Development and Application of Control Strategies for Signalized Intersections in Coordinated Systems

ALEXANDER SKABARDONIS, ROBERT L. BERTINI, AND BRIAN R. GALLAGHER

Modern controllers permit traffic signals in coordinated systems to operate as pretimed, semiautomated or fully actuated to improve the traffic performance at the particular intersection or over the total system. Criteria were established for selecting the type of control, and timing strategies were developed for signals in coordinated systems. The proposed strategies were evaluated through simulation on 14 representative real-world arterials and grid networks. Based on the analysis of the simulation results, guidelines were formulated to assist practicing traffic engineers in selecting the most appropriate control strategies at specific intersections in coordinated signal systems. The guidelines were then applied to select the type of signal control at several intersections in the City of Los Angeles. The results from before and after field studies indicate that the recommended control strategies improved traffic performance, and the study guidelines can be used as an operating tool for traffic signal management.

Traffic signals on urban arterials and in grid networks operate in coordinated systems to provide for progression of major traffic movements. Most of these systems currently operate under fixed-time control. A significant number of modern microprocessor signal controllers are in use on these systems and permit traffic signals to operate as semiautomated or fully actuated. This flexibility in signal operations may improve the traffic performance at a specific intersection or over the total system, because actuated signals are able to respond to cycle-by-cycle variations in traffic volumes, and better assign green times to conflicting movements, thus reducing unnecessary delays and stops.

Practitioners wishing to select the best timing strategy for coordinated systems must choose among a variety of options, including whether to operate particular intersections as pretimed, semiautomated, or fully actuated. However, existing guidelines for selecting the type of signal control apply only to isolated intersections (1). There is a clear need for guidelines for determining the most efficient type of control at specific intersections within a coordinated system. Such guidelines are likely to be of particular use to traffic engineers who are considering what kind of controller to install at an intersection within a system of pretimed signals, as well as to those who manage systems that already include actuated controllers.

The development, evaluation, and application of procedures for selecting the type of control for intersections in coordinated signal systems are described in this paper. First, the major factors that influence the type of signal control were identified, and criteria were established for selecting candidate intersections at which to apply alternative control strategies. Various signal control strategies were designed accordingly. Next, the performance of each strategy was simulated on 14 real-world data sets using the NETSIM microscopic simulation model (2). The resulting estimates of delays and stops were then analyzed to determine the effectiveness of each strategy and to identify relationships between the factors affecting the choice of signal control. Implementation procedures were then developed and applied at several intersections in the City of Los Angeles.

The paper is organized as follows. First, the development and testing of control strategies for intersections along arterials are described. Next, control strategies for grid networks are presented. The following section presents the implementation procedures formulated based on the analysis of the simulation results. The field application and evaluation of the procedures in Los Angeles are presented next. The final section summarizes the study findings and recommendations.

CONTROL STRATEGIES FOR SIGNALS IN ARTERIAL SYSTEMS

Actuated signals may operate as coordinated signals by virtue of a fixed yield point (offset) in the background cycle—normally the end of the green of the arterial through phases (sync phase). The green times of the actuated phases vary on each cycle between a minimum and a maximum green time, depending on the arrival rate of vehicles and the vehicle extension interval (gap). The actuated phases must terminate at fixed force-off points in the cycle. If an actuated phase terminates before reaching its force-off (gaps-out), then the spare green time becomes available to the other phase(s).

The spare green time for an actuated phase is determined as follows (assuming that the actuated signal is properly timed):

\[ G_s = G(1 - x) \]  

(1)

where \( G \) is the green time under fixed-time control (s), and \( x \) is the degree of saturation (volume/capacity ratio).

If the sync phase receives the spare green time, the delay and stops on the arterial are reduced at the expense of the approaches with actuated phases. The intersection performance improvements depend on the traffic patterns between the arterial and cross-streets as well as the utilization of the spare green time. If most of the through-platoons do not take advantage of the spare green time then the delay benefits are negligible. Also, Equation 1 shows that at higher volume-to-capacity (v/c) ratios the spare green time is negligible, and no improvements are expected from semiautomated control. This discussion illustrates the complexity and combination of factors to be considered for developing signal control strategies. In general, the following major factors should be considered for selecting the type of control:

