Traffic Operations of Basic Traffic-Actuated Control Systems at Diamond Interchanges

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This paper contains the results of field studies conducted to evaluate four types of basic, full-traffic-actuated signal control systems operated at three diamond interchanges. Two signal phasing strategies were tested: (a) three-phase and (b) four-phase with two overlaps. Two small-loop (point) detection patterns—single- and multipoint—were evaluated for each type of phasing. An assessment of these systems was conducted based on the results of statistical and observational evidence regarding their operational effects on queues and cycle lengths. Multiple and geometric linear regression were used to formulate models that relate queuing delay to traffic characteristics. Single-point detection was found to be the more cost-effective three-phase design. Multipoint detection was found to be the more delay-effective four-phase configuration. Four-phase control characteristically operates at a longer cycle length than does three-phase for a given traffic volume, and this feature may produce higher average delays unless the cycle increase is controlled to the extent that the internal progression features of four-phase can overcome this deficiency.

Efficient diamond interchange traffic control is a desirable objective and a necessary condition for providing safe and economic urban mobility. The diamond interchange is a critical interface between the freeway and arterial street system and, potentially, a system-threatening bottleneck to efficient traffic flow in an urban area.

Diamond interchanges are widely used in urban areas as a means to transfer freeway traffic to and from the surface street system. These interchanges are almost always signalized with traffic-actuated or pretimed signals *(1–4)*. This subject is addressed in this paper and useful information is provided for guiding future engineering decisions regarding the design and operation of traffic-actuated signals at diamond interchanges.

OBJECTIVES

This paper contains the results of field studies conducted to evaluate four types of basic, full traffic-actuated signal control systems. Two signal phasing strategies were tested: (a) three-phase, and (b) four-phase with two overlaps. Two small-loop (point) detection patterns, single- and multipoint, were evaluated for each type of phasing. An assessment of these four systems was conducted based on the results of statistical and observational evidence regarding their operational effects on queues and cycle lengths. Multiple and geometric linear regression were used to formulate models that relate queuing delay to traffic characteristics.

Description of the four control systems will be provided by the two principal categories of control; namely, three-phase and four-phase. All signal control systems tested provided basic, full-actuated control. No volume-density features were permitted. All systems were tested at diamond interchanges having continuous one-way frontage roads rather than exit ramps.

It was desired that the signal control units would be equally fine-tuned in the field by experienced traffic engineers to provide reasonably snappy operations. Gap sizes and minimum greens were set reasonably short for the various detector designs. No tendency to prematurely gap out within starting platoons was observed. In all cases, the same maximum phase settings (Max 1 and Max 2) were applied to the three-phase and four-phase control strategies. In retrospect, however, it cannot be proved that the actuated systems were equally fine-tuned, as no metric exists for this purpose. Therefore, direct comparisons between the operational performance of three-phase and four-phase control, in particular, should reflect the limitation of this study.

THREE-PHASE CONTROL

Phasing

The basic three-phase system used for traffic-actuated control of diamond interchanges in Texas is shown in Figure 1. Although there are three primary phases, six subordinate phases also are possible, depending on phase gap-out, phase calls, and controller programming, including ring rotation and overlaps.

Phase 1 initiates the sequence and includes both frontage road green signals to simultaneously provide protected movement into the interchange. This phase must be displayed if there is a call for either frontage road green. Following Phase 1, an extension of one of the two frontage road phases usually occurs during peak hours of traffic demand. The selected extension phase would reflect which green had the higher ramp volume.

Phase 2 is the cross-street, inbound-outbound phase without protected left turns. Inbound traffic is entering the interchange; outbound is exiting. Permissive left turns are sometimes allowed in Phase 2. Phase rotation from Phase 3 back to Phase 2 may occur during light traffic conditions when no frontage road

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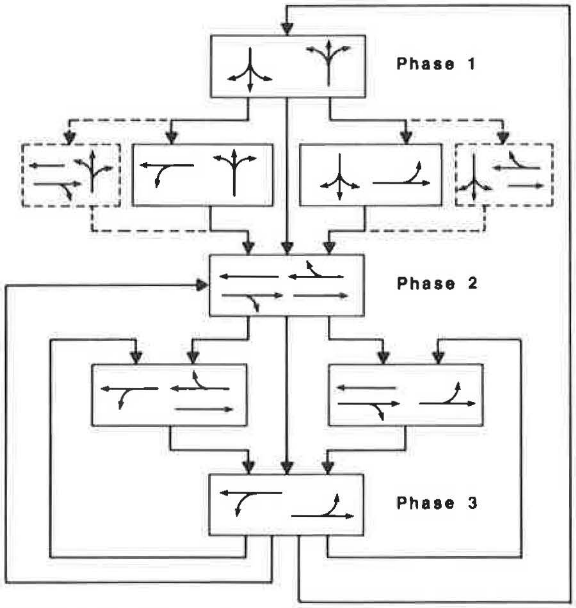

FIGURE 1 Three-phase, full-traffic-actuated diamond interchange phasing.

calls exist. Gap-out of an inbound through movement results in an early protected left-turn phase occurring before Phase 3.

Phase 3 is the simultaneous display of protected turn signals for both internal left turns serving outbound traffic. Both turn signals must simultaneously terminate. Right-of-way then normally goes to Phase 1 to start the sequence again.

