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TRANSPORTATION
INSTITUTE

STATE DEPARTMENT
OF HIGHWAYS AND
PUBLIC TRANSPORTATIOI

COOPERATIVE
RESEARCH

TRAFFIC OPERATIONS OF BASIC ACTUATED TRAFFIC CONTROL SYSTEMS AT DIAMOND INTERCHANGES

in cooperation with the
Department of Transportation
Federal Highway Administration

RESEARCH REPORT 344-2F
STUDY 2-18-83-344
DIAMOND INTERCHANGE CONTROL

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16. Abstract

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This report summarizes the research concucted within a HP&R study entitled "Guidelines for Diamond Interchange Control" sponsored by the Texas Department of Highways and Public Transportation in cooperation with the U. S. Department of Transportation, Federal Highway Administration.

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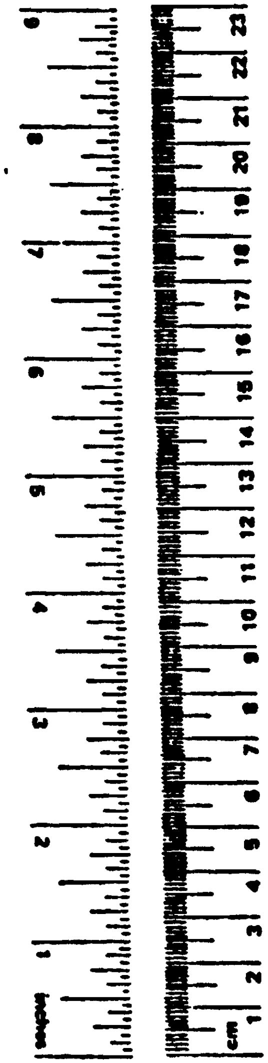
METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

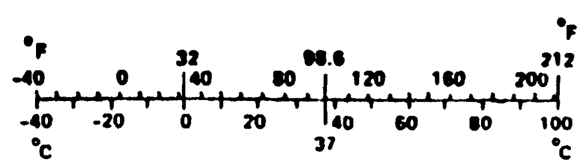
Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.



Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



TRAFFIC OPERATIONS OF BASIC ACTUATED TRAFFIC CONTROL SYSTEMS AT DIAMOND INTERCHANGES

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Research Report Number 344-2F
Research Study Number 2-18-83-344
Guidelines for Diamond Interchange Control

Sponsored by

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Federal Highway Administration

Texas Transportation Institute
The Texas A&M University System
College Station, Texas

August 1985

ABSTRACT

This report 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. These were three-phase and four-phase with two overlaps. Two small loop (point) detection patterns, single- and multi-point detection, 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 queueing delay to traffic characteristics.

This report summarizes the research conducted within a HP&R study entitled "Guidelines for Diamond Interchange Control" sponsored by the Texas Department of Highways and Public Transportation in cooperation with the U.S. Department of Transportation, Federal Highway Administration.

KEY WORDS: Diamond Interchange, Actuated Control, Traffic Signal Control, Three-Phase, Four-Phase with Two Overlaps, Detector Layout, Single-Point Detection, Multi-Point Detection

SUMMARY

Signalized diamond interchanges are a critical element of the urban transportation system. Inefficient signal control at these junctions can spread traffic congestion onto the freeway and arterial systems. Diversion from freeway incidents can also create major traffic congestion at diamond interchanges if adaptable control techniques are not provided.

The increasing demand for efficient traffic signal operations at diamond interchanges requires that effective traffic control systems be provided. In recognition of this need, State Department of Highways and Public Transportation (SDHPT) sponsored a cooperative research project with Texas Transportation Institute (TTI) entitled "Guidelines for Diamond Interchange Control." Phase I of the study developed guidelines for determining when and where traffic signals should be installed at diamond interchanges, replacing all-way stop control. Phase II of the study, covered in this report, evaluated the operational characteristics of four selected traffic control systems encompassing phasing strategies and detection plans. Three-phase and four-phase strategies were evaluated combined with single-point and multi-point detection plans.

This report describes the research conducted and the findings of the study. Field studies were conducted at four diamond interchanges in the Metroplex area of Dallas-Ft. Worth. A comprehensive series of statistical analyses of the data were performed. A systemmatic assessment of the study data yielded consistent and useful results.

Several important study findings were derived. Three-phase control frequently produced less delay than four-phase control. However, observations indicate that four-phase provides better progression and fewer stops within the interior of the interchange. Single-point detection was found to be cost-effective with three-phase control because it provided about the same traffic performance at considerably less cost. Multi-point detection was found to be delay-effective for four-phase control. Multi-point detection generally produced considerably lower delay than single-point detection for four-phase, but it requires more detectors.

