Volume Guidelines for Signalization of Diamond Interchanges

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ABSTRACT

The objective of the work described in this paper is to establish volume guidelines for the installation of traffic signal control at diamond interchanges where the base condition is all-way stop sign control. The guidelines are based on operational threshold values of traffic flow, above which signalization is expected to produce superior performance. Four diamond interchanges were studied with both types of control, from which the study results were based. The data-collection methods and procedures employed in the study to evaluate the operational effects of stop sign and signal control at diamond interchanges are discussed. An assessment of traffic control alternatives is described in terms of operational effects of queues and travel speed. Guidelines for all-way stop signs or signal control at diamond interchanges are provided in terms of internal volume, left-turn proportion within internal volume, and the sum of internal and external volume. The specific traffic volume guidelines were developed based on a combination of these variables, which affect operational performance.

Diamond interchanges are widely used in urban areas as a means to transfer freeway traffic to and from the surface street system. The selection of the proper traffic control system for each diamond interchange is a challenging task. When and where to use stop signs or signals for traffic control at a significant number of diamond interchanges is a principal concern. This complex subject is discussed in this paper and useful information is provided for guiding future engineering decisions in the selection of the appropriate diamond interchange control.

Signalization of a diamond interchange is often resorted to after public pressure is applied and one or both sides of the interchange are warranted by Manual on Uniform Traffic Control Device (MUTCD) (1) standards for a single intersection. However, MUTCD warrants for signalization neither explicitly reflect the operational characteristics of diamond interchanges nor are they sensitive to the traffic patterns associated with the two intersections at a diamond interchange.

Research conducted by the Texas Transportation Institute (TTI) regarding the operational characteristics of diamond interchange controllers led to a better understanding of different phasing patterns, and the development of frontage road progression strategies and a diamond interchange signal optimization and analysis program for timing pretimed diamond interchanges (2-4). FHWA also sponsored a series of research studies on signalized diamond interchanges, with particular emphasis on signal phasing (5-7).

The MUTCD provides national standards for determining when a signal is warranted at an intersection. The Texas manual (8) includes all eight MUTCD warrants plus an actuated control warrant. However, neither manual specifically considers diamond interchanges and their special requirements. One case study of a diamond interchange in Texas (9) illustrated a signal warranting situation where one side of an interchange was warranted and the other fell short. It was noted in this study that current signal warrant conditions do not appear to adequately address the different traffic movement patterns associated with two intersections at a diamond interchange.

The development of clear and effective guidelines for installing all-way stop signs or signals for traffic control at a significant number of diamond interchanges, whose traffic patterns and geometric physical characteristics vary quite widely between interchanges, would be a significant contribution to the traffic engineering technology.

The objectives of this study were as follows: (a) conduct an operational evaluation of the two types of traffic control (i.e., all-way stop and traffic signals) to include comparisons of vehicular delay and stops at diamond interchanges under various types of geometric and traffic patterns, (b) analyze operational results to determine the relative efficiency of each type of control, and (c) develop guidelines to aid in the selection of the appropriate control method for isolated interchanges.

EXPERIMENTAL PLAN AND ANALYSIS APPROACH

Type of Control

An experimental plan was developed to field evaluate the operational performance of two types of diamond interchange control strategies: all-way stop sign control, and traffic signal control. To provide a general guideline for signal control, signal operations were confined neither to a single controller type nor to a single phase pattern. Signal control in this study encompassed pretimed control, actuated control, three-phase operation, and four-phase overlap operation.

Study Sites

Field studies were conducted to evaluate the operational performance of stop sign and signal control. Four sites were selected for this study. The sites

TABLE 1 Operational Performance Data Collected at Study Sites

		Queue Counts		Travel Time	
Interchange Location	Traffic Control Studied	Stop Sign	Signal	Stop Sign	Signal
US-83 at South 7th in Abilene	Stop sign, three-phase operation, four-phase overlap	X	X	X	X
US-59 at Jetero Boulevard in Houston	Stop sign, four-phase overlap	X	X	NA	NA
I-10 at T. C. Jester in Houston	Stop sign, four-phase overlap	NA	NA	X	X
I-20 at Trail Lake in Fort Worth	Stop sign, four-phase overlap	NA	NA	X	X

Note: NA = not available.

were selected to provide a variety of geometric and traffic conditions.

Data on the locations of the four sites and the overall field data-collection effort, as conducted, are given in Table 1. A wide variety of geometrics, traffic volumes, and traffic patterns was provided by the four sites. Two interchanges were underpasses and the other two interchanges were overpasses. Separation between intersections ranged from 260 to 480 ft. The number of lanes for each approach at the four interchanges ranged from one to three.

Besides all being located in major Texas cities, there were some other similarities in the four sites. All frontage roads were continuous through the interchanges without any U-turn lanes. All interchanges studied, except I-20 at Trail Lake, had left-turn bays between the two intersections.