Detectors

Two types of detector configurations were studied for three-phase control: (a) single-point and (b) multipoint. Similar designations were also given to detector configurations for four-phase control. However, as subsequent coverage will show, the detector configurations for four-phase control on the frontage roads were considerably different for both cases.

Single-point detectorization for three-phase control provides a minimal number of detectors at the interchange while still maintaining full-actuated control; that is, at least one detector station per approach. Although there were on-site variations because of approach speed, geometry, and the presence or absence of left-turn bays, a basic plan existed for each detector configuration. In the single-point detector plan, one detector was placed on each frontage road approach. Detector setback from the stop bar varied with approach speed, but often was about 100 ft. This placement provides a minimum required phase time of about 14 sec. Phase operations are concurrent for the two frontage roads with memory "on" (locking memory). Detector placement for the single loop sensor per cross-street inbound approach again depends on the approach speed, but averaged only about 100 ft to the stop bar.

Multipoint detection in three-phase control added one more detector across all lanes on all inbound phases. One detector was located about 100 ft from the stop bar as in single-point detection, and the other detector was located midway to the stop bar at about 50 ft. Again, actual detector placement depends on approach speed.

Figure 2 shows explicitly the three-phase multipoint detection scheme. Single-point detection did not include the inner approach detectors. Multipoint detection permits a slightly smaller minimum green with only slightly smaller gaps for extension timing.

FOUR-PHASE CONTROL

Phasing

This type of signal phasing provides four primary input phases to the interchange, with additional input capacity provided by judicious arrangement of the four basic phases to allow two adjustable, fixed-duration overlap phases. This signal strategy is commonly referred to as "four-phase with overlaps." In reality, six discrete phases are required when all phases are calling. The phasing sequence is shown in Figure 3. Note that phase numbering is different between three-phase and four-

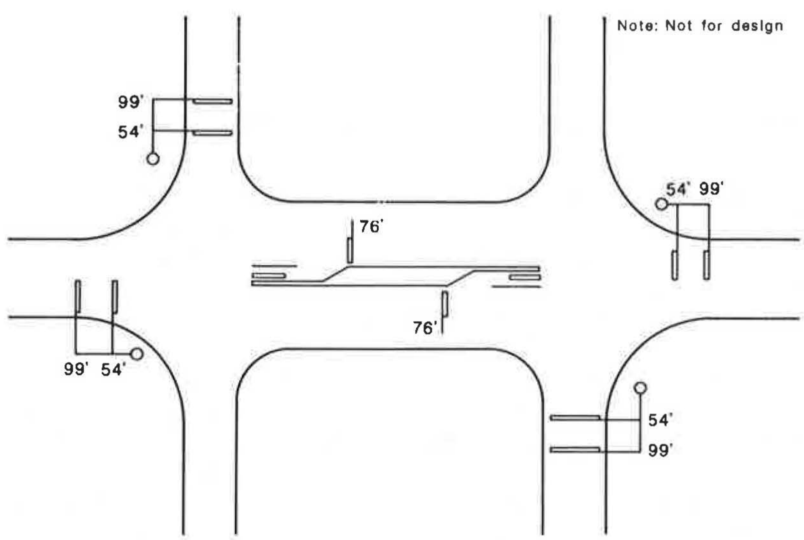

FIGURE 2 An illustration of three-phase detector layouts.

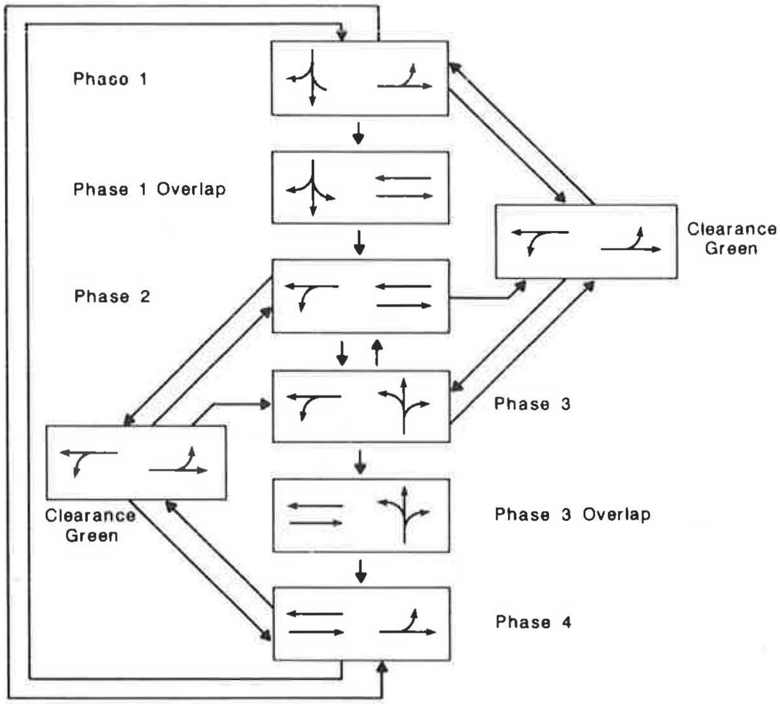

FIGURE 3 Four-phase, full-traffic-actuated diamond interchange phasing.