A. Skabardonis and R. L. Bertini, Institute of Transportation Studies, University of California, Berkeley, CA 94720-1720. B. R. Gallagher, City of Los Angeles Department of Transportation, 221 N. Figueroa Street, Suite 300, Los Angeles, CA 90012.
• Intersection Traffic Characteristics—Intersection degree of saturation (v/c ratio), ratio of the conflicting through critical volumes, turning movements, number and sequence of phases, and pedestrian activity;

• Intersection Design Characteristics—Layout and geometrics (T-intersection, number of lanes on the approaches, shared lanes), distance to adjacent intersections, and location in the system (e.g., boundary intersection); and

• System Characteristics—Length of the arterial, network configuration (e.g., crossing arterials, dense networks), variations in the arterial through volumes, and quality of progression.

The combination of these factors creates several scenarios for signal control:

• Fixed-Time Signal Control—Fixed-time signal control should be implemented at intersections operating close to capacity on all the approaches. Under semiactuated control, actuated phases would normally reach their force-offs (or maximum green times). However, if the actuated phase gaps-out because of slow moving vehicles or incidents, it would result in higher delays than pretimed control. Intersections may also operate as fixed-time, if an early start of the green would lead to additional delay and stops on the arterial at the downstream signals. For example, boundary intersections normally set the leading edge of the arterial green bandwidth. Operating these intersections as pretimed would not affect the progression along the arterial if the through green times of the internal semiactuated intersections start early, and it would also clear standing queues before the through platoon(s) arrive at the stop line. However, this strategy may not be appropriate for approximately equal directional arterial flows, or for boundary intersections with low volume actuated phases, because it would increase the total intersection delay.

• Semiactuated Signal Control—Semiactuated control is appropriate at intersections with low volumes on the actuated phases. Because the spare green time not used by the side-street traffic becomes available to the through arterial phase(s), delay and stops incurred by traffic on the arterial are reduced. Semiactuated signal control could also improve traffic performance at intersections that are critical for the arterial bandwidth (i.e., there is no green time available around the two-way green bands) by clearing any standing queues from the critical intersection before the main platoon arrives. Figure 1 shows a time-space diagram for a test arterial and the simulated number of stops at each intersection under fixed-time and semiactuated control. The largest reductions in stops from semiactuated operation occur at intersections 5 and 6, which are critical for the arterial bandwidth(s).

• Fully Actuated Signal Control—Fully actuated signals operate as uncoordinated. This type of control is most appropriate at intersections with complicated geometrics or phasing, which are operating close to saturation on all approaches, where the remaining signals can function as a system with a considerably lower cycle length (e.g., an intersection with eight phases in a network with mostly two or three phase signals). This strategy may reduce the total intersection delay, but it disrupts the progression and could create adverse effects at adjacent intersections. For example, queue spillbacks may occur at the upstream intersections for closely spaced signals because most of the traffic would arrive during the red time. Fully actuated control may also improve performance at intersections with low volumes, which could operate on a much lower cycle than the system cycle length, especially if they are located at the boundary of the system and do not influence the progression of major movements in the network.

Evaluation of Proposed Strategies

Seven arterials (Table 1) were selected for testing the proposed strategies. These data sets reflect a variety of geometrics, traffic patterns, speeds, and signal phasing. Optimal fixed-time plans (cycle

![Intersection Stops (Stops/hr)](image)

![MAXBAND: No. Michigan Ave.](image)

**FIGURE 1** Improvements from semiactuated control on Michigan Avenue.
length, splits, and offsets) were developed at each site by using the TRANSYT-7F model (3). The factors described above were applied to each of the test sites to select candidate intersections at which to apply alternative control strategies. Next, the performance of each strategy was simulated using the NETSIM model. The findings from the analysis of the simulation results are summarized below.

Detailed descriptions of the simulation experiments and analysis are given elsewhere (4).

Table 2 shows the average percent improvements in delay and stops from semiactuated control at selected intersections on arterials. Use of semiactuated signal control reduced the delay and stops at intersections with degrees of saturation on the actuated phases of less than 85 percent. The analysis of the simulation results indicated that benefits were greater for intersections with predominant arterial volumes (ratio of arterial to cross-street critical volumes greater than 1.3) by about 10 percent on average. The traffic performance worsened at a number of intersections with approximately equal volumes between the arterial and the side-street, and high opposed turning movements on the actuated approaches without turning lanes. In such situations, the actuated phases often gap-out prematurely, which results in higher delays for the side-streets. The consequent spare time reduces the delay on the arterial but does not improve the total intersection delay because the arterial and side-streets have approximately equal volumes.