IMPLEMENTATION

The findings of this study should be helpful to SDHPT traffic engineers who prepare actuated signal specifications, review signal plans, and to those local district traffic engineers who design and operate signal systems at diamond interchanges.

ACKNOWLEDGEMENT

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The Technical Advisory Panel annually met in Ft. Worth to review the direction and progress of the work. In addition, they assisted in selecting sites for study and provided timely coordination and support. Members of the Technical Advisory Panel were as follows:

Technical Advisory Panel

SDHPT	CITIES	
Bob O. Hodge, Dist. 2, Ft. Worth	Walter A. Cooper	Ft. Worth
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DISCLAIMER

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I. INTRODUCTION

DIAMOND INTERCHANGE FUNCTION

Efficient diamond interchange traffic control is a desirable objective and a necessary condition for providing safe and economic urban mobility in Texas. The diamond interchange is a critical interface and, potentially, a system threatening bottleneck to efficient traffic flow.

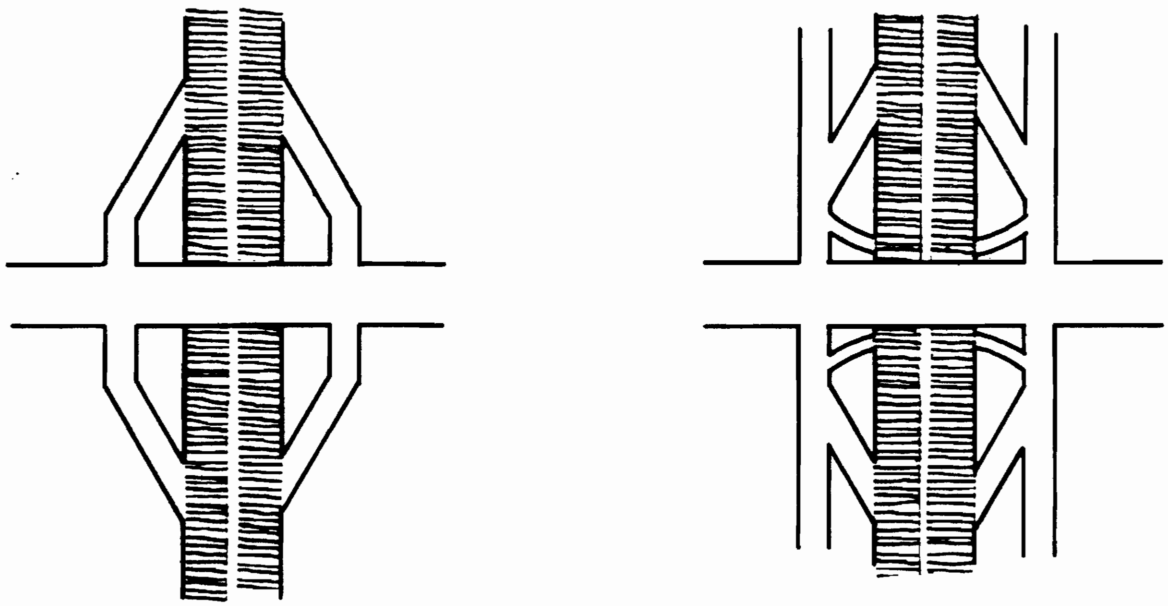
Diamond interchanges are widely used in urban areas as a means to transfer freeway traffic to and from the surface street system. These interchanges are almost always signalized with traffic actuated or pretimed signals. This report addresses this subject and seeks to provide useful information for guiding future engineering decisions regarding the selection and specification of traffic actuated signal control systems at diamond interchanges.

The following sections of this chapter provide background to the research study and the problems addressed. Texas urban freeway design will be examined to illustrate traffic flow problems unique to Texas cities requiring a wider set of efficient signal control strategies than is usually required in other states. With this background, the scope of research will be defined and study objectives noted. An overview of the report contents will be provided and related to implementation requirements.

TEXAS DESIGN

Policy and Practice

Early freeway design policy decisions were made by visionary highway engineers in Texas to provide frontage roads along all urban freeways in Texas. Exceptions were made only at major interchanges and other costly situations, such as at railroad and river crossings. Figure 1-a illustrates the normal full diamond interchange design configuration found in most of the United States (1). This design is practically non-existent in Texas cities. The common urban Texas diamond design has continuous one-way frontage roads as depicted in Figure 1-b. The crossroad may be an overpass or underpass, with overpasses being more prevalent in earlier designs. Turnarounds, or U-turn lanes, may be provided as a connection between the frontage roads.



(a) Full Diamond Interchange

(b) Full Diamond Interchange with Frontage Roads

Figure 1. Types of Full Diamond Interchanges (1).

