Advanced Traffic Signal Control for Diamond Interchanges

by

Roelof J. Engelbrecht
Associate Transportation Researcher
Texas Transportation Institute
Texas A&M University System
3135 TAMU
College Station, TX 77843-3135
Phone: 979-862-3559
Fax: 979-845-9873
E-mail: roelof@tamu.edu

and

Kirk E. Barnes
Transportation Operations Engineer
Bryan District
Texas Department of Transportation
1300 N. Texas Ave
Bryan, TX 77803-2760
Phone: 979-778-9756
Fax: 979-778-9703
E-mail: kbarnes@dot.state.tx.us

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Roelof J. Engelbrecht and Kirk E. Barnes

Roelof J. Engelbrecht
Texas Transportation Institute
Texas A&M University System
3135 TAMU
College Station, TX 77843-3135
Phone: 979-862-3559
Fax: 979-845-9873
E-mail: roelof@tamu.edu

Kirk E. Barnes
Texas Department of Transportation
1300 N. Texas Ave
Bryan, TX 77803-2760
Phone: 979-778-9756
Fax: 979-778-9703
E-mail: kbarnes@dot.state.tx.us

Abstract. Most modern traffic signal controllers contain “advanced” features that are not often used but may improve traffic operations under certain conditions. The Texas Transportation Institute recently completed a research project for the Texas Department of Transportation investigating how diamond interchange operations can be improved by using advanced controller features. The research evaluated advanced features available in the traffic signal controllers currently used for diamond interchange control in Texas. Eight potentially useful controller features were identified. The effectiveness of these features was evaluated using hardware-in-the-loop traffic simulation. The researchers considered the applicability of these features under different geometric and demand conditions and investigated the effect of detector technology and human factors issues on implementation. One of the main findings of the research was the potential usefulness of the separate intersection diamond control mode. The separate intersection diamond control mode is not commonly used, but if applied judiciously under specific geometric and demand conditions it can provide more efficient control than the three-phase or four-phase sequences that are typically used in Texas. The free separate intersection mode can significantly reduce stops at interchanges under low-volume conditions, especially if permissive interior left turns are allowed and steps are taken to reduce the activation of the interior left-turn phases. The coordinated separate intersection mode has the potential to provide more efficient operation than the three-phase or four-phase sequence under certain conditions that can be determined with signal optimization software such as PASSER III, Synchro, or TRANSYT-7F.

INTRODUCTION

Due to financial, environmental, and spatial constraints it is becoming increasingly difficult to improve diamond interchange operations through geometric improvements alone. An alternative to geometric improvements is to maximize the use of technology, for example by better using the capabilities of currently deployed traffic signal controllers. Modern traffic signal controllers include some advanced features that are not often used but have the potential to improve traffic operations at signalized diamond interchanges under certain conditions if applied correctly.

The Texas Transportation Institute (TTI) recently completed a research project for the Texas Department of Transportation (TxDOT) investigating how diamond interchange operations can be improved by using advanced controller features (1). This research project explored traffic signal control at diamond interchanges and in particular how the features of existing traffic signal controllers can be used to improve traffic operations at diamond interchanges. The researchers evaluated advanced features available in the traffic signal controllers currently used for diamond interchange control by TxDOT.
TxDOT typically uses a single traffic signal controller to control both sides of the interchange. Using a single controller holds certain benefits, including reduced deployment cost at some locations, easier troubleshooting and maintenance, and the ability to operate the interchange in a fully-actuated (free) mode while maintaining internal progression (2).

Since freeway frontage roads are typically provided in Texas where this research was performed, this paper will use the term “frontage roads” when referring to the interchange approaches providing access to and egress from the freeway. Except where specifically noted, the research results are also applicable to facilities without frontage roads. For interchanges without frontage roads, the term “ramp” can be substituted for the term “frontage road” except where noted.

RESEARCH METHODOLOGY

The research included a study of the TxDOT traffic signal controller specification (3) and the controllers that met the specification at that time. This study identified a number of candidate controller features for advanced diamond interchange control. These features were then tested on the actual traffic signal control hardware to ensure that they operate as understood from the documentation. The testing was conducted in the TransLink® Research Center Laboratory, a state-of-the-art facility at TTI that is designed and equipped for advanced research into traffic signal control equipment. The laboratory includes, among others, traffic signal controllers from multiple vendors, a variety of controller assemblies (cabinets), as well as traditional and next-generation controller testing equipment.