Traffic control was varied among the interchanges. Some interchanges had a protective left-turn-only phase, whereas others had protective and permissive left-turn phases. Except at Abilene, stop sign performance was observed before signal installation. For Abilene, signal control was converted to stop sign control for a day, and the performance was observed the next day. All pretimed signals were operated at a 60-sec cycle length. The signal at I-20 at Trail Lake was the only actuated signal observed. Neither interchange design features nor signal control promoted highly efficient signal operations.

The study plan called for data to be collected for 4 hr per day from 7:00 to 8:00 a.m., 10:00 to 11:00 a.m., 12:00 to 1:00 p.m., and 5:00 to 6:00 p.m., or some reasonable on-site modification if deemed appropriate.

Several types of performance data were to be collected. The initial plan called for tracing vehicles through the interchange to obtain their travel time or travel speed along with their stopped delay. This was performed by recording an arrival time to the interchange influence zone, stopping times at Intersections 1 and 2, and departure times at Intersections 1 and 2. The count of the number of stopped vehicles on each approach was added later. The data in Table 1 give the performance data collected for alternative traffic controls at each interchange.

Traffic volumes were collected manually or by using automatic counters on all four inbound approaches to the interchange and on both interior intersection approaches. Two people, one for each intersection, were used to manually count traffic volume. Each approach flow was obtained for 15-min time periods and expanded to an equivalent hourly volume.

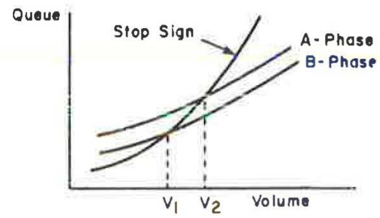
Additional manual observations were made every 15 sec during the study by six persons to determine the number of vehicles stopped on each of the six intersection approaches. Stopped vehicle data were recorded on scribble pads and then later reduced in the office. A 15-min time interval was used as the time base for data analysis.

The study supervisor observed general characteristics of traffic flow on the cross street and ramp traffic. Particular attention was paid to the effect of internal volume and its left-turn volume on traffic flow at an interchange.

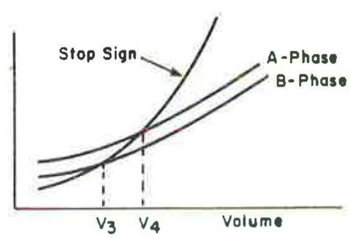
Analysis Approach

To provide guidelines for traffic control alternatives at diamond interchanges, the following three methods appear to be relevant:

1. Provide guidelines by separate signal control methods:

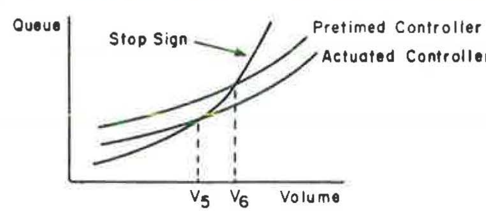


PRETIMED CONTROLLER

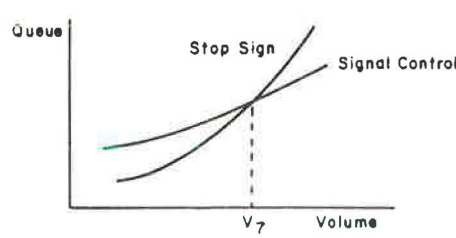


ACTUATED CONTROLLER

2. Provide guidelines by controller types:



3. Provide guidelines by general control alternatives:

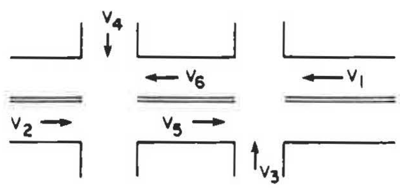


Because the objective of the study was to provide general guidelines for stop sign versus signal control, the third method was used throughout the study. However, every effort was made to distinguish performance differences between stop sign and signal control because of different interchange geometric and traffic characteristics.

Approach Used to Develop Guidelines

It is emphasized that guidelines should distinguish different geometric and traffic characteristics between different interchanges. The traffic volume on each approach was normalized with respect to approach lanes (i.e., the traffic volume on each approach was divided by its number of lanes) to distinguish geometric differences in the number of lanes on each approach among different interchanges. Thus the total interchange hourly volume per lane, which is the basic interchange volume used throughout this paper, was defined as the sum of the six intersection approach volumes per lane. Further, to distinguish different traffic patterns among different interchanges, two variables that characterize diamond interchange traffic movement were introduced:

1. Ratio of internal volume per lane to external volume per lane (RIE):



RIE = (Internal volume per lane)/(External volume per lane) = $(V_5 + V_6)/(V_1 + V_2 + V_3 + V_4)$.