Traffic Patterns

Traffic flow patterns through a diamond interchange can be very complex and highly variable depending on the design, location and conditions. Off-ramp traffic at a conventional diamond interchange without frontage roads generally takes one of two paths. It either turns right at the first signal and leaves the interchange area, or it makes a left turn and proceeds on through the other intersection of the interchange. Observations indicate that it is very uncommon for an off-ramp vehicle to come up, make a left turn at the first signal, make a left turn at the second signal, and then get back on the freeway proceeding in the opposite direction. In other states, almost no U-turn traffic occurs since no local access is provided to land use activities contiguous to the freeway. Turnaround (U-turn) lanes, consequently, are seldom provided outside of Texas.

Frontage roads used in Texas promote three other types of traffic flow not common to conventional full diamond interchanges without frontage roads. Firstly, Texas diamond interchanges may have considerable freeway off-ramp traffic traveling across the intersection, a move generally prohibited in conventional full diamond interchange design. Secondly, peak hour inbound and outbound tidal flows may occur along the frontage roads on many urban freeways in Texas, particularly the radial oriented ones. This additional flow adds to the traffic crossing the interchange. Thirdly, as traffic volumes on Texas urban freeways have steadily risen over the past 20-30 years, maintenance operations for repairing pavement, safety fixtures and bridges on freeways are becoming more numerous. Due to the resulting freeway congestion and available alternative routes, traffic diverts from the freeway to the frontage roads to reduce delay. Similar diversion responses occur due to major freeway accidents and incidents when substantial freeway delays (say, 20 minutes or more) are likely. This third type of traffic flow using frontage roads places additional traffic demand on the interchange signalization.

The level of service in the freeway corridor is significantly increased due to this capability of the frontage roads to handle traffic movement parallel to the freeway. However, the variability of traffic movements and traffic demands on Texas diamond interchanges are much higher than those located in any other state.

Signal Systems

Additional traffic functions are required of traffic control systems at diamond interchanges in Texas requiring advanced control capabilities and flexibility. Traffic actuated diamond interchange controllers are frequently used in signal systems either for progression of traffic flow across the interchange (along the cross street) or for progression along the frontage roads. Phase sequence flexibility provides for improved progression efficiency and smoother traffic flow.

Summary of Requirements

This discussion has shown that an unusually demanding requirement exists in Texas for efficient, responsive and reliable diamond interchange traffic signal control. A wider variety of traffic volumes, traffic patterns, control functions and geometrics probably exists in Texas than in any other state in America.

In response to these demanding requirements, approximately 100 isolated, full-actuated diamond interchange controllers have been installed in Texas that permit implementation of and switching between three-phase and four-phase operations. These controllers sense traffic volume and pattern changes and many actually switch automatically between the two phasing sequences based on existing traffic patterns.

STUDY PROBLEM STATEMENT

The selection of the optimal traffic control system for diamond interchanges is an important and challenging task. Little previous research has been conducted to determine the relative benefits of traffic actuated signal control. Preliminary traffic studies (2, 3, 4) of local problems indicated that traffic congestion might occur with inefficient control but these studies did not deeply explore system performance characteristics. The need to perform these detailed studies was recognized and identified in both of the previously reported traffic studies.

Exploration research studies were conducted by TTI to examine various data collection and reduction methods to identify the general nature of urban diamond interchange control and to develop detector subsystems to be further evaluated. Following these developmental feasibility studies, modification was made to an existing HPR research Study No. 2-18-83-344 entitled, "Guidelines for Diamond Interchange Control" to expand the scope of research.

The additional problem area addressed only signalized diamond interchanges in large urban areas having traffic actuated control. A complex interaction of design and performance variables was indicated. The TTI study showed that traffic flow depended on interactions involving the operational control of three-phase and four-phase control, signal controller timing parameters, and detector layouts. The development of clear and useful guidelines and specifications for designing and operating traffic signal control at diamond interchanges in Texas would require a comprehensive investigation of the interaction of decision variables; namely, the operational control of (1) three-phase and four-phase control, (2) signal timing parameters and (3) detector layouts.

STUDY OBJECTIVES

Two specific research objectives of Study 344 are addressed in this report. These study objectives were as follows:

1. Analyze operational results to determine the relative efficiency of traffic control systems involving three-phase and four-phase control and detector layouts for isolated signalized diamond interchanges.
2. Develop guidelines to aid in the selection of optimal traffic control systems for isolated diamond interchanges.

A technical advisory panel was formed early in the study to provide a broad field of operational expertise in diamond interchange control. State and city traffic engineers participated throughout the study and provided technical input and guidance to the research effort. The panel was helpful in finding sites for field studies that had the desired geometric, traffic and control attributes.