The CORSIM microscopic simulation model (4) was used to evaluate the controller features. The evaluation was conducted for generic interchange geometry and demand conditions as well as for the geometry and demand conditions at a number of actual interchanges in Texas. Since CORSIM’s internal traffic signal controller emulation does not implement the diamond interchange control specified by the TxDOT traffic signal controller specification, a technique called hardware-in-the-loop simulation was used to replace the internal CORSIM signal control logic with real signal controller hardware containing the features under evaluation.

Hardware-in-the-loop simulation refers to a computer simulation in which some of the components of the simulation have been replaced with actual hardware. Hardware-in-the-loop simulation has been successfully used in the aerospace and defense industries for a number of years, and has recently become popular in the traffic simulation field (5,6,7,8,9,10,11). TTI has used hardware-in-the-loop traffic simulation extensively in the analysis of diamond interchange operations since 1995 (12,13,14).

A simulation-based approach was selected for evaluation purposes due to (i) the extensive measures of effectiveness reported by the simulation model, (ii) the reproducibility of simulated results, and (iii) the ability to evaluate different scenarios. Simulation thus allows a very efficient evaluation of the operational effects of a particular controller feature. For a specific combination of geometry and demand, the same simulation could be run with and without the controller feature under consideration. Since the simulation model could reproduce vehicle demand exactly, it was possible to isolate the effect of the control feature from normal day-to-day variations in traffic demand, which is impossible to do in a field evaluation where the natural variation in traffic demand cannot be controlled (15).

ADVANCED DIAMOND CONTROL FEATURES

The research identified the eight controller features that are compatible with the diamond operational mode and can potentially improve diamond interchange operations under certain conditions:

- separate intersection mode,
- diamond phasing sequence change,
- conditional service,
- dynamic maximum green times,
- dynamic split,
- volume-density control,
- alternate maximum green and passage times, and
- adaptive protected-permissive left turns.
Due to space restrictions this paper will focus mainly on the separate intersection mode feature, which will be described in detail. An evaluation of the separate intersection mode at two interchanges will also be presented. The diamond phasing sequence change feature will be described, but no evaluation results will be reported. The operation of the remaining six features will be summarized. The inquiring reader is encouraged to refer to the research report (1) for a detailed description of the eight controller features, as well as application guidelines that address the applicability of each feature under different geometric and demand conditions and the compatibility with various detection technologies. Complete evaluation results are also provided in the research report.

Figure 1 indicates the phase numbering scheme that will be used throughout the discussion in this paper.

![Figure 1 Signal phase numbering scheme for diamond interchanges.](image)

**FIGURE 1** Signal phase numbering scheme for diamond interchanges.

**TxDOT Diamond Control Modes**

The TxDOT controller specification defines three diamond interchange control modes for implementation on a single controller: (i) four-phase mode, (ii) three-phase mode, and (iii) separate intersection mode. These control modes are shown in Figures 2, 3, and 4, respectively. The phase sequences shown in Figures 2(a), 3(a), and 4(a) are simplified in that they do not include phases 3 and 7 and their related clearance phases defined in the TxDOT specification. The phase sequences resulting from skipped phases are also not shown.

The four-phase and three-phase modes have been described in literature (16,17,18) and are often used in field deployments in Texas (19). The separate intersection mode is less well known and not used as often as the three-phase or four-phase mode. After a short summary of the four-phase and three-phase modes, the separate intersection mode will be discussed in detail.

**Four-Phase Mode**

In the late 1950’s, TTI developed a four-phase diamond interchange phasing sequence that later evolved into the four-phase mode in the TxDOT controller specification (16). The four-phase mode is best suited for application at relatively narrow interchanges, and typically performs best at interchanges with widths of 400 feet (120 m) or less (19). The four external approaches to the interchange (φ2, φ4, φ6, and φ8) are served sequentially in a clockwise direction, together with the appropriate downstream internal left-turn movement (φ1 or φ5) required for progression. Ideally, all movements except U-turns are permitted to move through the entire interchange upon receiving green.
(a) Phase Sequence

(b) Controller Ring Structure

Note:
*Phases 12 and 16 are transition intervals during which the frontage road and arterial on opposite sides of the interchange can be active at the same time.