The RIE variable reflects observations that stop sign control causes more delay to internal traffic and, subsequently, to overall interchange traffic than does signal control. Stop sign control requires double stops for all external volumes that use both intersections, whereas signal control usually provides progression through the interchange.

2. Composition of left-turn and through volume within internal volume: The reason for distinguishing left-turn from through volume within the internal traffic is that as more traffic turns left within the internal stations, overall interchange operation appears to be affected. Another reason for this distinction is to reflect the advantages and disadvantages of U-turn lanes to accommodate double left-turning traffic coming from frontage roads.

STUDY RESULTS

A presentation of the results of the field studies follows. A general description of the traffic volumes, travel speeds, and queue characteristics observed at each diamond interchange will introduce the findings. Detailed statistical analyses to assess stop sign and signal control and their results by type of traffic control conclude this section.

Traffic Volumes

The data in Table 2 present the range of interchange traffic volumes observed at the four interchanges. The four interchanges are sequenced according to the rank of highest volume levels. Observed total interchange hourly volume per lane at the four interchanges ranged between 600 and 2,000 vehicles.

TABLE 2 Ranking of Four Interchanges by Observed Total Interchange Hourly Volume per Lane

		Volume	
Rank	Interchange Location	Highest	Lowest
1	US-59 at Jetero Boulevard in Houston	1,999	692
2	I-20 at Trail Lake in Fort Worth	1,773	889
3	US-83 at South 7th in Abilene	1,658	886
4	I-10 at T. C. Jester in Houston	855	607

Travel Speeds

Travel times were traced at each of the four external stations at each interchange. The reference point from which traffic is assumed to be influenced by traffic control (stop sign or signal) was established as a utility pole or sign pole located approximately 300 to 500 ft away from the stopline on each approach. When a vehicle passed the reference point, its time was recorded. The vehicle was traced with regard to its travel time and direction of movement until it was completely out of the interchange. The stop delay is the sum of the differences between the departure time and stop time at an intersection within the interchange. Travel time is the difference in time between arrival time to the outer reference point and the departure time from the last intersection.

To normalize the differences in distances traveled by a vehicle at each interchange, all travel times were converted to travel speeds. Further, those directional movements passing through two intersections were distinguished to reflect the diamond interchange characteristics. In addition, through and left-turn movements were separated because their speeds appeared to be affected differently by the traffic control alternatives.

Travel speeds involving left-turning vehicles, observed at the four interchanges, ranged from 26.9 to 4.4 ft/sec for stop sign control, and from 29.1 to 5.0 ft/sec for signal control. For cross-street through traffic, travel speeds observed ranged from 23.1 to 5.6 ft/sec for stop sign control, and from 29.4 to 6.2 ft/sec for signal control. Generally, travel speeds were observed to decrease as total interchange traffic volume increased.

Queue Characteristics

It was noted in the previous discussion that the number of stopped vehicles was observed at six interchange stations (or approaches). Two stations (Stations 1 and 2) were on the arterial cross street and another two stations (Stations 3 and 4) were located on the frontage roads. The remaining two stations (Stations 5 and 6) were located between the traffic signals. To account for the different number of traffic lanes on each approach, the number of stopped vehicles was divided by the number of lanes on each approach.

Therefore the total interchange queue is defined as the sum of the average number of vehicles observed to be stopped per lane at the six stations of the interchange. The traffic queue on an approach (station) is an average value across all lanes and is not a critical lane value. Queue counts were taken every 15 sec and averaged over 15-min intervals.

Overall, less queue was observed for stop sign control than signal control when interchange traffic volume was low. As interchange traffic increased, such as during peak hours, more queue was observed for stop sign control than for signal control. These general trends were observed for all interchanges studied.

Figure 1 shows the queue characteristics observed at the interchange in Abilene, Texas. It revealed the following characteristics:

1. As traffic volume increased, signal control was a more effective alternative in reducing queue than stop sign control, and

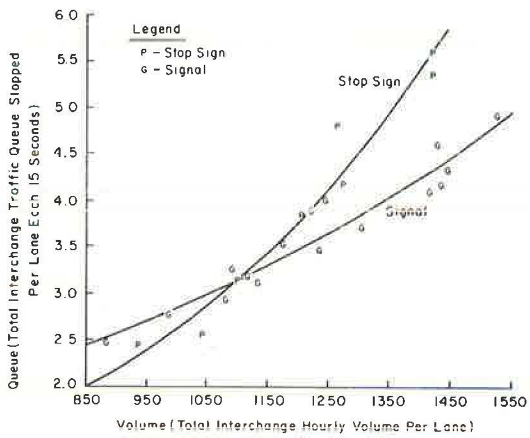


FIGURE 1 Queue versus volume by stop sign and signal control in Abilene.

2. As traffic volume increased to more than 1,100 per hour per lane, signal control was more effective than stop sign control.