Early in the research, it was agreed by all parties participating in the study that all evaluations would be based on field measurement and observation supported by a theoretical understanding of the processes involved. Assessment of system features would combine practical and statistical considerations. This approach was consistently followed throughout the project.

Other research objectives were addressed in a prior project report (5). This report dealt with the development of guidelines for the installation of signals at diamond interchanges where stop sign control presently exists.

REPORT OVERVIEW

The earlier studies showed a need to develop a clear and documented understanding of the operational performance of the various system design and control variables as related to traffic patterns and volume levels. Tradeoffs needed to be identified between three-phase and four-phase control as well as within detection configurations. This report addresses these issues to the extent that the data, statistical analysis and practical observations permit.

The following is an overview of the contents of the remaining chapters of this report. Chapter 2 describes the system design features of three-phase and four-phase control. Signal phasing patterns are illustrated. Single-point and multi-point detection plans used with each type of phasing are noted. Chapter 3 describes the research plan and methodology from site selection to statistical analysis.

Study results are presented in Chapter 4. Graphical plots of traffic performance versus volume are provided for each type of control and interchange. Statistical regression equations are developed to relate important input variables to traffic performance. Guidelines for designing optimal signal system configurations for diamond interchanges are provided.

The research results also contain some limitations. Field studies were conducted at four interchanges where three-phase and four-phase control systems could be tested. Field observations and subsequent statistical analysis of the data revealed that the experimental signal system installed at one interchange did not perform as expected. This problem site is further described on page 23. While the observational data were used to the extent possible, no aggregation of the data with the remaining three good data sets was possible. With the exception of one case where an accident occurred due to an inattentive driver reading a road map instead of watching the signal change to yellow (which by chance also occurred at the same problem site), no other noteworthy problems arose during the study. Due to data base limitations, however, causal relationships between traffic performance and specific signal settings (minimum green, gap timing and maximum green) could not be developed.

II. DIAMOND INTERCHANGE CONTROL

BACKGROUND

Traffic actuated control at diamond interchanges is similar in many respects to that used for intersection control. A solid-state traffic actuated controller unit is often used at diamond interchanges, sometimes with only minor phase-overlap programming and some external logic added to the basic controller unit. Traffic detectors are placed on all approaches to the interchange. Single-point or multi-point detection patterns may be used.

System design characterization of traffic actuated diamond interchange control studied in this research included the following four basic attributes:

1. Phasing (three-phase, four-phase),
2. Detection (single-point, multi-point),
3. Settings (initial, gap, max) and
4. Geometry (spacing, turnarounds).

Description of these control systems will be provided by the two principal categories of control; namely, three-phase and four-phase. Other system attributes will be included within these two signal phasings. All signal control systems tested provided basic, full-actuated control. No volume density features were permitted. The control units were fine-tuned in the field to provide reasonably snappy operations. Gap sizes and minimum greens were set reasonably short in relation to minimums provided by the various detector designs. No tendency to prematurely gap out within starting platoons was observed. In all cases, the same minimum phase settings (Max 1 and Max 2) were applied to the three-phase and four-phase control strategies.

THREE-PHASE CONTROL

Phasing

The basic three-phase system used for traffic actuated control of diamond interchanges in Texas is presented in Figure 2. While 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. Phase 1 includes both frontage green signals to simultaneously provide protected movement into the interchange.

