunset Blvd, as shown in Figure 3c.

Once the new offsets were implemented, we used Bluetooth travel time data to examine the effects of the change. In the northbound direction, we observed a slight reduction in travel times as a result of the new offsets (see Figure 4a), which was expected given that either of the two LA-ATCS alternatives shown in Figures 3a and 3b imposed a large delay on northbound traffic between Sunset Blvd and Topanga Canyon Blvd. Bluetooth data for the southbound direction indicated slight improvements as well (see Figure 4b), which suggested that the ATCS’s offsets were providing no measurable benefit in travel time for either direction of PCH. The average improvement in travel time as a result of the new experimental offsets was 8.2 sec/veh in the northbound direction (an improvement of 2.4%) and 4.0 sec/veh southbound (also an improvement of 2.4%). A Wilcoxon Rank-Sum test indicated that the improvement in travel times was significant at a 5% level in the northbound direction 21% of the time (using 5-minute bins between 2 PM and 8 PM), and 18% of the time in the southbound direction.

In comparing volume data for the days with and without the new offsets shown in Figure 3c, we find that there was no statistically significant change in demand between the two periods. A two-tailed Student’s t-test yielded a p-value of 0.506 for the volumes past Topanga Canyon Blvd.
FIGURE 3  Northbound platoon progression downstream of Sunset Blvd. Offset pattern (a) was chosen by the ATCS 57% of the time, (b) was chosen by the ATCS 43% of the time, and (c) was implemented as part of a signal timing experiment on PCH.
Travel time median and inter-quartile range for adaptive system’s offsets (see Figures 3a and 3b)

Travel time median and inter-quartile range for experimental offsets (see Figure 3c)

FIGURE 4 Travel times on PCH (a) northbound from Coastline Dr to after Topanga Canyon Blvd, and (b) southbound from before Topanga Canyon Blvd to after Sunset Blvd.
Blvd in the northbound direction and a p-value of 0.997 in the southbound direction. Thus, the travel time improvements could not be attributed to a drop in traffic volumes on PCH.

We note that the Bluetooth data for the southbound direction captures travel times from before Topanga Canyon Blvd to after Sunset Blvd, while the northbound data is limited to the segment from Coastline Dr to after Topanga Canyon Blvd. This was a consequence of the limited detector placement (see Figure 1) and a desire to exclude the northbound queue before Sunset Blvd, as changes in the behavior of the Sunset Blvd bottleneck due to splits adjustments (which were another part of the timing experiment) would have had a confounding effect on travel times from before Sunset Blvd to Coastline Drive. Probe vehicles were also used to collect travel time data (a total of 195 trajectories were recorded over four days), but the Bluetooth data was determined to be a superior source owing to the richness of that data (i.e., over 200,000 travel time samples per week), which enabled us to perform statistical tests on the results.

Considering these results, we conclude that although the offsets identified by the ATCS may be local optima, engineering judgment should be used to check that they do not have any obvious issues related to progression (particularly in the critical direction) or shock wave propagation to the critical bottleneck. In the case of PCH, the ATCS offsets resulted in unnecessary delays to traffic in both directions, and put the critical bottleneck at risk of being blocked by a reverse-propagating shock wave from an inappropriately timed red signal 1550 feet downstream. A simple alternative offset pattern (see Figure 3c) reduced average travel times in both directions, and minimized the risk of shock waves from downstream intersections affecting bottleneck capacity.

DISCUSSION

We have seen here that adaptive systems may make inefficient choices regarding splits and offsets when oversaturated conditions occur. In this paper, we have identified three potential issues that can arise on an oversaturated, adaptively-controlled corridor, and have used data from PCH in Los Angeles to confirm their validity. Agencies and practitioners must take care to monitor for and address these issues to ensure that their major corridors are operated efficiently when oversaturated conditions are common.

At the bottleneck, improperly set splits can reduce mainline capacity during the critical periods when it is needed most, leading to increased delays, longer queues and later dissipation times. Downstream of the bottleneck, inappropriate offsets can add to delays in both directions and reduce the capacity of the bottleneck as well. Upstream of the bottleneck, inefficient splits and offsets can add to delays for side-street traffic and mainline traffic in the opposite direction. Causal mechanisms for each of these issues were discussed in the opening paragraphs of the respective sections earlier.

All three of these issues have been explored in the context of the ATCS-managed PCH corridor in northwestern Los Angeles, where we found that the adaptive system was giving the undersaturated side street at least 20% more green time than necessary at the critical intersection during periods when the mainline bottleneck was active. At the first major intersection upstream of the bottleneck, we also discovered inefficient operation with respect to the offset and northbound split on the mainline. In this case, we concluded that at least 7 seconds per cycle could be safely reallocated from northbound PCH to conflicting movements to reduce intersection delays without negatively affecting traffic in the critical direction. Finally, at the intersections downstream of the bottleneck, our analysis revealed that the offsets selected by the
ATCS were increasing travel times in both mainline directions by 2.4% and had the potential to reduce the capacity of the critical bottleneck as well.

Although the improvements achieved through our experimental changes may not be operationally significant in some cases (e.g., a travel time savings of 4-8 seconds), they provide proof of concept for the three issues we have identified. Knowing that these issues are valid concerns regarding ATCS operation is of much greater significance than the degree to which they degraded performance on PCH, because it suggests that these issues may materialize on other adaptive corridors as well, and may do so with much more severe consequences depending on specific traffic conditions and roadway configuration. For example, if the offsets downstream of the bottleneck are improperly set so that queues spill back to the bottleneck intersection for an extended period of time every cycle, the impacts on bottleneck capacity can be substantial.

The value of our findings, therefore, is primarily in recognizing the potential for these issues to affect adaptive corridors in general, and in showing that with proper treatments, these impacts can be mitigated. The key contribution of this work is not in the details of the impacts seen on PCH, but in the confirmation that these issues do in fact occur, and are such that there is no reason to expect that they are specific to LA-ATCS. Both diagnosis and treatment of these issues can be accomplished by following the procedures and logic used in our preceding analysis of each issue on PCH.

Specifically, our findings reinforce the importance of checking that the offsets and splits produced by an ATCS are reasonable, rather than trusting that the “black box” system will always find the best ones. Regarding offsets, the non-convex nature of offset optimization problems makes it possible that an adaptive system will narrow in on a local optimum through incremental adjustments while missing a much better distant global optimum. This was observed downstream of the bottleneck on PCH, where the ATCS jumped between two widely different offset patterns from one day to another.

Although the issues identified in this paper were examined in the context of an adaptively-controlled arterial rather than a grid network, they may still be applicable to adaptive network control as well. For example, when a particular intersection becomes oversaturated, care must be taken to ensure that queues from downstream nodes in the network do not spill back to the critical location and reduce its capacity. However, if the assumption of no major destinations between intersections is violated, the issues discussed here (and the potential improvements we considered) may no longer apply.

Future work may investigate how well other adaptive systems handle these issues, with particular emphasis on ATCSs that are specifically designed to handle such conditions (1, 10). Furthermore, researchers may examine to what extent these issues apply in the context of grid networks, and what changes are necessary to make the proposed improvements relevant to such networks. Future work may also focus on the prevalence of these issues in ATCS-controlled environments that suffer from oversaturation, to provide insight into how widespread the benefits of addressing these problems could be.
REFERENCES