Figure 2 shows the queue characteristics observed at the interchange in Houston, Texas. It revealed the following characteristics:

1. It confirmed the general expectations that as traffic volume increased, traffic signal control was more effective in reducing queue than stop sign control, and
2. As traffic increased beyond 600 vehicles per hour per lane, traffic signals were more effective than stop signs.

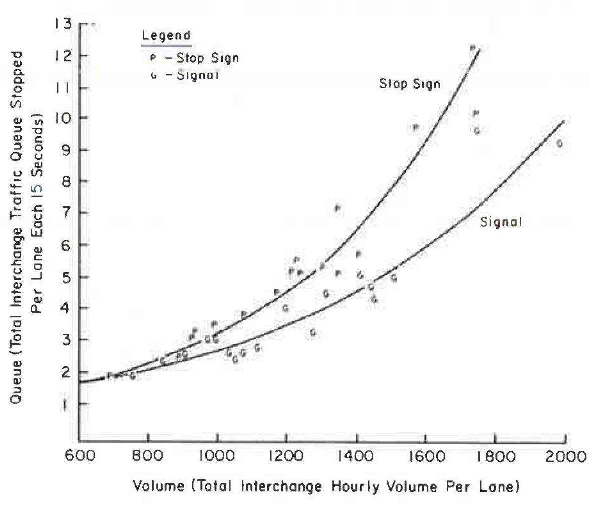


FIGURE 2 Queue versus volume by stop sign and signal control in Houston.

Comparing Figure 1 for Abilene with Figure 2 for Houston, it is noted that the intersecting point, which has approximately equal queue generation for both stop signs and signal controls, is different between the interchanges. These differences are caused in part by different interchange traffic patterns. This consequence is reflected in the development of guidelines on when and where a stop sign or traffic signal is preferred.

Assessment of Traffic Control Alternatives

The assessment of traffic control alternatives involves two areas. The first examines performance differences between stop sign and signals for their effects on queue. The second evaluates differences between stop sign and signals for their effects on travel speed and travel time. These two areas of interest initially will be analyzed separately. Later, the queue and travel speed information will be combined to suggest volume guidelines for signal control.

Relationship Between Queue and Volume by Traffic Control

The initial data analysis from Abilene and Houston revealed that when more traffic flows between the two intersections (such as left turns from the ramp and through traffic on the arterial), traffic signals are more effective at lower interchange volumes than in the case of traffic using only a single intersection (such as through traffic from ramps and right-turn traffic from arterials).

The queues observed from Abilene and Houston were pooled together. Two-dimensional plots of queue versus total interchange traffic volume per hour per lane indicated that an exponential function would fit the observed data well. Another variable that characterizes traffic movements that encompass two intersections between signals--the ratio of internal volume to external volume--was added. The exponential form used is as follows:

$$Q = \mathrm{Exp}(a + bV + cRIE)$$
$$Q = A\ \mathrm{Exp}(bV + cRIE) \qquad (1)$$

where

Q = total interchange traffic queue stopped per lane as observed each 15 sec,
V = total interchange traffic volume per hour per lane,
RIE = ratio of internal volume to external volume, and
A,a,b,c = derived coefficients.

The logarithm transformation of Equation 1 can be linearized as log Q = a + bV + cRIE. By using the Statistical Analysis System (SAS) (10), models for stop sign and signal control were derived. Models that describe the total number of stopped vehicles at interchange per lane were developed as follows:

Stop sign control: $$Q_p = 0.26\ \mathrm{Exp}(1.89\ v/1000 + 0.94\ RIE) \qquad (2)$$

Signal control: $$Q_s = 0.29\ \mathrm{Exp}(1.25\ V/1000) \qquad (3)$$

The coefficients of determination (R^2) for stop sign and signal control were 0.95 and 0.93, respectively. All variables are significant at the α = 0.01 level. The RIE variable for signal control was not statistically significant (α = 0.25). Signal progression apparently handles substantial internal traffic more efficiently than stop sign control.

Plots of queue versus volume for stop sign and signal control are shown in Figure 3. The plot of stop sign control is represented by the typical ratio of internal volume to external volume observed in the field (i.e., four cases of RIE = 0.4, 0.5, 0.6, and 0.7). Note in Figure 3 that the faster more internal traffic occurs at an interchange (i.e., larger RIE), the sooner signal installation is needed.

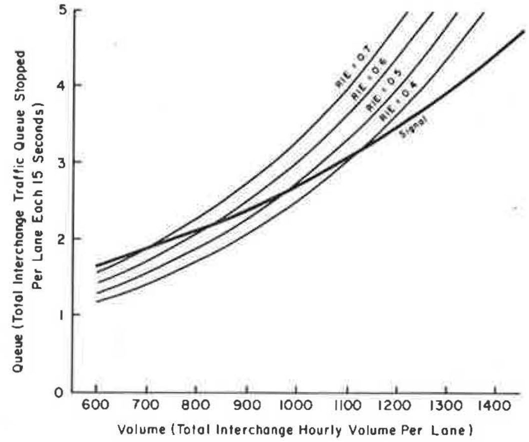


FIGURE 3 Queue versus volume by stop sign and signal control.