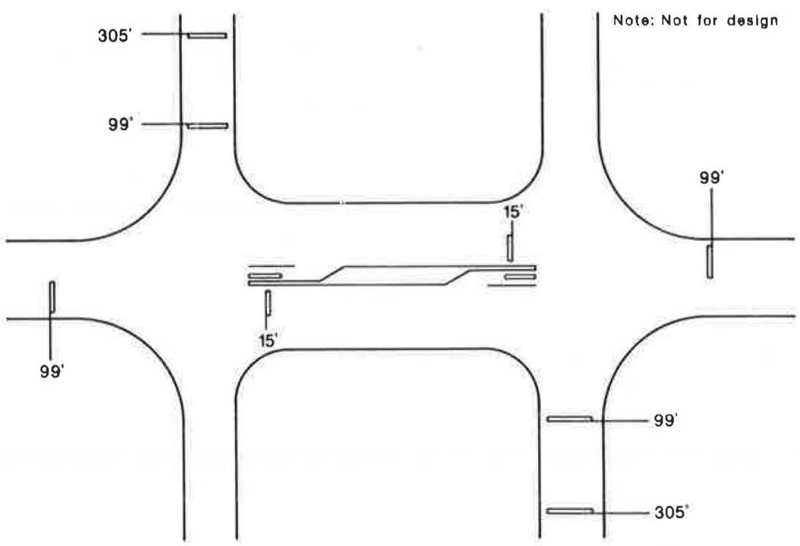

FIGURE 4 An illustration of four-phase, single-point detector layouts.

phase control. Other phase numbering schemes are also used in the literature.

Phase 1 in four-phase control is the lead, inbound frontage road phase. The choice of which frontage road leads is arbitrary. Phase 1 overlap is a fixed-duration phase equal to the travel time between intersections.

Proceeding clockwise around the interchange, Phase 2 is primarily an inbound, actuated, cross-street phase. Note, however, that only one arterial approach at a time initially receives the green.

Phase 3 likewise is the other frontage road movement. This phase operates similarly to Phase 1 and is followed by Phase 3 overlap.

Phase 4 concludes the services of actuated phases for this type of control. Phase 4 is the arterial inbound phase and is similar to Phase 2.

Detectors

Two detector configurations were also tested for four-phase control: (a) single-point and (b) multipoint detection. Figure 4 shows a typical detection plan for four-phase, single-point detection, whereas Figure 5 shows a common detector layout for four-phase with multipoint detection. Some variation in the detection plan was made at each site to best accommodate each interchange's geometrics and approach speeds.

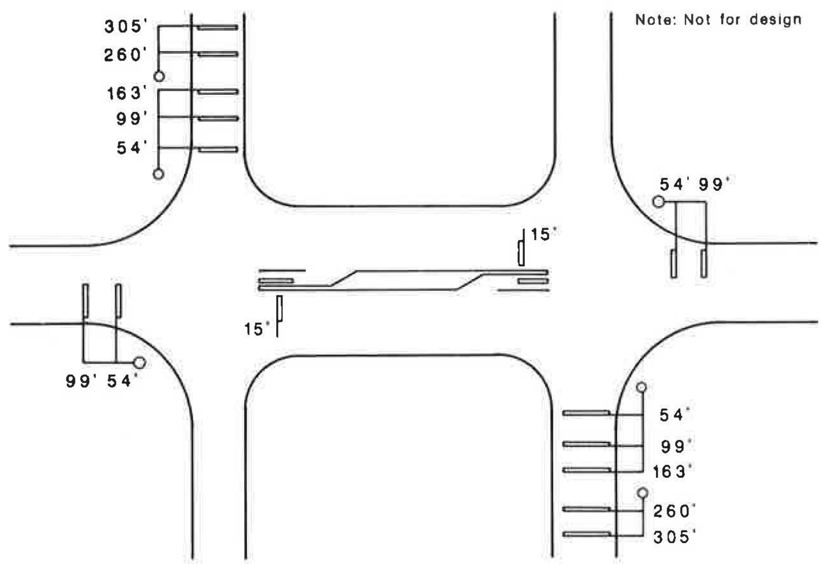

FIGURE 5 An illustration of four-phase, multipoint detector layouts.

Because of high volumes of low speed, turning traffic observed on the cross-street inbound approaches, practically no variation in single-point and multipoint detection configurations on the cross street was tested with three-phase or four-phase control at an interchange. In four-phase, single-point detection, one detector (set) was used at about 100 ft from the stop bar, the same as three-phase. In four-phase, multipoint detection, an additional detector was placed about 50 ft from the stop bar, which provided better signal change protection and shorter minimum greens but more actuations and only a slight reduction in gap timing for promoting gap-out.

Multipoint detection on the frontage roads used the five-detector system shown in Figure 5. The three detectors located closer to the intersection are connected to one amplifier. This special detector amplifier's output is routed through an external logic card to process inputs. When speeds of 40 mph (or related occupancy time) are recognized, this detector set is disabled by the logic card, and phase extension immediately switches to the upstream extension set of detectors. The upstream detectors will extend the green when headways of 2.1 to 2.5 sec are maintained and provide protection against possible dilemma zone problems for speeds up to 55 mph. Using these upstream detectors, gap-out for Phase 1 termination usually occurs at the desired time such that the end of the platoon arrives at the stop bar at the termination of Phase 1 overlap. The detector switching thus effectively promotes full utilization of Phase 1 overlap.