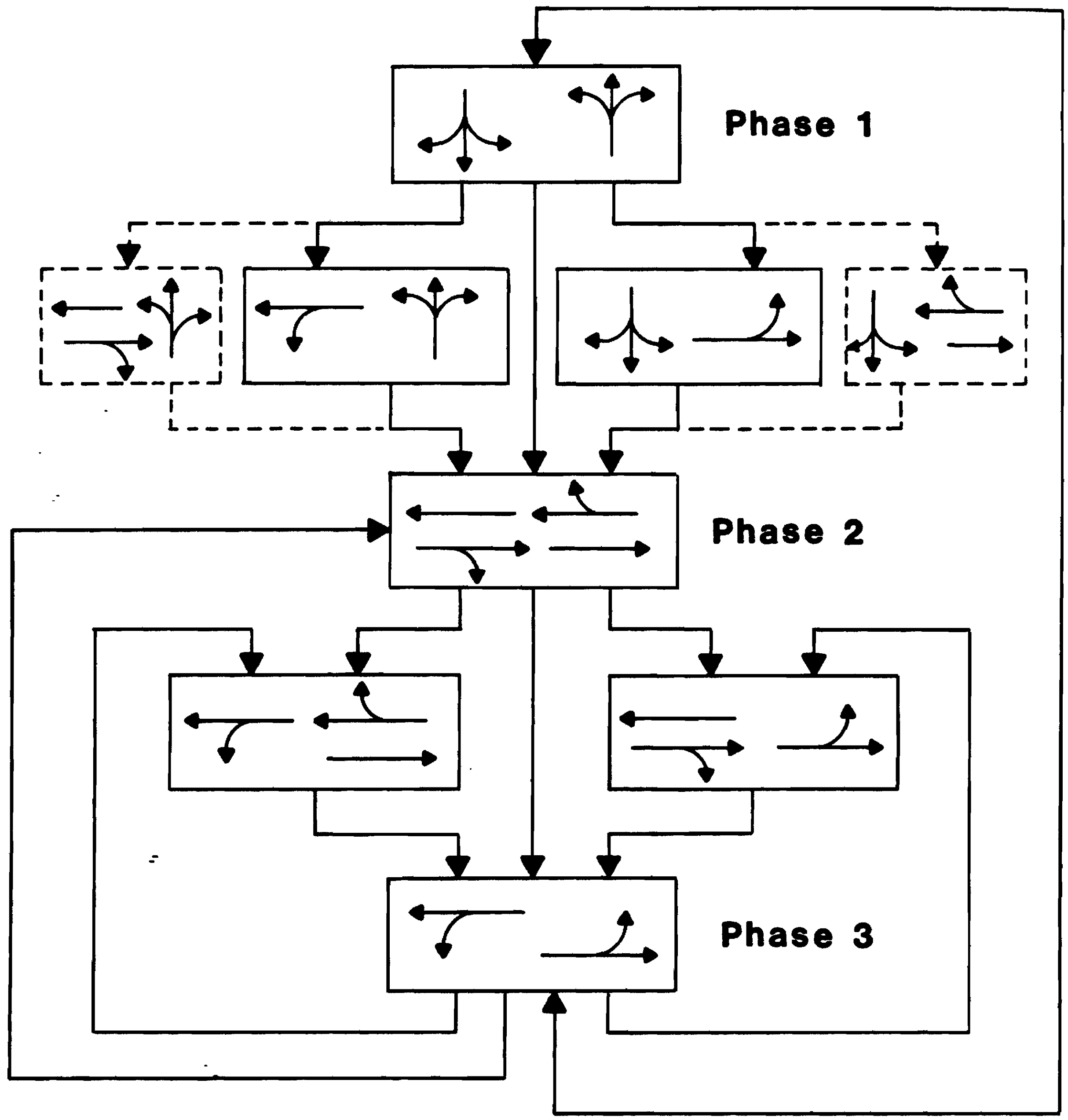


Figure 2. Three-Phase Full Traffic Actuated Diamond Interchange Phasing.

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.

Phase 2 is the main cross-street, inbound-outbound phase without protected left turns. Permissive left turns, when permitted, are infrequently observed during heavy traffic. Phase rotation from Phase 3 back to Phase 2 may occur during light traffic conditions when no frontage road calls exist. Outbound gap-out of a through movement results in an early protected left turn phase occuring prior to Phase 3.

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

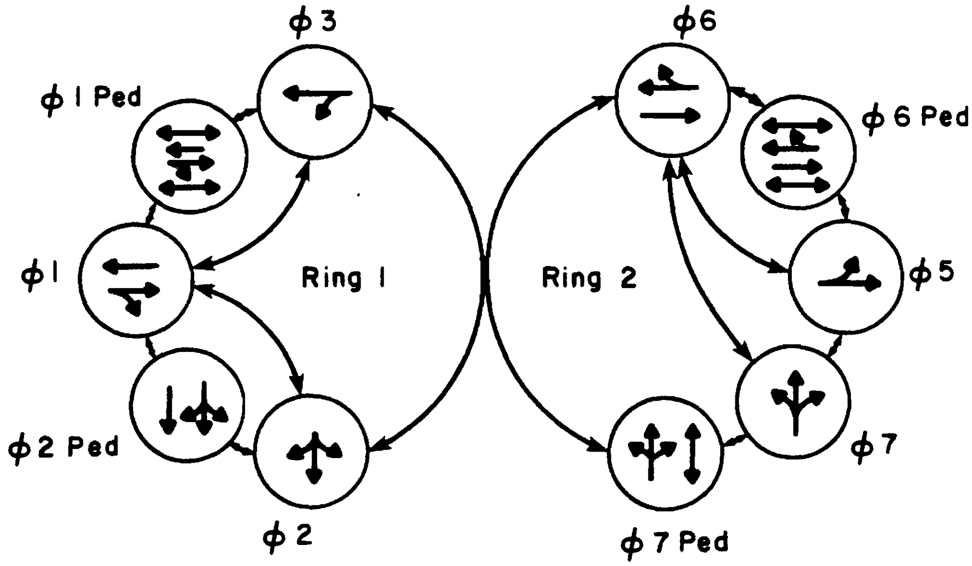
All phase movements shown in Figure 2 for Phases 1, 2 and 3 move concurrently during a portion of a phase. Each movement individually gaps out, however, depending on the immediate traffic demand. The alternative phases, noted by the dashed lines in the figure, can be programmed by the engineer to selectively replace the depicted phases. Pedestrian and vehicle change intervals are not shown.