FIGURE 2  Simplified four-phase diamond interchange phasing.

(a) Phase Sequence

(b) Controller Ring Structure

Note:
*Phases 10 and 14 are used for conditional service and as clearance phases in the absence of calls on phase 4 or phase 8.

FIGURE 3  Simplified three-phase diamond interchange phasing.
Efficiency is improved by providing two transition intervals ($\phi_{12}$ and $\phi_{16}$) where the frontage road and arterial movements on opposite sides of the interchange are serviced simultaneously. Progression through the interchange is maintained by limiting the duration of these transition intervals to less than the travel time through the interchange. Four-phase control can be implemented in both the free (fully actuated, noncoordinated) and coordinated mode.

### Three-Phase Mode

The three-phase mode was one of the first phasing strategies implemented at signalized diamond interchanges (18). The TxDOT controller specification requires that the three-phase mode operate with lagging internal left-turn movements ($\phi_1$ and $\phi_5$). The three-phase mode typically performs best at relatively wide interchanges with widths greater than 600 feet (180 m), where the demand is directionally balanced and not very heavy (19). The three-phase mode is most suited for application under these conditions because progression for the frontage road left-turn movements are provided when the travel time through the interchange exceeds the duration of the frontage road phases ($\phi_4$ and $\phi_8$), as would be the case for wide interchanges with relatively short front frontage road phases. Like four-phase control, three-phase control can be implemented under both free and coordinated mode.

### Separate Intersection Mode

The separate intersection mode is less well known and not used as often as the three-phase or four-phase mode. In the separate intersection mode defined by the TxDOT controller specification, interior left turns ($\phi_1$ and $\phi_5$) lead the external arterial through movements ($\phi_2$ and $\phi_6$). One ring controls each side of the diamond interchange, and no barriers exist between rings. Under free (noncoordinated) control, the two rings operate independently of each other, and there is no internal offset to provide progression through the interior of the interchange. If progression through the interchange is required, the controller can be run in coordinated mode. The controller does not need to be coordinated with any other controllers; coordination is only used to provide the structure required to create a fixed
relationship (offset) between the rings. The separate intersection diamond control mode is valuable under both free and coordinated mode.

**Free Separate Intersection Mode**

The free separate intersection mode is very effective in handling low-volume conditions. For example, this mode can be used to control an interchange during the late night and early morning hours when traffic volumes are low. Under low-volume conditions the progression provided by four-phase or three-phase control is typically not needed, since traffic streams consist of single vehicles rather than platoons of vehicles.

If permissive internal left-turn movements are allowed, detector switching can be used to switch detector actuations from the internal left-turn phase ($\phi_1$ or $\phi_5$) to the opposing arterial phase ($\phi_2$ or $\phi_6$) to avoid unnecessary activation of the internal left-turn phases. The internal left-turn phases can also be omitted by time-of-day control if there is no doubt that the permissive left-turn movements would have sufficient capacity for the time the left-turn phases are omitted. If recalls are placed on the arterial phases ($\phi_2$ and $\phi_6$) and the left turns are treated as described above, the controller will only leave the arterial phases to service frontage road demand.

The free separate intersection mode is efficient in serving low frontage road demand in the absence of high arterial demand for two reasons:

- The controller does not need to wait for the current phase at other side of the interchange to terminate before a frontage road phase can be serviced.

- When the controller changes to the frontage road requiring service, the arterial phase on the other side of the interchange remains green. This operation is in contrast to the three-phase mode, where the other side of the interchange changes to the internal left-turn phase ($\phi_{10}$ or $\phi_{14}$) when only one frontage road has a call, even if there is no interior left-turn demand on the other side of the interchange.

**Coordinated Separate Intersection Mode**

Under low-flow conditions it may be acceptable to operate without any guaranteed progression through the interchange, but for higher volumes it is desirable to provide progression. The lack of progression in the separate intersection diamond mode can be addressed by running the controller in coordination and establishing an internal offset or “ring lag” between the coordinated phases in each ring, as shown in Figure 5.