Specifically, the models and plots of queue performance revealed the preferences to the type of traffic control given in Table 3. Note in Table 3 that the diamond interchange should be considered as a special category different from intersections in which interchange operation is sensitive to the degree of internal traffic movements between the two signals.

TABLE 3 Traffic Control Alternative Performance Based on Queue Only as Related to Total Interchange Volume

	Volume	
RIE	Shorter Queue During Stop Sign Control	Shorter Queue During Traffic Signal Control
0.4	< 1,140	> 1,140
0.5	< 990	> 990
0.6	< 840	> 840
0.7	< 690	> 690

Note: Total interchange volume is the sum of internal and external traffic volume per hour per lane at an interchange.

Relationship Between Travel Speed and Volume by Traffic Control

Travel speed is analyzed by traffic movements because the travel speed for through movements on the cross street is different from traffic movements that involve left turns from cross streets and ramps. Further, it is hypothesized that travel time is affected by the degree of internal traffic at an interchange. The model used to evaluate the travel speed at an interchange was developed as follows.

For arterial through traffic movements:

Stop sign control: $U_p = 26.61 - 9.07\ V/1000$ (4)

Signal control: $U_s = 81.93\ \mathrm{Exp}(-0.53\ V/1000 - 1.62\ \mathrm{RIE})$ (5)

For left-turn traffic movements:

Stop sign control: $U_p = 28.93 - 10.17\ V/1000$ (6)

Signal control: $U_s = 39.66\ \mathrm{Exp}(-0.35\ V/1000 - 0.88\ \mathrm{RIE})$ (7)

where

U_p = travel speed for stop sign control (ft/sec),
U_s = travel speed for signal control (ft/sec),
V = total interchange traffic volume per hour per lane, and
RIE = ratio of internal traffic volume to external traffic volume.

Travel speed for stop sign control did not statistically depend on the degree of internal traffic movements. The reason appears to be that the relative stop delay for stop sign control is not sensitive enough because of its regularity by all approach traffic. However, travel speed for signal control is sensitive to internal traffic movements because they influence progression speed from the cross street and ramps.

Plots of travel speed versus volume for left-turn and arterial through traffic are shown in Figures 4 and 5, respectively. The model and plot of travel speed performance revealed the following:

1. For arterial through traffic, signalization appears to perform better than stop sign control

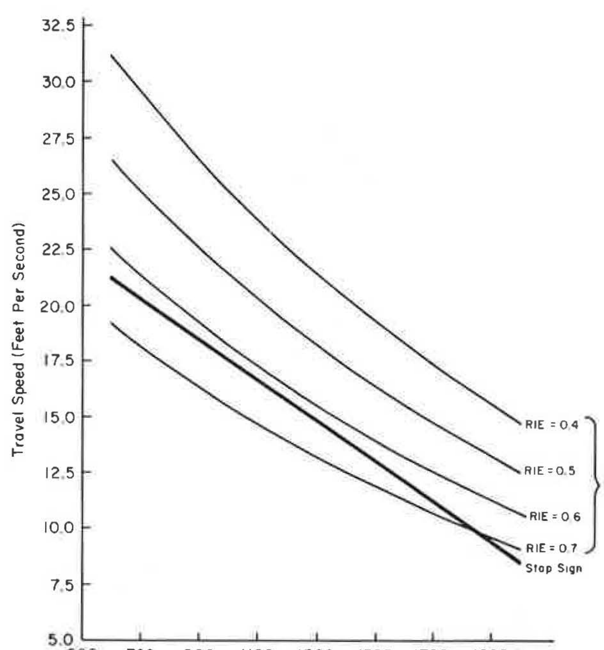


FIGURE 4 Travel speed versus volume for arterial through traffic by stop sign and signal control.

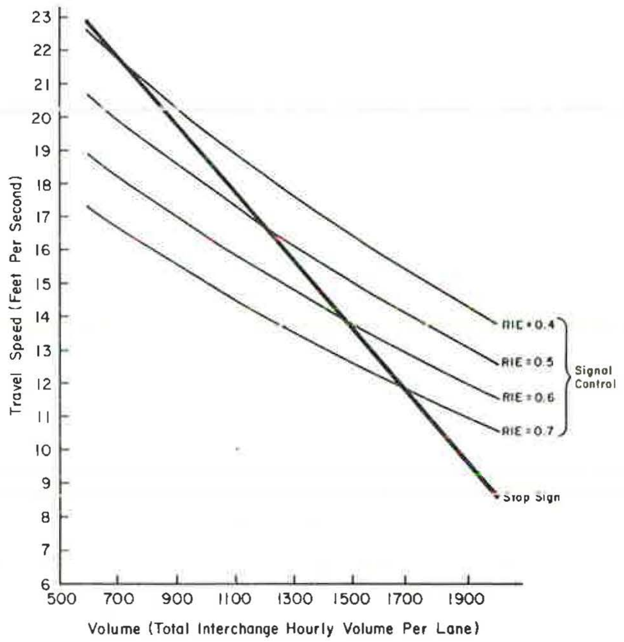


FIGURE 5 Travel speed versus volume for left-turn traffic by stop sign and signal control.

unless internal volume reaches 70 percent of external traffic. The reason appears to be that signal control can maintain relatively good progression until internal volume becomes substantial enough to affect external approach traffic.