Figure 3 presents a description of the individual phase movements phase that are combined by rings, rotation and overlaps in the actuated controller to produce the observed signal phases shown in Figure 2. One intersection contains ring 1 and phase movements *1, *2, and *3. The other intersection contains phase movements *5, *6, and *7. Outbound through movements are paired with the contiguous left turns and overlapped with the inbound through movement phases.

Detectors

Two types of detector configurations were studied for three-phase control; namely, (1) single-point and (2) multi-point. 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, i.e., at least one detector station per approach. While there were on-site variations due to approach speed, geometry and presence/absence of



INDIVIDUAL PHASE MOVEMENTS

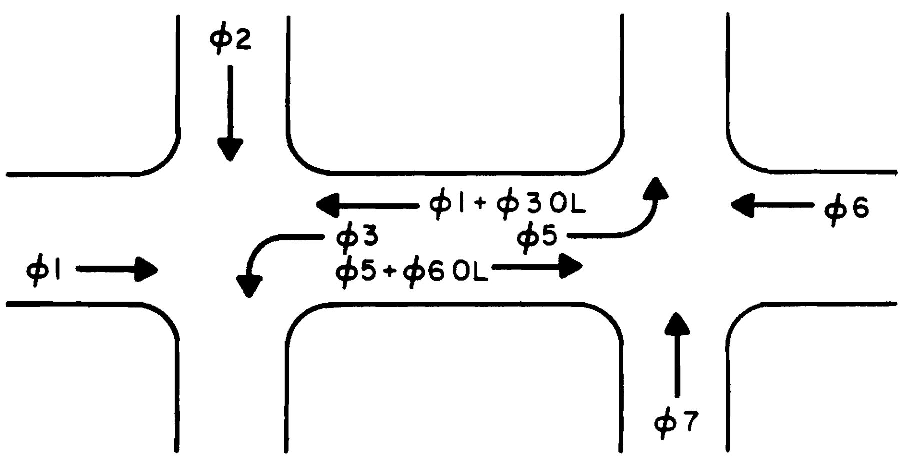


Figure 3. Individual Phase Movements and Ring Rotation for Three-Phase Control.

left-turn bays, there was a basic plan for each detector configuration. In the single-point detector plan, illustrated in Figure 4, one detector is placed on each frontage road approach. Detector setback from the stop bar varied with approach speed, but often was about 100 feet. This placement gives a minimum required phase time of about 14 seconds. 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 feet to the stop bar; for South Drive, it was only about half this value.

Detector design for the interior movements also depended on whether a left-turn lane was present. At South Drive in Ft. Worth, where no left-turn bay existed, permissive left turns were allowed and a long loop with non-locking operation was provided. At other locations, all having turnaround lanes and left-turn lanes, single calling loop detectors were used. Single calling and extension detectors for the outbound through movements were provided. The average distance to the stop bar was about 75 feet.

Multi-point detection in three-phase control added one additional detector across all lanes on all inbound phases (*1, *2, *6, and *7 of Figure 3) as depicted in Figure 5. One detector was located about 100 feet from the stop bar as in single-point detection and the other detector was located midway to the stop bar at about 50 feet. Again, actual detector placement depends on approach speed. Multi-point detection permits a slightly smaller minimum green with only slightly smaller gaps for extension timing.

Features

Three-phase operations provide several features of traffic actuated control that should be noted and contrasted to those provided by four-phase control. Three-phase moves the four principal inbound movements in only two of the three basic phases. Frontage road movements (*2 + *7 in Figure 3) initially move concurrently in Phase 1 while the cross-street movements (*1 + *6) initially move simultaneously in Phase 2. From an input capacity standpoint, the internal left turn phase (*3 + *5), or Phase 3, used to clear the interior of the interchange, is a nonproductive phase. However, the fact that the four principal movements move in two phases substantially offsets this one clearance phase. Fewer phases usually means a shorter cycle length thereby resulting in lower delay than provided by a longer cycle. Some