![FIGURE 5 Coordinated separate intersection mode diamond interchange phasing.](image-url)
By running the separate intersection diamond mode in coordination with the appropriate ring lag, it is possible to implement nonstandard diamond phasing schemes in the diamond control mode. These nonstandard phasing schemes may be appropriate under nonstandard geometric or demand conditions. The PASSER III (20), Synchro (21), and TRANSYT-7F (22) traffic signal optimization models can be used to generate such nonstandard diamond phasing schemes. For example, the PASSER III lead-lead phasing sequence lends itself well to implementation with the coordinated separate intersection diamond mode with ring lag.

One drawback of the coordinated separate intersection mode is the potential negative effect that coordination transitions may have on the interior operation of the interchange. Since there are no barriers in the separate intersection mode, the rings operate completely independently of each other during transition. This could result in a loss of progression through the interior of the interchange during transition and the consequent development of excessive interior queues. Therefore, where frequent transitions are expected—for example, due to emergency vehicle preemption or frequent plan changes—use of the coordinated separate intersection mode may be more appropriate at wider-spaced interchanges that are more “forgiving” towards poor interior operation.

Diamond Control Sequence Change

The TxDOT traffic signal controller specification requires that controllers provide the capability of changing the diamond control sequence by time-of-day or closed-loop system control. This is a convenient feature, since traffic demand changes during the day and different diamond phasing schemes may be optimal at different times of the day. For example, peak period traffic may perform optimally under coordinated four-phase operation, off-peak day and evening traffic may perform optimally under free (noncoordinated) three-phase operation, and late-night traffic may perform optimally under the free separate intersection mode.

If periods of similar traffic demand can be identified, the controller can be programmed to change to the most appropriate diamond control sequence at the start of each period. Typically, practitioners use turning movement counts to identify periods of similar traffic demand, and then use a PASSER III or Synchro analysis to determine the optimal diamond control sequence for each period.

Timely changes in the diamond control sequence have the potential to optimize traffic flow through the interchange by providing the best possible diamond phasing type for any particular demand condition. Changes in the diamond control sequence should not take place too often, however. Diamond control sequence changes typically result in periods of transition that can be disruptive to traffic flow. For example, some movements may receive longer reds or shorter greens than usual, resulting in traffic backup under heavy volumes. Also, the controller may drop out of coordination when changing diamond control sequence, requiring a transition sequence to return to coordination. This transition period may impact traffic flow adversely. Due to these inefficiencies, the diamond control sequence should not be changed more than once every 15 minutes (23).

The engineer should also take into account driver expectancy when considering changing the diamond control sequence by time of day. Drivers moving through the upstream intersection of an interchange may expect the downstream intersection to be green, especially if the intersections are closely spaced or if a bridge or other structure obscures the traffic signal of the downstream intersection. A change in the diamond control sequence may violate this expectancy and create a potential safety hazard.

Other Advanced Features

The following advanced features are not evaluated in this paper, and are only summarized for completeness.

Conditional Service

Conditional service is an alternative method of phase selection that allows the controller to activate phases outside their place in the ring structure. This feature is available in the three-phase mode, where the frontage road phases (φ4 and φ8) can be programmed for conditional service. The ring structure of the three-phase control mode (see Figure 2) allows phases 4 and 8 to conditionally service special internal left-turn phases (φ10 or φ14), allowing the insertion of an interior left turn phase between the end of a frontage road phase and the start of the arterial through phase.
Dynamic Maximum Green Times

Under dynamic maximum control, the maximum green time of a phase can vary between the normal phase maximum and a user-defined “dynamic max limit.” The effective maximum green time is called the “running max.” When a phase maxes out twice in a row and on each successive max out thereafter, the running max is increased by a user-defined value. When a phase gaps out twice in a row and on each successive gap out thereafter, the running max is decreased by the same step value. If a phase gaps out in one cycle and maxes out in the next cycle, or vice versa, the running max will not change.

Dynamic Split

The goal of the dynamic split feature is to dynamically find and use the most advantageous split possible. The splits of the noncoordinated phases can be adjusted, and the cycle length is retained. If a phase is forced off by coordination in two consecutive cycles, the phase becomes a candidate for an increase in split. Conversely, if a phase gaps out in two consecutive cycles, the phase becomes a candidate for a decrease in split. Split time is taken away from the phases marked as candidates for giving up split and added to the phases marked as candidates for increasing split.