EXPERIMENTAL PLAN

Successful field studies were conducted at three diamond interchanges in Texas. Both three-phase and four-phase control systems were tested at each site. A control system is considered to be one type of controller phasing combined with one type of detector plan. The scope of the study limited field observations to only 1 day per type of signal control system studied per interchange.

Interchange Characteristics

The three sites offered a typical variety of geometric and traffic patterns for Texas. Some geometric commonality was also present. All interchanges provided continuous, one-way frontage road operations in a suburban environment. All interchanges were traffic actuated with each city having some experience with three-phase and four-phase control. All three interchanges could provide three-phase and four-phase control with existing equipment. However, the four-phase control tested used a special NEMA four-phase controller that had to be temporarily installed to provide single-point and multipoint detection. Three-phase control used the existing controller units.

A summary of selected diamond interchange attributes is given in Table 1. The schematic layout of Ocean and Pine

TABLE 1 INTERCHANGE SITE CHARACTERISTICS

Interchange Cross-street File Name	Dimensions Curb-to-Curb		Queue Storage Distance	Turnaround Lanes Present	Left-Turn Lane
	Outside	Inside			
North	232	160	150	No	No
Ocean	382	310	290	Yes	Yes
Pine	470	396	360	Yes	Yes

Streets were similar. Both had turnaround lanes on both sides. However, North Avenue was a fairly small interchange, Ocean Avenue was moderately sized, and Pine was a large interchange. Interchange lengths (distance along the cross street) ranged from 278 to 470 ft. North Avenue was the only one studied that was on a cross-street bridge at grade with the frontage roads. No left-turn or U-turn lanes were provided on the bridge.

The data collected at each site contained three types of

measures: (a) traffic demand variables, (b) interchange control and geometric attributes, and (c) traffic performance measures. Field observations of system activity together with incidental records were also maintained in a log book for each day of the study.

Statistical considerations of randomness, stability, and sample size combined with previous experiences led to the selection of a 15-min time interval as being the time base for study. Each 15-min period was considered one independent study, or data point. Volumes and system performance (delay) queue counts to be described in following sections were obtained for each 15-min interval.

Traffic Volume

Traffic volume was used as the primary input variable. Traffic counts were made at each intersection by turning movement using manual observers. Time-lapse turning movement recorders with assistant recorders attached were used to initially record the turning movement counts by approach lane. Turning movement summaries were prepared for each approach by lane. The maximum volume [expressed in vehicles per hour per lane (vphpl)] observed on each approach for each 15-min study period was identified. These six "critical" volumes, three at each intersection, were then added together to form an "interchange total critical volume" for each study interval. That is

$$V = V_{1c} + V_{2c} + V_{3c} + V_{4c} + V_{5c} + V_{6c} \quad (1)$$

where V is the interchange total critical lane volume, vphpl, and V_{ic} is the critical lane volume on approach i, vphpl. Subscripts 1, 2, and 3 relate to the three approach legs on one intersection; whereas Subscripts 4, 5, and 6 relate to the corresponding movements on the other intersection. V_{3c} and V_{6c} represent the larger of the outbound through or left-turn flows at the respective intersections.

Computer programs were prepared during the data reduction phase to automatically make these critical volume determinations and summarize the total interchange results.

Cycle Length

Cycle length was measured for each study period and tested as a dependent variable and as an independent variable at various stages of the analysis process. Cycle length for actual control changes with each succeeding phasing sequence. Unlike pretimed control, the time of each cycle length for basic actuated control depends on short-term traffic volumes, number of phases, and traffic controller settings of (a) initial green, (b) gap extension, and (c) maximum green for each phase, together with other factors. An average cycle length over each 15-min period was determined by averaging the cycle lengths recorded by an observer.

Queue Delay

Signal efficiency is normally described in terms of delay, delay per vehicle or, as in the *1985 Highway Capacity Manual (5)*, in terms of stopped delay per vehicle. Stopped delay per vehicle on an approach serving an arrival flow of "v" vehicles per hour is

$$d = \frac{q}{v} \quad (2)$$

where

d = stopped delay, sec/veh;
q = average number of vehicles stopped in queue at an approach to the interchange during the study interval, veh, and
v = approach flow, veh/sec.

For each approach to the interchange, counts of the number of vehicles stopped in each lane for each approach were recorded every 15 sec. Averages by lane per approach were then determined for each of the 60 (4 × 15) samples over the respective 15-min period. A maximum average queue per lane per approach was then obtained. Maximum queues per lane per approach were determined during data reduction. Each maximum (critical) queue per lane per approach was denoted c_i.

Total interchange critical queue was used as the traffic control system performance measure of operational efficiency. Total interchange queue was derived from the six approaches similar to total input volume. Total interchange critical queue for a 15-min period is equal to

$$Q = Q_{c1} + Q_{c2} + Q_{c3} + Q_{c4} + Q_{c5} + Q_{c6} \quad (3)$$

where Q is the total interchange critical queue, veh/lane, and Q_{ci} is the maximum queue per lane on approach i, veh/lane.