### Table 2: Estimated Improvements From Semiactuated Control at Selected Intersections on Arterials

<table>
<thead>
<tr>
<th>Cross Street Traffic</th>
<th>Arterial Volume/Cross Street Volume (R)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>R ≤ 1.3</td>
</tr>
<tr>
<td>V/c ≤ 0.85</td>
<td>Delay</td>
</tr>
<tr>
<td></td>
<td>3.5%</td>
</tr>
<tr>
<td>V/c &gt; 0.85</td>
<td>1.0%</td>
</tr>
</tbody>
</table>

The largest improvements were obtained for T-intersections, intersections with significant turning traffic onto the arterial from upstream signals, and multiphase signals. Semiactuated control also resulted in about 11 percent reduction in delay and 15 percent reduction in stops at those intersections which are critical for the arterial bandwidth.

The majority of intersections with high degrees of saturation had similar performance under pretimed and semiactuated signal control because, most of the time, the actuated phases terminated at the fixed force-off points or reached their maximum green times. Reductions in delay of about 10 percent were obtained from semiactuated control at a few intersections which are critical for the arterial bandwidth. Again, this could be due to the premature termination of green under semiactuated control on the approaches with actuated phases.

Fully actuated control produced mixed results. It reduced total delay at a number of intersections, but the number of stops was increased. The delay and stops on the arterial generally increased at all locations because the system was broken into subsystems with different cycle lengths, therefore, continuous progression could no longer be maintained. In addition, much of the through traffic arrives at the fully actuated signal during the red time, and queues may thus spill back on the arterial links. The delay on the side-streets decreased in the systems in which shorter cycle lengths were implemented on some subsystems because vehicles arrive randomly on the side-streets and the delay depends on the cycle length and green time instead of the quality of progression on the arterial.

### CONTROL STRATEGIES FOR SIGNALS IN GRID NETWORKS

Operation of coordinated actuated signals in grid networks is more complicated than on arterials because there is a need to provide pro-

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**Table 1: Selected Test Sites for the Simulation Experiments**

<table>
<thead>
<tr>
<th>Data Set</th>
<th>No. of Signals</th>
<th>No. of Lanes</th>
<th>Average Spacing (m)</th>
<th>Two Phase</th>
<th>Four Phase</th>
<th>Eight Phase</th>
<th>Cycle Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Arterials</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1. El Camino Real</td>
<td>11</td>
<td>6</td>
<td>265</td>
<td>0</td>
<td>7</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>2. Fannin Blvd.</td>
<td>29</td>
<td>6/8</td>
<td>217</td>
<td>4</td>
<td>10</td>
<td>1</td>
<td>90</td>
</tr>
<tr>
<td>3. No. Michigan Ave.</td>
<td>24</td>
<td>6/6</td>
<td>96</td>
<td>10</td>
<td>1</td>
<td>0</td>
<td>90</td>
</tr>
<tr>
<td>4. University Avenue</td>
<td>30</td>
<td>4/6</td>
<td>140</td>
<td>3</td>
<td>4</td>
<td>1</td>
<td>80</td>
</tr>
<tr>
<td>5. Nicholasville Rd.</td>
<td>24</td>
<td>6/6</td>
<td>12</td>
<td>360</td>
<td>0</td>
<td>8</td>
<td>4</td>
</tr>
<tr>
<td>6. M Street</td>
<td>32</td>
<td>6/6</td>
<td>250</td>
<td>1</td>
<td>9</td>
<td>0</td>
<td>80</td>
</tr>
<tr>
<td>7. Walnut Creek Rd.</td>
<td>33</td>
<td>8/10</td>
<td>332</td>
<td>0</td>
<td>8</td>
<td>4</td>
<td>124</td>
</tr>
</tbody>
</table>