Volume-Density Control

Volume-density control provides two features: (i) variable initial timing and (ii) gap reduction timing. With variable initial timing the duration of the initial (minimum) portion of the green can increase dependent on the number of vehicle actuations that occurs while its signal is displaying yellow or red. The variable initial timing period therefore operates like a variable minimum green and is most effectively used when setback detectors are provided without any stop-bar detection. Gap reduction timing is typically used with setback detectors on high-speed approaches. With setback detectors, the time allowed for a vehicle to pass from the detector to the intersection (the passage time) is usually longer than the gap that would normally be required to retain the right of way. The gap reduction feature reduces the allowable gap from the passage time to a minimum allowable gap that equals the required gap for right-of-way retention.

Alternate Maximum Green And Passage Times

Since traffic volumes vary through the day, traffic signal control efficiency may be improved by using different maximum green values, passage times, and other controller settings throughout the day to reduce the amount of time that the signal controller operates with nonoptimal settings. This feature has the potential to improve traffic operations, but it may be challenging to implement successfully, since proper implementation requires knowledge of traffic demand variation through the day, as well as the ability to determine when alternate settings should be in effect and the appropriate value of those settings.

Adaptive Protected-Permissive Left Turns

The adaptive protected-permissive left turn feature can automatically determine whether left-turns should operate as protected-permissive or permissive only, depending on the left-turn demand and the availability of gaps in the opposing through movement. If sufficient gaps exist in the opposing movement so that left turns can operate as permissive only, the left-turn phase is automatically omitted.

EVALUATION RESULTS

The separate intersection mode was evaluated under generic interchange geometry and demand conditions as well as for the geometry and demand conditions at a number of actual interchanges in Texas. The evaluation results from two actual interchanges will be reported in this paper:

- the Briarcrest Drive interchange on Texas 6 in Bryan, Texas; and
- the Bagby Avenue interchange on Texas 6 in Waco, Texas.
Briarcrest Drive Interchange

In this evaluation, the coordinated separate intersection diamond control mode was compared to the coordinated three-phase diamond control mode during the afternoon peak hour. At the time of the evaluation the interchange was operating under coordinated separate intersection mode control during the afternoon peak period.

The evaluation was conducted using hardware-in-the-loop traffic simulation. Ten simulation replications were performed. Geometric data was obtained from site measurements. Demand data in the form of turning movement counts were obtained from a video camera survey. The traffic signal controller settings were downloaded from the controller in the field and uploaded into the controller used in the hardware-in-the-loop simulation.

The CORSIM simulation network consisted of an east-west arterial section (Briarcrest Drive) containing the diamond interchange and three adjacent intersections, two with minor street stop control, and one with signal control. The spacing between the two diamond interchange terminals is a relatively wide 1150 feet (350 m). In the simulation, the two interchange terminals were controlled with a real signal controller operating in actuated-coordinated diamond control mode, while the other signalized intersection was controlled with CORSIM’s emulated fixed-time controller.

Paired evaluation runs were performed, each pair consisting of two runs with the same traffic demand and random number seed, but with a different diamond interchange control strategy (separate intersection vs. three-phase). Only the random number seed varied between evaluation pairs, the overall traffic demand and turning movements remained the same. The simulation runs determined four performance measures:

1. overall network delay,
2. maximum eastbound internal left-turn queue length;
3. delay on the eastbound internal left-turn movement of the interchange, and
4. delay on the east-bound external approach to the interchange

The evaluation focused on the eastbound direction because it carried a significantly higher traffic volume than the westbound direction during the afternoon peak hour for which the analysis was conducted.

The paired sample means and standard deviations were used to determine if the separate intersection mode and the three-phase mode resulted in statistically significantly different performance. Performance differences were identified by testing the null hypothesis that the performance is the same, in other words, that the mean of the paired sample differences is zero. The test statistic, \( t \), was calculated as follows:

\[
    t = \frac{\overline{d}}{s_d / \sqrt{n}},
\]

where \( \overline{d} \) and \( s_d \) are the sample mean and standard deviation of the \( n \) (10 in this case) differences. The null hypothesis could be rejected (implying that the performance is different) if \( |t| > t_{\alpha/2} \), where \( \alpha \) is the probability of erroneously rejecting the null hypothesis, also called the significance level. For this analysis, a value of 0.05 was chosen for \( \alpha \).