2. For left-turning traffic, stop signs appear to perform better than signal control unless interchange traffic and internal traffic reach critical volume levels. The reason appears to be that left-turning traffic often has to wait a cycle with signal control, whereas stop sign control does not require this traffic to wait a cycle.

Development of Guidelines Combining Queue and Travel Speed Results

A sample problem is introduced to illustrate the procedure employed to develop volume guidelines of signal control considering the queue and travel speed findings. A complete set of guideline volumes will be presented after the sample problem illustration.

Assume an interchange has an RIE (i.e., the ratio of internal volume over external volume) equal to 0.50. The volume guideline for signalization at this interchange would be 990 vehicles per hour per lane if queue were the only measure of effectiveness considered (see Figure 3 and Table 3).

Considering travel speed or travel time, signals are more efficient for arterial through traffic, but stop signs are more efficient for left-turning traffic at this volume level (see Figures 4 and 5).

The adjustment procedure for travel speed is as follows. Assume that 40 percent of internal traffic turns left and the other 60 percent goes through. The speed ratios observed between stop sign and signal control for left-turn and arterial through traffic are as follows:

For the left-turn speed ratio:

$$\text{Stop/Signal} = (28.93 - 10.17 \times \text{Volume}/1000) \div [39.66\ \text{Exp}(-0.35\ V/1000 - 0.88\ \text{RIE})]$$

$$= (28.93 - 10.17 \times 0.99)/[39.66\ \text{Exp} \times (-0.35 \times 0.99 - 0.88 \times 0.5)]$$

$$= 18.9/18.1 = 1.04 \quad (8)$$

For the arterial through traffic speed ratio:

$$\text{Stop/Signal} = (26.61 - 9.07\ V/1000)/[81.93\ \text{Exp} \times (-0.53\ V/1000 - 1.62\ \text{RIE})]$$

$$= (26.61 - 9.07 \times 0.99)/[81.93\ \text{Exp} \times (-0.53 \times 0.99 - 1.62 \times 0.5)]$$

$$= 17.6/21.6 = 0.81 \quad (9)$$

Because there is 40 percent left-turn traffic and 60 percent through traffic at this interchange, the adjustment ratio is

$$\text{Stop/Signal} = 40\ \text{percent} \times \text{left-turn ratio} + 60\ \text{percent} \times \text{through ratio}$$

$$= 0.4 \times 1.04 + 0.6 \times 0.81$$

$$= 0.90 \quad (10)$$

This means that a signal is more efficient than stop signs in travel speed for this traffic pattern. Specifically, signal control is 11 percent faster (i.e., 1/0.90 = 1.11) than stop sign control.

Considering this travel speed efficiency, traffic engineers would like to install a signal sooner than the 990 volume level. This means that an adjustment should be made to reflect travel speed efficiency in addition to queue considerations, as follows:

Guideline based on travel speed = 990 x 0.90 = 890 vehicles.

Figure 6 shows the adjustment effect based on travel speed. Assuming an equal weight between queue and travel speed performance, the guideline would be about 940 vehicles [i.e., (990 + 890)/2] in this example.

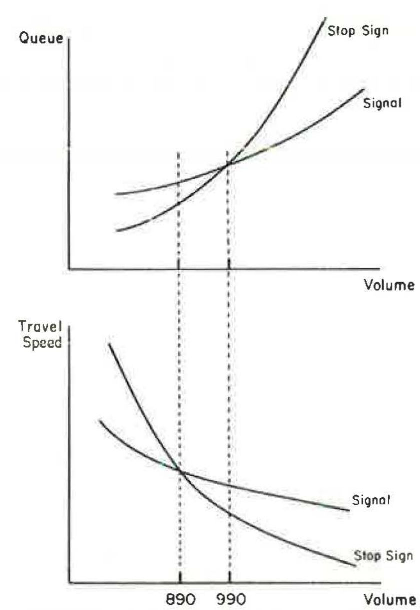


FIGURE 6 Adjustment effect of queue and travel speed.