**Grid Networks**

<table>
<thead>
<tr>
<th>No. of Sites</th>
<th>Location</th>
<th>Average Spacing (m)</th>
<th>Two Phase</th>
<th>Four Phase</th>
<th>Eight Phase</th>
<th>Cycle Time (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Ann Arbor CBD</td>
<td>Ann Arbor, MI</td>
<td>155-855</td>
<td>27</td>
<td>1</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>2. Daytona Beach</td>
<td>Daytona Beach, FL</td>
<td>75-290</td>
<td>5</td>
<td>4</td>
<td>3</td>
<td>100</td>
</tr>
<tr>
<td>3. Memphis CBD</td>
<td>Memphis, TN</td>
<td>75-350</td>
<td>21</td>
<td>2</td>
<td>0</td>
<td>65</td>
</tr>
<tr>
<td>4. Ogden CBD</td>
<td>Ogden, UT</td>
<td>125-670</td>
<td>19</td>
<td>0</td>
<td>0</td>
<td>70</td>
</tr>
<tr>
<td>5. Post Oak</td>
<td>Houston, TX</td>
<td>135-825</td>
<td>5</td>
<td>1</td>
<td>7</td>
<td>120</td>
</tr>
<tr>
<td>6. Silver Lake</td>
<td>Los Angeles, CA</td>
<td>170-765</td>
<td>2</td>
<td>9</td>
<td>4</td>
<td>90</td>
</tr>
<tr>
<td>7. Walnut Creek CBD</td>
<td>Walnut Creek, CA</td>
<td>105-525</td>
<td>14</td>
<td>5</td>
<td>4</td>
<td>100</td>
</tr>
</tbody>
</table>

**Notes:**

1. Number of lanes includes left turn lanes on arterial.
2. Four phase signals: protected left turn on arterial only.
3. Eight phase signals: protected left turn on both arterial and cross streets.
gression on intersecting routes. Most signal systems use a yield point for the through phase(s) with the higher volume. For two-phase signals, this provides both a fixed point for progression in one direction and a fixed beginning of the green for the conflicting through phase without a yield point (Phase B). However, Phase B may gap-out because of dispersion or late start of the platoons from the upstream intersection. For multiphase signals, both the start and end of Phase B could vary on each cycle, because the phase may start early if the preceding left-turn phase gaps-out, and could terminate before reaching its force-off. Thus, several systems employ yield points for both through phases to guarantee cross-street coordination. Other systems use only force-offs as a means of coordination. This approach works only if at least one phase is continually extended to its force-off (i.e., the traffic for that phase is heavy enough to fully utilize the spare time in the cycle).

Control strategies for signals in grid systems can be formulated as an extension of the strategies for signals along arterials. For networks that include a single arterial or major parallel arterials, the same criteria can be used for choosing the type of control at specific intersections as for arterials. The following scenarios apply for intersections located in systems consisting of major crossing arterials or dense networks:

- **Pretimed Control**—Pretimed control is appropriate at intersections with high volumes on all the approaches (typically, intersections of two major arterials). Pretimed operation avoids the premature termination of green and maintains progression on both through routes. The same is true for intersections with lower but approximately equal volumes on both through movements that are critical from the progression standpoint.

- **Semiactuated Control**—This type of control should be implemented at intersections with unbalanced approach volumes because the approach with the higher volume would receive the spare green time, which reduces the total intersection delay. This strategy is also appropriate for multiphase signals with heavy through volumes. The spare green time from the termination of left-turn actuated phases is used by the through traffic.

- **Fully Actuated Signal Control**—Fully actuated control should be used for signals operating close to saturation on all approaches and where coordinating them with the rest of the system may substantially increase the delay on most of the other intersections (by increasing the system cycle length). Also, this strategy is appropriate for minor intersections that could operate on a much lower cycle than the system cycle length and are located at the edge of the system and do not influence the progression. Fully actuated control should also be implemented at signals located in dense networks with heavy turning movements, no major through routes, and consisting of a mixture of two-phase and multiphase signals. In such systems, signal coordination is of little benefit and the free signal operation would reduce the total intersection delay.

**Evaluation of Proposed Strategies**

Seven representative existing grid networks (Table 1) were selected for testing the proposed strategies. Optimal fixed-time plans were developed at each site using TRANSYT. The factors described above were applied to each of the test sites to select candidate intersections at which to apply alternative control strategies. Next, the performance of each strategy was simulated with NETSIM. The findings of the analysis of the simulation results are summarized below.