Table 1 shows the aggregated results from the ten paired simulation runs together with results from the hypothesis test for the four measures of effectiveness. The \( p \)-value in Table 1 is the probability of observing a test statistic as extreme as or more extreme than that actually observed, and was obtained from the two-tailed Student’s \( t \)-distribution with \( n-1 \) degrees of freedom. The \( p \)-value can be compared with the significance level \( \alpha \) to determine the outcome of the hypothesis test. A \( p \)-value smaller than \( \alpha \) indicates that the null hypothesis is false and should be rejected.

Table 1 indicates that the null hypothesis is rejected for all four performance measures, indicating that the difference between the separate intersection mode and the three-phase mode have a statistically significant effect on all four performance measures.
### TABLE 1 Briarcrest Interchange Evaluation Results

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Three-Phase Mode</th>
<th>Separate Intersection Mode</th>
<th>Paired Sample Difference</th>
<th>Null Hypothesis (H₀): Performance is Not Different</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Overall Network Delay (sec/veh)</td>
<td>59.0</td>
<td>1.96</td>
<td>55.8</td>
<td>1.65</td>
</tr>
<tr>
<td>Maximum Eastbound Internal Left-Turn Queue Length (veh)</td>
<td>17.3</td>
<td>6.90</td>
<td>29.7</td>
<td>2.50</td>
</tr>
<tr>
<td>Eastbound Internal Left-Turn Delay (sec/veh)</td>
<td>22.7</td>
<td>4.61</td>
<td>52.7</td>
<td>5.13</td>
</tr>
<tr>
<td>Eastbound External Delay (sec/veh)</td>
<td>27.4</td>
<td>3.88</td>
<td>18.2</td>
<td>2.84</td>
</tr>
</tbody>
</table>

Note: The paired sample difference was calculated by subtracting the separate intersection mode performance measure value from the three-phase mode performance measure value. Consequently, a reduction in the performance measure under the separate intersection mode is represented by a positive paired sample difference.

In summary, this analysis indicated that the coordinated separate intersection mode is more efficient in handling the afternoon peak-hour traffic at the Briarcrest interchange than the three-phase mode. Specifically, the analysis indicated that on average, the separate intersection mode results in a significant delay reduction over the three-phase mode. There are some trade-offs involved, however. The analysis indicated that the eastbound interior left-turn queues and delays are significantly higher under the separate intersection mode than under the three-phase mode, but that the delays on the eastbound exterior approach are significantly less under the separate intersection mode. At this particular interchange this trade-off was not problematic because of the large interchange spacing allowing enough interior storage space to handle the longer interior queue lengths resulting from the separate intersection mode.

**Bagby Avenue Interchange**

At the time of the evaluation, the Bagby Avenue interchange operated in the three-phase sequence at all times except during the morning and afternoon peak period, when it operated in the four-phase sequence. The evaluation compared the use of the free separate intersection mode to the free three-phase mode under low-volume conditions. The CORSIM simulation network for the Bagby Avenue evaluation consisted of a north-south arterial section (Bagby Avenue) containing the diamond interchange. The spacing between the two diamond interchange terminals is 560 feet (170 m). Traffic counts were not conducted at this interchange; instead, traffic demand volumes were selected to fall within the thresholds for free separate intersection control developed as part of the research project (1):

- a combined arterial volume of 300 vehicles per hour or less,
- a volume of 125 vehicles per hour or less on each frontage road.

Specifically, a combined arterial volume of 228 vehicles per hour with a 58:42 split was used. Frontage road volumes were 49 and 63 vehicles per hour.

Four grouped evaluation runs of a one-hour period were performed, each group consisting of four runs with the same traffic demand and random number seed, but with a different diamond interchange control strategy. Only four runs were performed due to the good convergence obtained as a result of the relatively low traffic volumes.
The following control strategies were evaluated at the Bagby Avenue interchange:

- three-phase mode (the existing control mode),
- separate intersection mode without detector switching,
- separate intersection mode with detector switching on the internal left-turn detectors, and
- separate intersection mode with internal left-turn phases omitted.