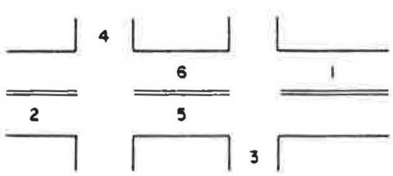
Signalization Guidelines

Following the procedure illustrated in the previous example, various combinations of internal traffic and left-turn traffic observed in the field were considered. RIEs from 0.4 to 0.7 were evaluated together with left-turn proportions from 30 to 70 percent. The results obtained are given in Table 4, which gives the recommended volume guidelines for installing signals at diamond interchanges.

TABLE 4 Guidelines for Installing Traffic Signals at Diamond Interchanges

RIE	Left Turn (%)	Minimum Interchange Volume for Signal Control
0.4	30	1,005
	50	1,035
	70	1,060
0.5	30	935
	50	955
	70	980
0.6	30	850
	50	865
	70	885
0.7	30	750
	50	760
	70	775

Note: RIE is the sum of internal traffic volume per hour per lane divided by the sum of external traffic volume per hour per lane; left turn (%) is the proportion of left-turn traffic within internal traffic; interchange volume for signal control is the sum of internal and external traffic per hour per lane at an interchange; internal traffic is traffic at Stations 5 and 6; and external traffic is traffic at Stations 1, 2, 3, and 4:



If the suggested guideline volumes presented in Table 4 are applied following MUTCD practice, then these volume levels must be exceeded for each of any 8 hr of an average day. However, the exact number of hours required to meet the guideline volume levels for implementation should be determined from further study and testing in practice.

Simplified Guidelines

It is noted in Table 4 that the interchange volume guidelines for signal control are practically insensitive to left-turn proportion within internal volume. Considering the effort required to collect the data, the left-turn proportion could be practically negligible for implementation. From these considerations, the simplified guidelines given in Table 5 are also provided for this practical reason.

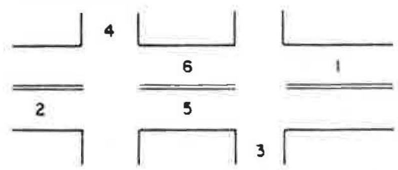
Comparison with MUTCD Warrants

The MUTCD states that traffic control signals should not be installed unless one of the signal warrants in the manual is met. Two of the warrants in the manual are related to traffic volume.

TABLE 5 Simplified Guidelines for Installing Traffic Signals at Diamond Interchanges

RIE	Minimum Interchange Volume for Signal Control
0.4	1,050
0.5	950
0.6	850
0.7	750

Note: RIE is the sum of internal traffic volume per hour per lane divided by the sum of external traffic volume per hour per lane; interchange volume for signal control is the sum of internal and external traffic per hour per lane at an interchange; internal traffic is traffic at Stations 5 and 6; and external traffic is traffic at Stations 1, 2, 3, and 4:



The first warrant--Minimum Vehicular Volume--is intended for application where the volume of intersecting traffic is the principal reason for signal installation. The warrant is satisfied when, for each of any 8 hr of an average day, the traffic volumes given in Table 6 exist on the major street and on the higher-volume minor street approach to the intersection.

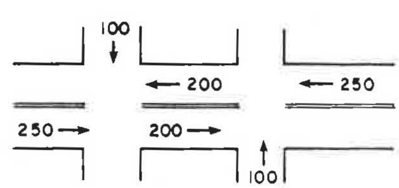
TABLE 6 MUTCD Minimum Vehicular Volumes for Warrant 1

No. of Lanes for Moving Traffic on Each Approach: Major Street	No. of Lanes for Moving Traffic on Each Approach: Minor Street	Vehicles per Hour on Major Street (total of both approaches)	Vehicles per Hour on Higher-Volume Minor Street Approaches (one direction only)
1	1	500	150
2+	1	600	150
2+	2+	600	200
1	2+	500	200

The second warrant--Interruption of Continuous Traffic--applies to operating conditions where the volume on the major street is so heavy that traffic on the minor intersecting street suffers excessive delay or hazard in entering or crossing the major street. Thus the second warrant is only applicable to two-way stop sign control. Therefore, the second warrant is not applicable to all-way stop sign control at diamond interchanges.

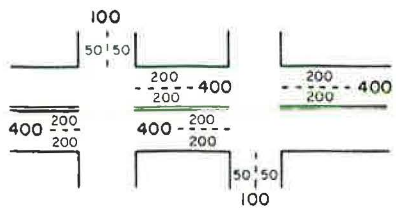
Examples are presented to compare the MUTCD warrant with the guidelines derived from this study (which are called diamond interchange guidelines).

1. Example 1: One lane for all approaches that have traffic volumes:



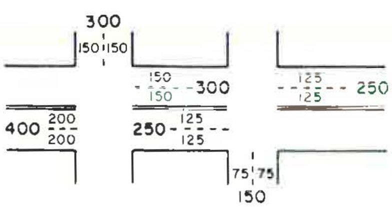
Because the major street carries 450 vehicles and the minor street carries 100 vehicles, neither intersection will satisfy MUTCD warrant 1. However, because the total interchange volume is 1,100 vehicles per lane at an internal ratio of 0.6, this sample interchange will satisfy the diamond interchange guidelines.