Pretimed control improved performance at intersections with most approaches operating close to saturation. Benefits were obtained at the intersections of crossing arterials with approximately equal volumes. Delay was reduced by an average of 27 percent, and stops dropped by 17 percent compared with semiactuated operation. Also, fixed-time control reduced the delay by 7 percent at the intersections of major crossing arterials that are critical to the progression of both routes.

Semiactuated operation improved the delay by an average of 5 percent and stops by 13 percent at intersections with unbalanced through volumes and degree of saturation less than 85 percent. The delay reductions from actuated operation of left-turn phases ranged from 2 to 8 percent among the different sites, depending on the through and left-turn approach volumes, number of phases, location of the intersection in the system, and the amount of turning traffic from the upstream intersection(s).

In dense networks, fully actuated control reduced delay by 21 percent compared to pretimed control and by 27 percent compared to semiactuated operation at multiphase signals located at the boundary of the system. The number of stops did increase by 4 to 8 percent, much less than the delay benefits, because the vehicles arrive randomly on the entry links of the system. Also, the delay at the low volume intersections was reduced by more than 30 percent compared to other types of control because of the much lower natural cycle length under free signal operations. The number of stops increased by 24 to 30 percent as a result of breaking up the progression. The delay improvements would probably overcompensate for the increase in stops, because most of the vehicles would probably stop at the downstream signal(s).

**IMPLEMENTATION PROCEDURES**

Guidelines for practical implementation of the study findings were formulated based on the analysis of the simulation results and a detailed review of operational experiences from researchers and practitioners. These guidelines are presented below for arterials and grid systems.

**Arterial Systems**

When choosing the type of signal control at intersections in arterial systems, one should first consider (in order of importance) the traffic patterns, intersection v/c ratio, the ratio of arterial to cross-street critical volume, and the proportion of turning movements on the arterial. Additional features that should be considered include design characteristics (T-intersections, shared lanes) and the quality of through progression. Table 3 provides guidelines for selecting pretimed or semiactuated signal control at specific intersections along arterials based on these criteria.

Fully actuated control may be implemented at intersections with complicated geometrics and phasing where the rest of the system can operate with a considerably lower cycle length (e.g., an eight-phase controller within a system with mostly two- to three-phase signals), and one or more of the following conditions apply:

- The signal spacing is long enough to avoid queue spillback because the platoons from the upstream and downstream signals would mostly arrive during the red time.
The intersection is located at the boundary of the system with heavy traffic entering the system.

The intersection is located in the middle of a long arterial with different traffic patterns between the upstream and downstream sections so that continuous progression is difficult to maintain (e.g., at freeway interchanges). Free signal operation would essentially create two subsystems that can be more efficiently timed independently.

Grid Networks

For grid network systems that consist of a single major arterial or parallel major arterials with minor streets, the selection criteria for signal operation are essentially the same as for arterials. This is also true for systems in which the majority of traffic movements follow a unidirectional path (e.g., N-S or E-W) even though major crossing routes may exist in the network.

Table 4 shows the recommended control strategies for signals located in networks that are dominated by crossing arterials, as well as systems with complicated traffic patterns, and for dense networks lacking well-defined through routes. The appropriate control strategy is selected based on the traffic levels (as expressed by the intersection v/c ratio) and turning movements (signal phasing).

### APPLICATION OF RECOMMENDED PROCEDURES

As part of a pilot field implementation study, the proposed procedures for selecting the control strategies for signals along arterials and within grid networks have been applied and evaluated at three test sites by the City of Los Angeles Department of Transportation (LADOT) (5). LADOT has prepared a Signal Mode Operation Worksheet, based on Tables 3 and 4, which classifies the intersection type and determines the appropriate mode of operation using intersection geometrics, traffic counts, and signal-timing parameters.

### Determining Intersection Control Strategy

First, for each intersection, the relationship between that location and adjacent signalized intersections is determined. From two-way, peak-

### Table 3: Proposed Signal Control at Specific Intersections along Arterials

<table>
<thead>
<tr>
<th>Cross Street Traffic V/c</th>
<th>Turning Movements*</th>
<th>Arterial Volume/Cross Street Volume ≤ 1.3</th>
<th>&gt; 1.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low - Moderate V/c ≤ 0.8</td>
<td>≤ 20 Percent</td>
<td>Actuated (1)</td>
<td>Actuated (2)</td>
</tr>
<tr>
<td></td>
<td>&gt; 20 Percent</td>
<td>Actuated (2)</td>
<td>Actuated</td>
</tr>
</tbody>
</table>

*Percent of Arterial Through Traffic

Notes:
1. Pretimed control at intersections with balanced volumes and high turning traffic from the cross street without exclusive lanes.
2. Pretimed operation if the early start of the green leads to additional stops and delay at the downstream signal. Also, boundary intersections may operate as pretimed if they are critical to the arterial's time-space diagram and define the leading edge of the green bandwidth.