The evaluation compared the percentage of stops at the interchange under the different control strategies since delay and queue lengths are less sensitive quality-of-service indicators under low-volume conditions. Figure 6 shows the percentage of stops at both sides of the interchange as a function of the phasing type. The leftmost bar in Figure 6 indicates the percentage of stops when using the three-phase sequence. The other bars show reduced stops using the free separate intersection mode with different left-turn phasing treatments. The rightmost bar represents the free separate intersection mode with the interior left turns omitted, which results in a 34 percent reduction in stops compared to the three-phase sequence.

![Figure 6: Summarized Bagby Interchange simulation results.](image)

Next, a hypothesis test was performed to evaluate the results in Figure 6. The test was conducted using the same approach as in the Briarcrest Drive interchange evaluation, also using a value of 0.05 for $\alpha$. Three sets of paired samples were compared:

1. the three-phase mode against the separate intersection mode without detector switching,
2. the three-phase mode against the separate intersection mode with detector switching on the internal left-turn detectors, and
3. the three-phase mode against the separate intersection mode with internal left-turn phases omitted.
Table 2 shows the results of the hypothesis test. The null hypothesis is rejected for all three sets of paired samples, confirming that in all cases the separate intersection mode results in fewer stops than the three-phase mode.

### TABLE 2 Bagby Interchange Evaluation Results

<table>
<thead>
<tr>
<th>Percentage of Stops (Both Sides)</th>
<th>Three-Phase Mode</th>
<th>Separate Intersection Mode</th>
<th>Paired Sample Difference</th>
<th>Null Hypothesis ($H_0$): Performance is Not Different</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>No Detector Switching</td>
<td>53.1</td>
<td>3.2</td>
<td>44.5</td>
<td>3.6</td>
</tr>
<tr>
<td>With Detector Switching</td>
<td>53.1</td>
<td>3.2</td>
<td>38.7</td>
<td>2.7</td>
</tr>
<tr>
<td>With Internal Left Turns Omitted</td>
<td>53.1</td>
<td>3.2</td>
<td>34.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Notes

- The paired sample difference was calculated by subtracting the separate intersection mode performance measure value from the three-phase mode performance measure value. Consequently, a reduction in the performance measure under the separate intersection mode is represented by a positive paired sample difference.
- Detector switching and omitted left turns were not evaluated in the three-phase mode, only in the separate intersection mode. The same sample was used for the three-phase mode for all three comparisons.

### SUMMARY AND CONCLUSIONS

This study identified eight controller features that can improve diamond interchange operations under certain conditions, indicating the potential for applying advanced traffic signal control at diamond interchanges.

One of the main findings of this project was a realization of the potential usefulness of the separate intersection diamond control mode. The separate intersection diamond control mode is not commonly used, but if applied judiciously it has the potential to provide more efficient control than the three-phase or four-phase sequences that are typically used for diamond interchange control in Texas. The separate intersection mode can be used in both free and coordinated mode.

The free separate intersection mode can significantly reduce stops at interchanges under low-volume conditions, especially if the interior left turns can operate as permissive left turns and steps are taken to reduce the activation of the interior left-turn phases. The coordinated separate intersection mode has the potential to provide more efficient operation than the three-phase or four-phase sequence under certain conditions that can be determined with signal optimization software such as PASSER III, Synchro, or TRANSYT-7F. The “ring lag” feature can be used to specify the offset between the coordinated phases, allowing the separate intersection mode to provide progression through the interchange under a wide range of geometric and demand conditions.