Comparisons between system design attributes can be effectively made at the same total volume levels. However, Equation 2 indicates that comparisons of observed queues for different control systems cannot be made at different volume levels because the case having higher total interchange queue could have higher volumes, but less average delay per vehicle.

Study Plan

Field studies at the three interchanges were conducted from Tuesday through Friday during the Spring and Summer of 1984. A typical field study team was composed of eight field observers plus one study supervisor. Three study periods per day were provided to sample a wide range of volume levels and traffic patterns. A typical daily schedule ran from 7:30 a.m. to 9:00 a.m. followed by a breakfast break. A 2-hr study of off-peak and noon-hour traffic began at 11:00 a.m. and lasted until 1:00 p.m. Several traffic patterns occur during this period. Following lunch and a brief break, the afternoon study lasted from 4:30 p.m. until 6:00 p.m. Again, 15-min study intervals were obtained by all staff synchronizing their watches before each study. The study plan thus provided 5 hr of observation time per day with four data points per hour for a total of 20 (5 × 4 = 20) data points obtained per system configuration per interchange.

Data Reduction

Three levels of data reduction were performed. All manually recorded queue and turning movement counts were routinely logged following each study period. Dates and station locations were checked for accuracy. All turning movement counts were transferred from the counter boards to data sheets before departure from the site.

A considerable quantity of data had to be manually reduced in the office by staff personnel. Queue counts, in particular, required substantial time. Queue counts were being recorded on scribble pads at six approaches by lane every 15 sec. This sampling rate results in about 1,000 queue samples for all lanes during each 15-min study period, or a total of about 86,000 samples per interchange. All of these data points had to be manually tallied, averaged, and tabulated for coding into the computer.

The study data were coded into the Amdahl computing system at Texas A&M University using remote job entry WYLBUR terminals. Routine statistical summaries were prepared for each data set for visual inspection of the data for any apparent coding errors. Range and limit tests were conducted to further check for coding errors. Preliminary testing revealed that each data set contained consistent and expected trends in attributes. The data were then pooled to evaluate the performance characteristics of the four alternative diamond interchange control systems.

Data Analysis

The pooled data were analyzed by using statistical analysis techniques. The Statistical Analysis System *(6)* was used throughout the data analysis phase. Basic summary and descriptive statistics were used to illustrate diamond interchange traffic and queue characteristics. Further, multiple regression models and general linear hypothesis testing were used to evaluate the different signal phasings and detector configurations at the diamond interchanges. The detailed analysis techniques used, variables considered, and the evaluation processes followed to select the models describing the diamond interchange operational characteristics will be presented later.

STUDY RESULTS

The derived performance characteristics of four alternative diamond interchange control systems introduce the study results. These performance characteristics will be represented by a series of models or graphs illustrating relationships such as cycle versus critical volume, and critical queue versus critical volume and traffic pattern. Subsequently, alternative control systems, given either phasing plan or detection scheme, will be presented to illustrate performance differences. In the following sections, the four signal control systems are denoted as follows:

3S = three-phase, single-point detection
3M = three-phase, multipoint detection
4S = four-phase, single-point detection
4M = four-phase, multipoint detection

Cycle Length Versus Critical Volume and Traffic Pattern

The four alternative control systems were evaluated to determine the average cycle length that would be expected given the critical volume at the diamond interchange. The models developed are as follows:

3S, $C = 21.8 + 14.4\ (V/1{,}000)$, $R^2 = 0.68$
3M, $C = 20.8 + 13.5\ (V/1{,}000)$, $R^2 = 0.64$
4S, $C = 27.7 + 31.7\ (V/1{,}000)$, $R^2 = 0.72$
4M, $C = 21.5 + 25.4\ (V/1{,}000)$, $R^2 = 0.73$

where C is the cycle length in seconds and V is the sum of critical lane volumes at the interchange, vphpl.

Operating cycle lengths were found to increase with critical volume, as expected. The effect of traffic pattern was studied in the next step of the analysis process.

Because not only traffic volume but also traffic pattern affect cycle length, other variables representing traffic pattern were individually added to the model. The best models found from stepwise regression are as follows:

3S, $C = 14.5 + 14.4\ (V/1{,}000) + 20.1\ \mathrm{RILCVE}$, $R^2 = 0.80$
3M, $C = 15.9 + 12.9\ (V/1{,}000) + 15.8\ \mathrm{RILCVE}$, $R^2 = 0.76$
4S, $C = 38.7 + 32.3\ (V/1{,}000) + 33.8\ \mathrm{RILCVE}$, $R^2 = 0.79$
4M, $C = 16.9 + 25.8\ (V/1{,}000) + 11.4\ \mathrm{RILCVE}$, $R^2 = 0.75$

where RILCVE = internal left-turn volumes per sum of external critical volumes. Figure 6 shows the relationships found between cycle length and critical volume for the range of volumes studied using RILCVE = 0.4, the mean of the field studies. Several observations determined from Figure 6 are as follows:

1. Three-phase, multipoint detection consistently produced the shortest cycle length given traffic conditions.
2. Three-phase, multipoint detection had little advantage in cycle length when compared to three-phase, single-point detection.
3. Four-phase, single-point detection generated the longest cycle length given traffic conditions.
4. Four-phase, multipoint detection provided substantial reduction in cycle length as compared with four-phase single-point.
5. Three-phase control produced shorter cycles than did four-phase control.