### Table 4: Proposed Signal Control at Specific Intersections in Grid Systems

<table>
<thead>
<tr>
<th>Network Configuration</th>
<th>Intersection V/c</th>
<th>Number of Phases</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crossing Arterials</td>
<td>0.80</td>
<td>Pretimed</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.80</td>
<td>Pretimed</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Pretimed (2)</td>
</tr>
<tr>
<td>Dense Network</td>
<td>0.80</td>
<td>Fully Actuated (3)</td>
</tr>
<tr>
<td></td>
<td>&gt; 0.80</td>
<td>Pretimed</td>
</tr>
</tbody>
</table>

Notes:
1. The through phases may operate as pretimed if the volumes on each arterial are approximately equal, or semi-actuated operation leads to additional stops at the downstream signal(s).
2. Left turn phases at critical intersections may operate as actuated. Any spare green time from the actuated phases can be used by the through phases.
3. Intersections that require a much lower cycle than the system cycle length and are located at the edge of the network where the progression would not be influenced.
4. Intersections in dense networks with heavy turning traffic and a mixture of two phase and multiphase signals. In such cases, coordination is of little benefit and fully actuated operation reduces intersection delay.
hour volumes and link lengths, the coupling index, \( I \), is calculated for each link (6):

\[
I = \frac{V}{L}
\]

(2)

where \( V \) is the two-way, peak-hour volume (vph), and \( L \) is the link length (m/ft).

When \( I \) is greater than 0.5, signal progression is recommended. As the link volume increases, so does the need to provide signal progression. Based on the coupling index, the signal is classified as an isolated, arterial, crossing arterial, or dense network intersection:

1. Isolated: \( I \leq 0.5 \) for all directions.
2. Arterial: \( I > 0.5 \) for major street only.
3. Crossing Arterial: \( I > 0.5 \) for major street, and at least one side-street link.
4. Dense Network: \( I > 0.5 \) for both the major-street and minor-street links.

Following the intersection classification, the critical volume ratio, \( (v/c) \), and turning movement percentages are determined. The critical volumes are found by converting peak-hour volumes for each approach to volume per lane, then dividing the major street critical volume by the minor street critical volume to get a comparison of the relative importance of each street. The \( v/c \) ratio can be calculated using the Highway Capacity Manual (7) operations method for signalized intersections (7), or some other method, to determine how likely the approach is to function as pretimed. The turning movement percentages are obtained from traffic counts.

Next, the quality of signal progression is determined using a time-space diagram to identify the green bandwidth at the target intersection and its effect on the overall progression of the arterial. Alternatively, the quality of progression can be determined by matching the platoon arrival patterns at the intersection to one of the six arrival types used in the Highway Capacity Manual (7). An optimized time space diagram should be used if necessary, rather than the existing time-space diagram, as it is easier and less costly to change an offset compared to actuating the intersection approach(es) to achieve a similar effect.

After the intersection type is established, and the critical volume ratio, \( v/c \) ratio, turning percentages, and quality of progression are found, the best signal operational strategy is selected from the most appropriate of the two signal-control tables (Tables 3 and 4). Depending on the variability of traffic patterns during the day, multiple worksheets can be prepared to justify a combination of signal operation modes used at different times of the day.

Field Implementation Study

The Signal Mode Operation Worksheet was used to determine the peak-hour control strategy for several signals in the City of Los Angeles. For 7th Street and Vermont Avenue, and Sheldon Street and Hollywood Freeway Northbound Ramps, the type of control was chosen on an intersection-specific basis. One arterial, Laurel Canyon Boulevard from Mulholland Drive to Hollywood Boulevard (five intersections) was also evaluated to identify the appropriate operation during both the peak and late night periods.