### ACKNOWLEDGMENTS

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<td>Sample Mean</td>
<td>Std. Dev.</td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>Overall Network Delay (sec/veh)</td>
<td>59.0 1.96</td>
<td>55.8 1.65</td>
<td>3.2 2.12</td>
<td>4.584 0.0013</td>
</tr>
<tr>
<td>Maximum Eastbound Internal Left-Turn Queue Length (veh)</td>
<td>17.3 6.90</td>
<td>29.7 2.50</td>
<td>-12.4 5.52</td>
<td>6.737 0.0001</td>
</tr>
<tr>
<td>Eastbound Internal Left-Turn Delay (sec/veh)</td>
<td>22.7 4.61</td>
<td>52.7 5.13</td>
<td>-30.0 2.82</td>
<td>31.910 &lt;0.0001</td>
</tr>
<tr>
<td>Eastbound External Delay (sec/veh)</td>
<td>27.4 3.88</td>
<td>18.2 2.84</td>
<td>9.1 4.12</td>
<td>6.680 0.0001</td>
</tr>
</tbody>
</table>

**Note**

$a$ The paired sample difference was calculated by subtracting the separate intersection mode performance measure value from the three-phase mode performance measure value. Consequently, a reduction in the performance measure under the separate intersection mode is represented by a positive paired sample difference.
**TABLE 2 Bagby Interchange Evaluation Results**

<table>
<thead>
<tr>
<th>Percentage of Stops (Both Sides)</th>
<th>Three-Phase Mode</th>
<th>Separate Intersection Mode</th>
<th>Paired Sample Difference</th>
<th>Null Hypothesis ($H_0$): Performance is Not Different</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
<td>Sample Mean</td>
<td>Std. Dev.</td>
</tr>
<tr>
<td>No Detector Switching</td>
<td>53.1</td>
<td>3.2</td>
<td>44.5</td>
<td>3.6</td>
</tr>
<tr>
<td>With Detector Switching</td>
<td>53.1</td>
<td>3.2</td>
<td>38.7</td>
<td>2.7</td>
</tr>
<tr>
<td>With Internal Left Turns Omitted</td>
<td>53.1</td>
<td>3.2</td>
<td>34.6</td>
<td>1.9</td>
</tr>
</tbody>
</table>

Notes

- The paired sample difference was calculated by subtracting the separate intersection mode performance measure value from the three-phase mode performance measure value. Consequently, a reduction in the performance measure under the separate intersection mode is represented by a positive paired sample difference.
- Detector switching and omitted left turns were not evaluated in the three-phase mode, only in the separate intersection mode. The same sample was used for the three-phase mode for all three comparisons.
LIST OF FIGURES
FIGURE 1  Signal phase numbering scheme for diamond interchanges.
FIGURE 2  Simplified four-phase diamond interchange phasing.
FIGURE 3  Simplified three-phase diamond interchange phasing.
FIGURE 4  Simplified separate intersection diamond interchange phasing.
FIGURE 5  Coordinated separate intersection mode diamond interchange phasing.
FIGURE 6  Summarized Bagby Interchange simulation results.
FIGURE 1 Signal phase numbering scheme for diamond interchanges.
Note:
*Phases 12 and 16 are transition intervals during which the frontage road and arterial on opposite sides of the interchange can be active at the same time.

FIGURE 2  Simplified four-phase diamond interchange phasing.
**Phase Sequence**

$\phi_{4} + \phi_{14}^{*}$

$\phi_{4} + \phi_{8}$

$\phi_{10}^{*} + \phi_{8}$

$\phi_{4}^{+}$

$\phi_{14}^{*}$

$\phi_{4}^{+}$

$\phi_{8}$

$\phi_{1}^{+}$

$\phi_{5}$

$\phi_{2}^{+}$

$\phi_{6}$

**Controller Ring Structure**

<table>
<thead>
<tr>
<th>$\phi_{10}^{*}$</th>
<th>$\phi_{4}$</th>
<th>$\phi_{2}$</th>
<th>$\phi_{1}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_{14}^{*}$</td>
<td>$\phi_{8}$</td>
<td>$\phi_{6}$</td>
<td>$\phi_{5}$</td>
</tr>
</tbody>
</table>

*Note: Phases 10 and 14 are used for conditional service and as clearance phases in the absence of calls on phase 4 or phase 8.*

**FIGURE 3** Simplified three-phase diamond interchange phasing.
FIGURE 4  Simplified separate intersection diamond interchange phasing.
Phases 2* and 6* are coordinated phases in this example.

FIGURE 5  Coordinated separate intersection mode diamond interchange phasing.
FIGURE 6  Summarized Bagby Interchange simulation results.