Critical Queue Versus Critical Volume and Traffic Pattern

The effect of critical volume on critical queue for alternative control schemes was evaluated. The models developed are as follows:

3S, $Q = 1.12 + \mathrm{Exp}\ [0.87\ (V/1{,}000)]$, $R^2 = 0.79$
3M, $Q = 1.22 + \mathrm{Exp}\ [0.85\ (V/1{,}000)]$, $R^2 = 0.74$
4S, $Q = 1.75 + \mathrm{Exp}\ [0.88\ (V/1{,}000)]$, $R^2 = 0.74$
4M, $Q = 1.09 + \mathrm{Exp}\ [1.06\ (V/1{,}000)]$, $R^2 = 0.79$

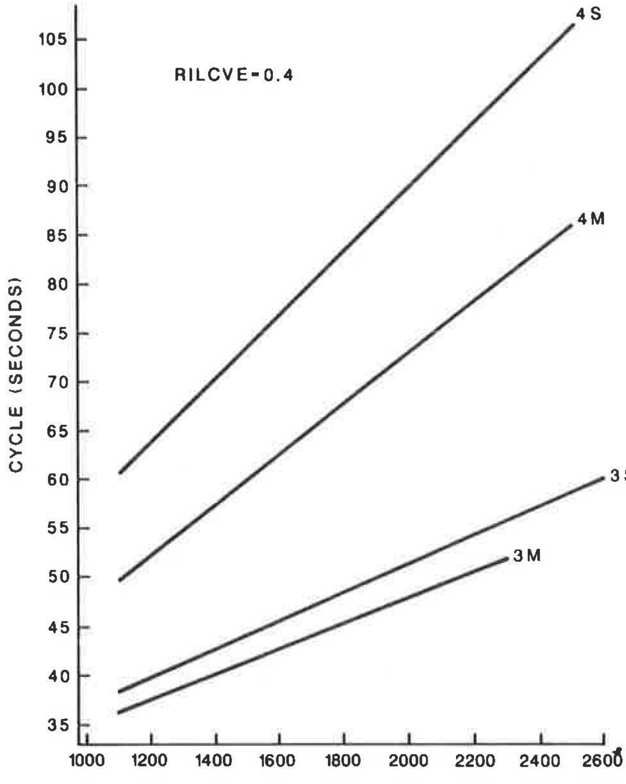

FIGURE 6 Relationship between cycle length and critical volume.

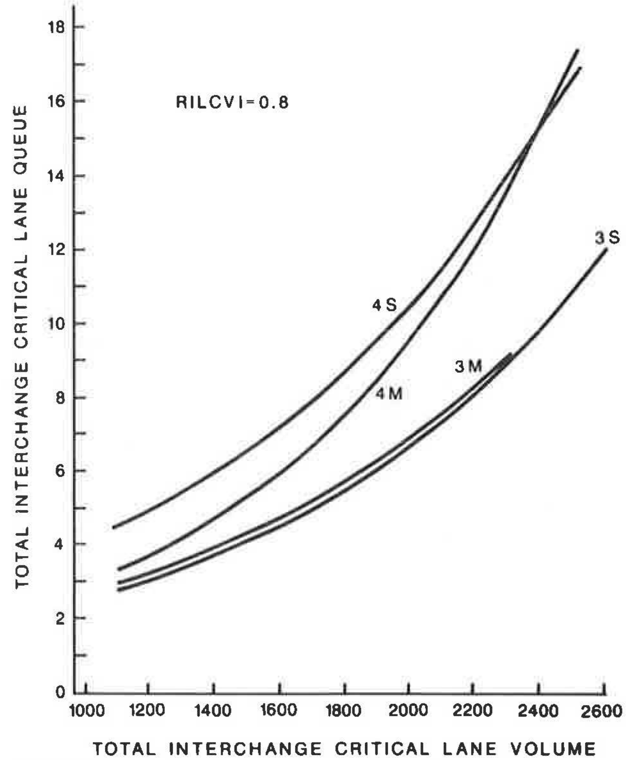

FIGURE 7 Relationships between critical queue versus critical volume and traffic pattern for RILCVI of 0.8.

As expected, these models predict that average queue increases with increasing critical volume.

The effect of different traffic pattern, in addition to traffic volume, on interchange queue performance was evaluated. Several variables previously explained to define traffic pattern at an interchange were individually tested. The best models found are as follows:

3S, $Q = 0.72 + \text{Exp}\ [0.976\ (V/1{,}000) + 0.35\ \text{RILCVI}]$, $R^2 = 0.84$

3M, $Q = 0.70 + \text{Exp}\ [0.938\ (V/1{,}000) + 0.50\ \text{RILCVI}]$, $R^2 = 0.89$

4S, $Q = 1.39 + \text{Exp}\ [0.943\ (V/1{,}000) + 0.17\ \text{RILCVI}]$, $R^2 = 0.76$

4M, $Q = 0.67 + \text{Exp}\ [1.185\ (V/1{,}000) + 0.36\ \text{RILCVI}]$, $R^2 = 0.84$

where RILCVI = internal left turns per sum of critical internal lane volumes.