The effectiveness of the recommended control strategies was evaluated using a combination of intersection delay measurements and floating car studies. Before traffic counts and delay data were collected for each location. Once the signal mode operation worksheet was completed, the signal timing parameters were modified in the field to reflect the recommendation of the worksheet, and an additional set of after delay data were collected in order to evaluate the control strategy. The procedures from the Manual of Traffic Engineering Studies (8) were followed, and all of the data were collected within the same week, during the same times of day.

7th Street and Vermont Avenue

The intersection of 7th Street and Vermont Avenue is located within a dense grid network of 250 signalized intersections, just west of downtown Los Angeles. There are closely spaced signalized intersections on all four legs, within 122 m (400 ft) to 238 m (780 ft). The coupling indices for the four links range from 1.16 to 3.76, verifying that the intersection is located within a dense signal network. The ratio of critical volumes for Vermont Avenue to 7th Street is 2.83, indicating that some preference should be given to Vermont Avenue. A capacity analysis done for the intersection revealed that there was a capacity problem for the southbound left-turn movement (which had an estimated v/c ratio of 1.3), and that the v/c ratio for most approaches was about 0.67. The existing operation during the peak hours was semiautomated, but was changed to pretimed based upon the results of the worksheet.

Sheldon Street and Hollywood Freeway Northbound Ramps

The Hollywood Freeway forms a T-intersection with Sheldon Street, and originally operated as fully actuated. There are signalized intersections 289 m (947 ft) and 486 m (1,596 ft) away. Because the coupling indices were 1.58 and 0.96, the intersection was classified as an arterial, instead of isolated. With the critical volume ratio of 1.10, very little arterial turning traffic, near perfect progression from an optimized time space diagram, and a v/c ratio of 0.46, the optimal operational mode of the signal was found to be semiautomated.

Laurel Canyon Boulevard from Mulholland Drive to Hollywood Boulevard

The test section consists of five intersections along a canyon road that serves as a freeway alternate between the San Fernando Valley and Hollywood. This arterial is fairly isolated due to geographical and signal system boundaries, so the adjacent intersections (except those on Laurel Canyon) were not considered for this study. Although the spacing between many of the intersections is over 0.8 km (0.5 mi), heavy volumes during the peak period produced coupling indices greater than 0.5. The critical volume ratios were all high because the minor streets serve residential areas, whereas Laurel Canyon has peak hour volumes up to 1,500 vehicles per hour per lane. The v/c ratios for the side streets were usually low, and turning percentages were also low. During the peak hours, Laurel Canyon Boulevard, functions as an arterial, but in the off-peak, the volumes drop considerably, reducing the coupling index enough to suggest that fully actuated operation would be best most of the day. The Signal Mode Worksheet values are shown in Table 5. The results recommended that the five intersections be semiautomated and coordinated during the
peak hours, but in the off-peak hours, the three northern signals should run as fully actuated.

Evaluation of Field Implementation Results

At 7th Street/Vermont Avenue, and at the Sheldon Street/Hollywood Freeway northbound ramps, intersection delay for all of the approaches was manually measured. For Laurel Canyon Boulevard, floating car studies were conducted to determine the measures of effectiveness on the arterial. Intersection delay studies were performed during the same time to quantify the delay on the side streets. Before and after data were collected in the peak and late-night. Tables 6 and 7 provide an indication of the benefits produced by changing the signal operation to the mode determined by the recommended procedures.

At 7th Street and Vermont Avenue, the existing operation was semiactuated, with detectors and pushbuttons for 7th Street (east-west). The v/c ratios were high, and there was a lot of pedestrian activity, so the signal was basically functioning as pretimed. Changing to pretimed operation provided a longer average green for 7th Street and improved signal progression for both approaches. The field data show that the average delay has been reduced by 42 percent, with major improvements for the westbound, eastbound, and northbound approaches, at the expense of southbound.

The intersection of Sheldon Street and the Hollywood Freeway northbound off-ramp was running fully actuated. The procedures suggested a change to semiactuated, most likely to provide signal coordination along Sheldon Street. However, after changing the signal control, the intersection delay increased by 11 percent. Once the signals were put on a cycle length, the southbound movement had to wait for a yield point before getting the green, whereas previously the first actuation would often result in an instant yellow for Sheldon Street, followed by green for the off-ramp. The delay for the southbound approach increased from 10 to 22 seconds/vehicle. Because the off-ramp had about 25 percent of the total volume, this increase in delay outweighed any delay savings to Sheldon Street from the improved signal progression.