2. Example 2: Two lanes for all approaches that have traffic volumes:



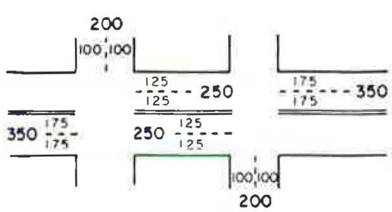
Because the major street carries 800 vehicles and the minor street carries 100 vehicles, neither intersection completely satisfies the warrant. However, because the total interchange volume is 900 vehicles per lane at an internal ratio of 0.8, this sample interchange will satisfy the diamond interchange guidelines.

3. Example 3: Unbalanced traffic flow:



Intersection 1 satisfies MUTCD warrant 1 but Intersection 2 does not. The option of installing two separate traffic controls (e.g., signals at Intersection 1 and stop signs at Intersection 2) at the interchange is too risky to use. Assume that signals are installed at this interchange because Intersection 1 warrants signalization. However, because the diamond interchange carries 825 vehicles per lane at an internal ratio of 0.5, this interchange will not satisfy the diamond interchange guidelines for signalization.

4. Example 4: MUTCD warrant is met but diamond interchange guidelines are not met:



Because the major street carries 600 vehicles and the minor street carries 200 vehicles, both intersections meet MUTCD warrant 1 for signalization. However, because the interchange carries 800 vehicles per lane at an internal ratio of 0.45, it does not meet the diamond interchange guidelines.

Numerous other examples can be illustrated in which the following four cases exist:

1. MUTCD warrant is met, but diamond interchange guidelines are not met;
2. MUTCD warrant is not met, but diamond interchange guidelines are met;
3. MUTCD warrant is met for one intersection and is not met for another intersection, but diamond interchange guidelines are met; and
4. MUTCD warrant is met for one intersection and is not met for another intersection, but diamond interchange guidelines are not met.

From these possible cases it is noted that the two intersections at a diamond interchange cannot be separated regarding their operational characteristics. The independent treatment of two intersections at a diamond interchange is improper. Thus diamond interchanges should be treated as a separate warrant category in the MUTCD. The interchange traffic volume levels provided in Table 4 or 5 are recommended to be considered as signal guideline volumes for diamond interchanges.

CONCLUSIONS

The following conclusions were drawn from the data collected and field observations made within this study. They apply within the operational environment of one-way frontage roads.

1. Although each side of a diamond interchange is an intersection, a diamond interchange operates much differently than would two isolated intersections due to the close spacing.
2. Because diamond interchanges operate differently from isolated intersections, criteria for warranting diamond interchange signalization should be a separate MUTCD procedure from that for isolated intersections.
3. Diamond interchange models that uniquely combine the complex interactions of internal and external traffic appear to be the most representative approach on which to base diamond interchange guidelines for signalization.
4. There is a discriminating diamond interchange volume level beyond which traffic signal control is better than stop sign control in terms of the combined performance of queue and travel speed. The specific volume levels proposed for considering implementation of signalization at diamond interchanges are presented in Tables 4 and 5.

RECOMMENDATIONS

1. The guidelines presented in Tables 4 and 5 are recommended for implementation and testing to ascertain their acceptability for determining when and where installation of traffic signalizations is needed at diamond interchanges.
2. Separate signalization warrants for diamond interchanges are recommended. The guidelines provided in Tables 4 and 5 should be considered in the development of diamond interchange signal warrants in the MUTCD.
3. Further research is recommended to determine the exact number of hours during the average day that should meet the guideline volume levels for implementation purposes.

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Optimal Timing Settings and Detector Lengths of Presence Mode Full-Actuated Control

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ABSTRACT

The operation of presence mode full-actuated signal control at individual intersections is governed primarily by the choice of detector length and the timing settings of vehicle interval and maximum green. The relationships between these control variables and the control efficiency vary with the flow pattern at an intersection. Based on the results of computer simulations, the optimal combinations of detector length, vehicle interval, and maximum green are identified for a wide range of flow conditions. The analyses performed in this study concern only intersections where vehicle approach speeds are less than 35 mph.

Full-actuated signals based on long loop presence detectors are being widely used for the regulation of traffic flows at individual intersections. This presence mode control, which is also referred to as loop-occupancy control, can rely on a variety of timing settings and detectors. Nevertheless, the typical operation of this mode of control is governed by three basic control variables: vehicle interval, maximum green, and detector length. Vehicle interval determines the longest duration in which detectors can be left unoccupied without prompting the termination of a green duration. Maximum green limits the maximum green duration allowable to a signal phase after a vehicle actuates a detector of a competing phase.

Some researchers have attempted to quantify the performance of the presence mode control under certain operating conditions, but so far the findings