Figure 7 shows the effect of traffic volume and traffic pattern at an interchange on traffic delay experienced for the range of volumes studied, using the mean RILCVI = 0.8 observed in the field studies. Several observations can be derived from Figure 7 as follows:

1. There was no significant difference in queue performance between three-phase, single-point, and multipoint detection given traffic volume at an interchange.
2. The four-phase, single-point system generated the highest delay among other alternative control schemes for a given traffic volume.
3. Three-phase control produced less delay than four-phase control given traffic volume at an interchange.

Three-Phase Control Detector Configurations

Figure 8 shows the queue performance characteristics between single-point and multipoint detection for three-phase control. Traffic pattern, given in terms of RILCVI, is shown at 0.4 and 1.0. It can be observed from Figure 8 that there appears to be no significant difference between single-point and multipoint detection for three-phase control at a given traffic volume and traffic pattern.

A general linear hypothesis test was performed to evaluate whether queue performance between single-point and multipoint detection for three-phase control was statistically different. No significant difference in queue performance was detected between single-point and multipoint detection for three-phase control.

Four-Phase Control Detector Configurations

Figure 9 shows the queue performance characteristics derived for single-point and multipoint detection for four-phase control. Traffic pattern is also depicted at 0.4 and 1.0 values of RILCVI. It can be observed from Figure 9 that multipoint detection for four-phase control generated shorter delay except when heavy

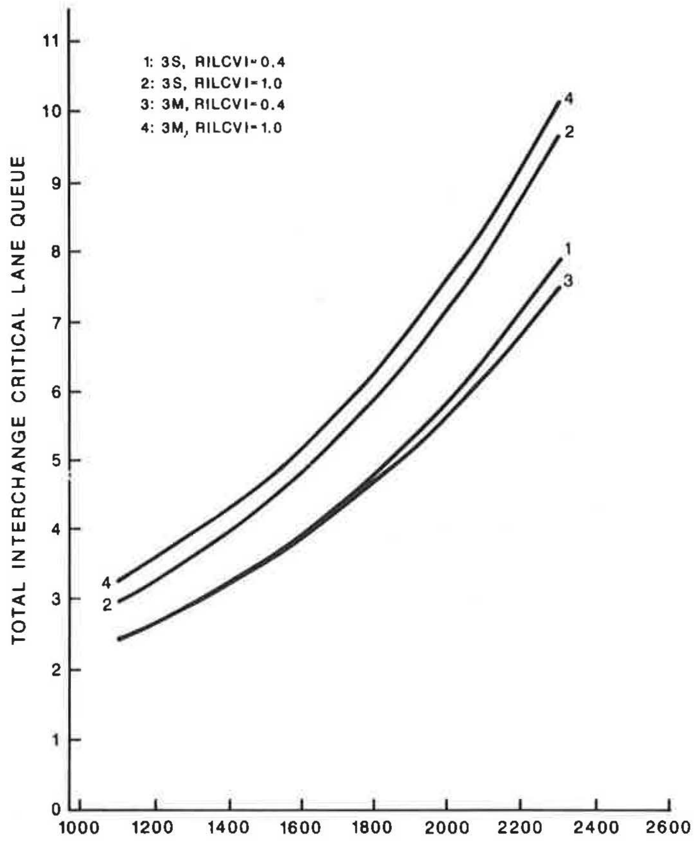

FIGURE 8 Queue performance characteristics between single and multipoint detection for three-phase control.

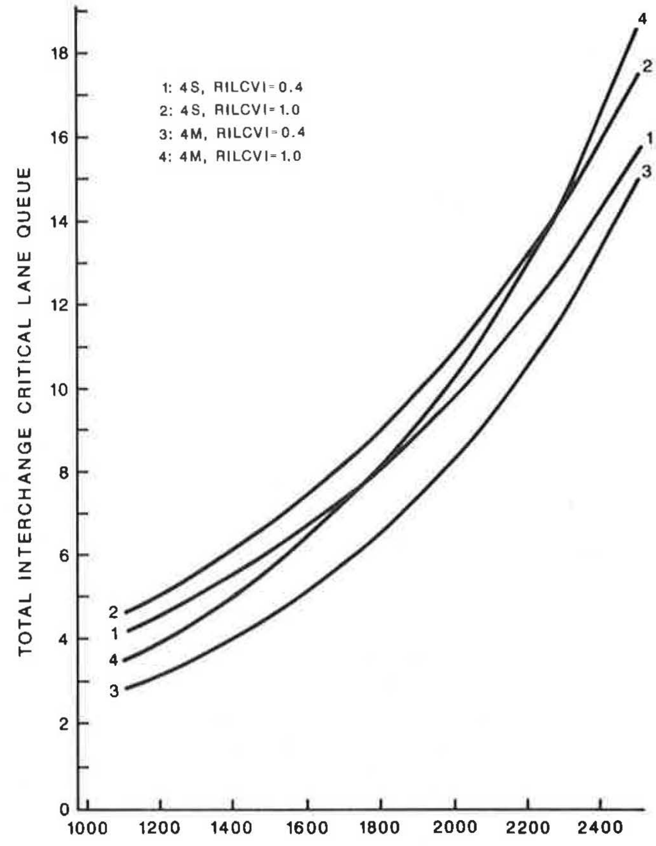

FIGURE 9 Queue performance characteristics between single and multipoint detection for four-phase control.

traffic flow together with heavy internal left turns exist at an interchange.