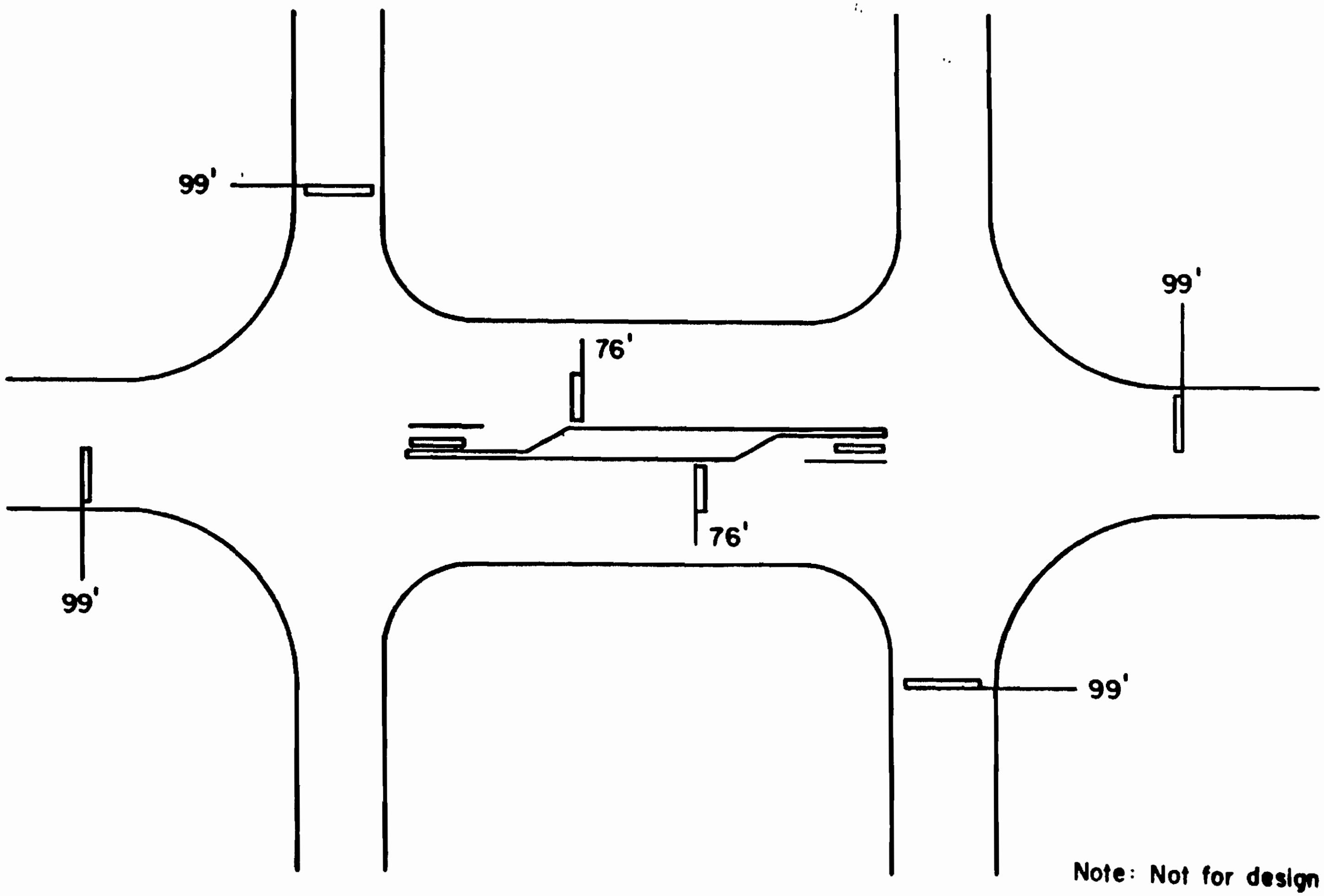


Figure 4. An Illustration of Three-Phase, Single-Point Detector Layouts.