Laurel Canyon was studied as an arterial, with five intersections being adjusted based on the recommended procedures. Initially, the signals on Laurel Canyon were running semiactuated, except at Mulholland Drive, which was fully actuated. For peak hours, the procedures recommended semiactuated control on all five intersections. The off-peak hours were also evaluated, and the model suggested that Hollywood Boulevard and Mt. Olympus Drive be semiactuated and coordinated, and the other three signals to the north should be changed to fully actuated.

Table 7 lists the delay values for northbound and southbound Laurel Canyon Boulevard that were obtained from the floating car runs during the a.m. peak period. There was a 24 percent reduction in delay along Laurel Canyon Boulevard and a 14 percent reduction in stops. The signal coordination allowed the platoons to reach the intersections on the green, rather than stop for a single vehicle exiting from a fully actuated side street. As expected, the delay to most of the side street approaches increased by about 10 percent. This may be due to reducing the opportunities for right-turn on red due to better utilization of the green time on the arterial; the highest increase in delay, where the traffic volumes are also the heaviest for any side-street approach, was at Mulholland Drive, which was running fully actuated but was changed to semiactuated.

<table>
<thead>
<tr>
<th>Approach</th>
<th>Measured Delay (sec/veh) Before</th>
<th>Reduced Total Average Delay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>W/B</td>
<td>29.38</td>
<td>14.4</td>
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<tr>
<td>E/B</td>
<td>31.68</td>
<td>18.39</td>
</tr>
<tr>
<td>N/B</td>
<td>12.98</td>
<td>2.43</td>
</tr>
<tr>
<td>S/B</td>
<td>7.03</td>
<td>13.57</td>
</tr>
<tr>
<td>Total</td>
<td>15.20</td>
<td>8.76</td>
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</tbody>
</table>

Table 7 Comparison of Existing and Proposed Signal Controls for Laurel Canyon Boulevard

<table>
<thead>
<tr>
<th>Case</th>
<th>Approach</th>
<th>Measured Delay (sec/veh) Before</th>
<th>Delay (veh-hr/hr)</th>
<th>Reduced Total Average Delay (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Before</td>
<td>N/B</td>
<td>12.2</td>
<td>3.29</td>
<td>17.93</td>
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<tr>
<td></td>
<td>S/B</td>
<td>35.5</td>
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<td>Total</td>
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<td>26.28</td>
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<td>17.93</td>
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<tr>
<td>After</td>
<td>N/B</td>
<td>11.8</td>
<td>3.18</td>
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<td></td>
<td>S/B</td>
<td>25.3</td>
<td>10.44</td>
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<tr>
<td>Total</td>
<td></td>
<td>19.96</td>
<td>13.62</td>
<td>24.05%</td>
</tr>
</tbody>
</table>
DISCUSSION

Control strategies were developed for signalized intersections in coordinated systems and were evaluated through simulation on 14 representative real-world arterials and grid networks. Based on the analysis of the simulation results, guidelines and application procedures were formulated to assist practicing traffic engineers in selecting the appropriate type of control at specific intersections in coordinated signal systems. The guidelines were applied to select the type of signal control at several intersections in the City of Los Angeles. The results from before and after field studies indicate that the recommended control strategies improved traffic performance. Ongoing field application of the procedures in Los Angeles and elsewhere will result in refinement of the guidelines for general application as an operating tool for traffic signal management.

The effectiveness of coordinated actuated signals depends significantly on the procedures for determining the signal control parameters (yield points, force-offs, and maximum green times). Inappropriate settings of those parameters may degrade intersection performance by not effectively utilizing the spare green time and not providing sufficient green times for the actuated phases. In this study, optimal control parameters for coordinated actuated operation were determined for fixed-time plans using procedures developed as part of the same study and reported elsewhere (4,9).

The signal operating strategies developed and tested in this study are applicable to and easily implementable in most signal control systems currently in operation. The strategies are not directly applicable to traffic responsive systems such as SCOOT and SCATS. These control systems have demonstrated that they can improve overall system performance, but their implementation requires significant hardware and software investment. There is a need to develop guidelines for when/where to implement traffic responsive control and to estimate the impacts for both the total system and individual intersections.

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REFERENCES