CONCLUSIONS AND RECOMMENDATIONS

The operational performance of traffic-actuated, signalized diamond interchange control systems has been examined in this study. Basic traffic-actuated controller units were used. All interchanges were operated isolated from all other intersections or interchanges. None of the interchanges was located within frontage road progressive systems. A wide range of volume levels were observed, but excessively heavy (or over capacity) volumes were infrequently observed, if at all.

Conclusions

The following conclusions were drawn from the data collected and field observations made in this study. They apply within the volume levels measured, traffic patterns experienced, and operational environment of one-way frontage roads in an urban area using basic actuated signal control.

1. Single-point detection is the more cost-effective three-phase detection system because it provides the same effectiveness as does the more costly multipoint detection system.
2. Multipoint detection is the more delay-effective, four-phase detection system. It provides more effectiveness but with a more expensive system. Its true cost-effectiveness is unknown.
3. Shorter cycle lengths are, in general, a desirable attribute for isolated interchange control. Phase terminations should be "snappy," with prompt phase termination becoming more critical as volume increases.
4. Four-phase control characteristically operates at a longer cycle length than does three-phase for a given traffic volume, but provides superior internal progression within the interchange.
5. Three-phase control can produce less overall queuing delay than four-phase for the same volume and level of detection. In most cases, however, this lower delay arises at a price of undesirable secondary stops within the interchange.
6. Three-phase control can be a good phasing strategy under selective geometric, traffic and control conditions. Three-phase works better when the interchange is wide and there is a high proportion of through flow, either on the frontage roads or on the cross street, or on both. In most cases, three-phase requires the use of relatively short cycle times with wider interchanges permitting better phase flexibility and smoother flow through the interchange.
7. Four-phase is an acceptable signal phasing strategy for typical urban interchange applications. Control stability and progressive flow are routinely provided but usually at a price of

increased cycle length and overall interchange delay unless the control is finely tuned.

8. Single-point detection produces, in general, longer cycle lengths than does multipoint detection. The trend toward longer cycle times for single-point detection is greater for four-phase than for three-phase control. Multipoint detection also can become susceptible to producing long cycle lengths under some heavy volume conditions.

Recommendations

The following recommendations are offered based on the results of this study. These recommendations apply to situations in which the signalized diamond interchange is operated isolated from all adjacent interchanges or intersections and the inside-to-inside, curb-to-curb dimensions between the frontage roads are 450 ft or less. In addition, only basic, full-actuated traffic signal controller units using small-area (point) detection are considered.

1. Single-point detection should be considered as a basic system component for three-phase control.
2. Multipoint detection on the frontage roads should be considered as a basic system component for four-phase control.
3. Four-phase with overlap control should be considered as a viable alternative in all cases of isolated, diamond interchange control where one-way frontage roads exist.
4. Three-phase control should be considered a viable alternative when any of the following isolated interchange control conditions exist:

a. When there is a small percentage of left-turn traffic on the frontage roads; or

b. When the interchange has sufficient internal queue storage capacity to store traffic without locking-up the turning movements within the interchange; or

c. When the interchange experiences freeway exit ramp or frontage road backup such that the backup affects freeway operation; and

d. The cycle length is kept short, phase termination snappy, and adequate visibility of the interchange signal operations exists.

5. Traffic control techniques should be considered for implementation at actuated diamond interchanges that delay phase calls and rapidly gap-out phases of lighter traffic in heavier traffic-demand situations. At high-volume interchanges, control features such as traffic-responsive, variable timings may be desired to reduce delays and minimize phase max-out even for multipoint detection.
6. There is a need to develop standard field test procedures for determining when an actuated diamond interchange controller unit is optimally fine-tuned to existing traffic conditions.
7. A traffic controller unit providing a combination of three-phase and four-phase operations could efficiently service a wide range of traffic and geometric conditions. The additional feature of providing improved progression along the cross street or frontage roads, or both, would be an additional attractive feature.

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REFERENCES

1. C. Pinnell and D. C. Capelle. Operational Study of Signalized Diamond Interchanges. *HRB Bull. 324*, HRB, National Research Council, Washington, D.C., 1962, pp. 38–72.
2. P. K. Munjal. An Analysis of Diamond Interchange Signalization. In *Highway Research Record 349*, TRB, National Research Council, Washington, D.C., 1971, pp. 47–64.
3. C. J. Messer and D. J. Berry. Effects of Design Alternatives on Quality of Service at Signalized Diamond Interchanges. In *Transportation Research Record 538*, TRB, National Research Council, Washington, D.C., 1975, pp. 20–31.
4. *Diamond Interchange Program—Users Manual.* Report FHWA-IP-80-4. FHWA, U.S. Department of Transportation, Dec. 1980.
5. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
6. *SAS User's Guide.* SAS Institute Inc., Cary, N.C., 1979.

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