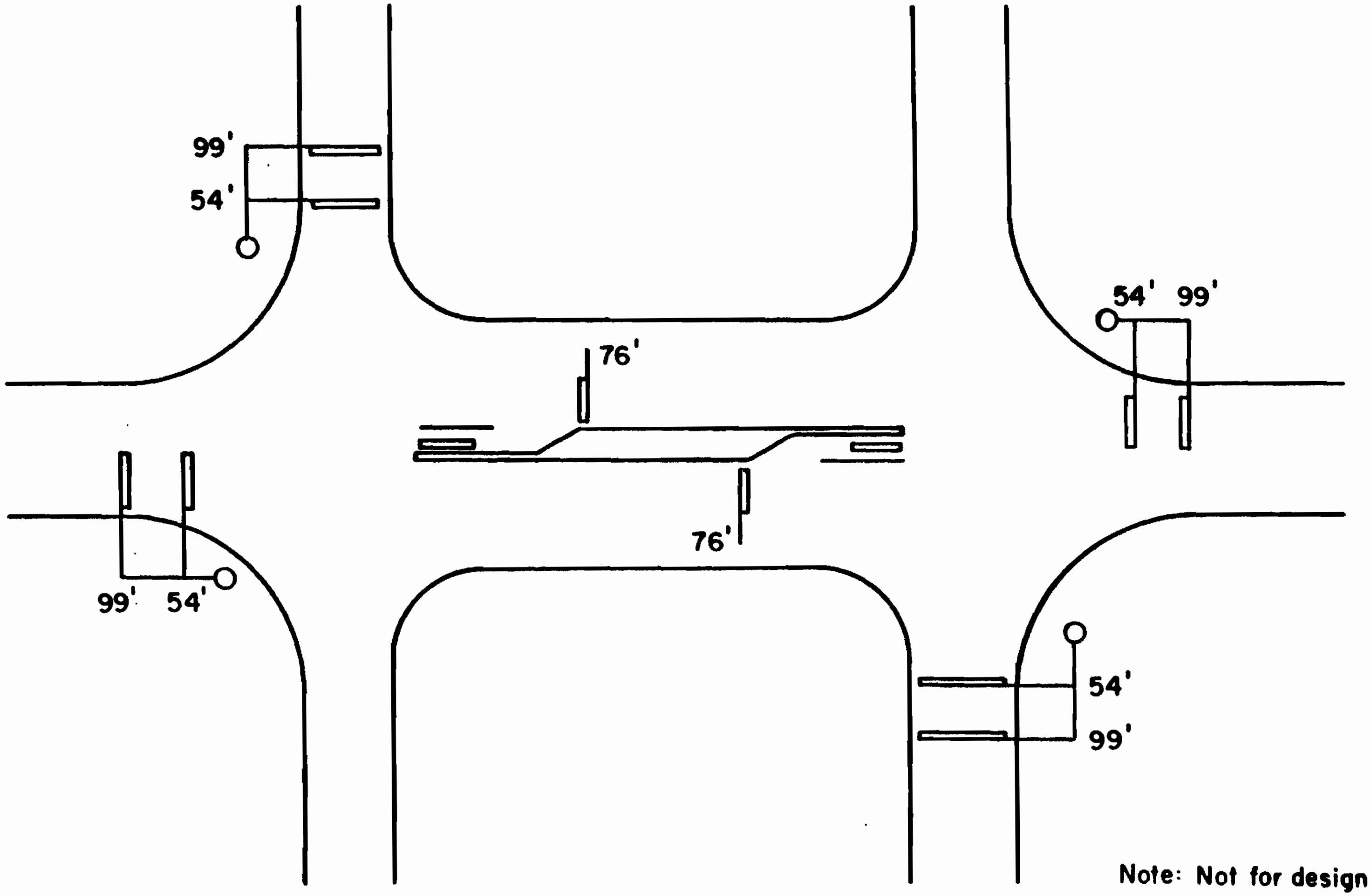


Figure 5. An Illustration of Three-Phase, Multi-Point Detector Layouts.

capacity increase is possible under light left turn traffic within the interchange together with permissive left turns in light traffic associated with phase movements *3 and *5 in Figure 3. In addition, with control dwelling in Phase 2 with light traffic and permissive left turns, a phase change is not required to service a cross-street left turn at either intersection, i.e., both signals can be in permissive green with long loop operation with the detector in the delay timing state. It is also possible to have two left turn phases in a cycle, one following Phase 1 and one following Phase 2. This may be an attractive feature under some traffic conditions.

Three-phase also was observed to have a few negative features. Phase 1 tends to fill the interchange with vehicles as the phase continues to extend and as the volume of simultaneous left turning vehicles increases. Queueing tends to become pronounced within narrow interchanges (distance between frontage roads is short) if simultaneous frontage road left turning volumes are large. Phase 1 must be kept relatively short for three-phase control to work well under moderate-to-high volume conditions particularly at small (narrow) interchanges. The smaller the interchange, the shorter Phase 1 should be. Otherwise, unexpected stoppage of frontage road turning traffic may arise. Generally speaking, three-phase control tends to be susceptible to locking up and thereby losing capacity at higher volumes and smaller interchanges. This is because two output movements are potentially blocked in each phase. In Phase 1 of Figure 2, the two left turns from the frontage roads may be blocked; in Phase 2, two arterial left turns are blocked; and in Phase 3, the protected lefts may be blocked by long storage queues that in themselves may be blocked if left turns are present. Thus, the cycle length in three-phase control generally should be kept short.

FOUR-PHASE CONTROL WITH OVERLAP TIMING

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 "TTI 4-phase with overlaps." In reality, six discrete phases are required when all phases are calling. The phasing sequence is as depicted in Figure 6. Note that phase

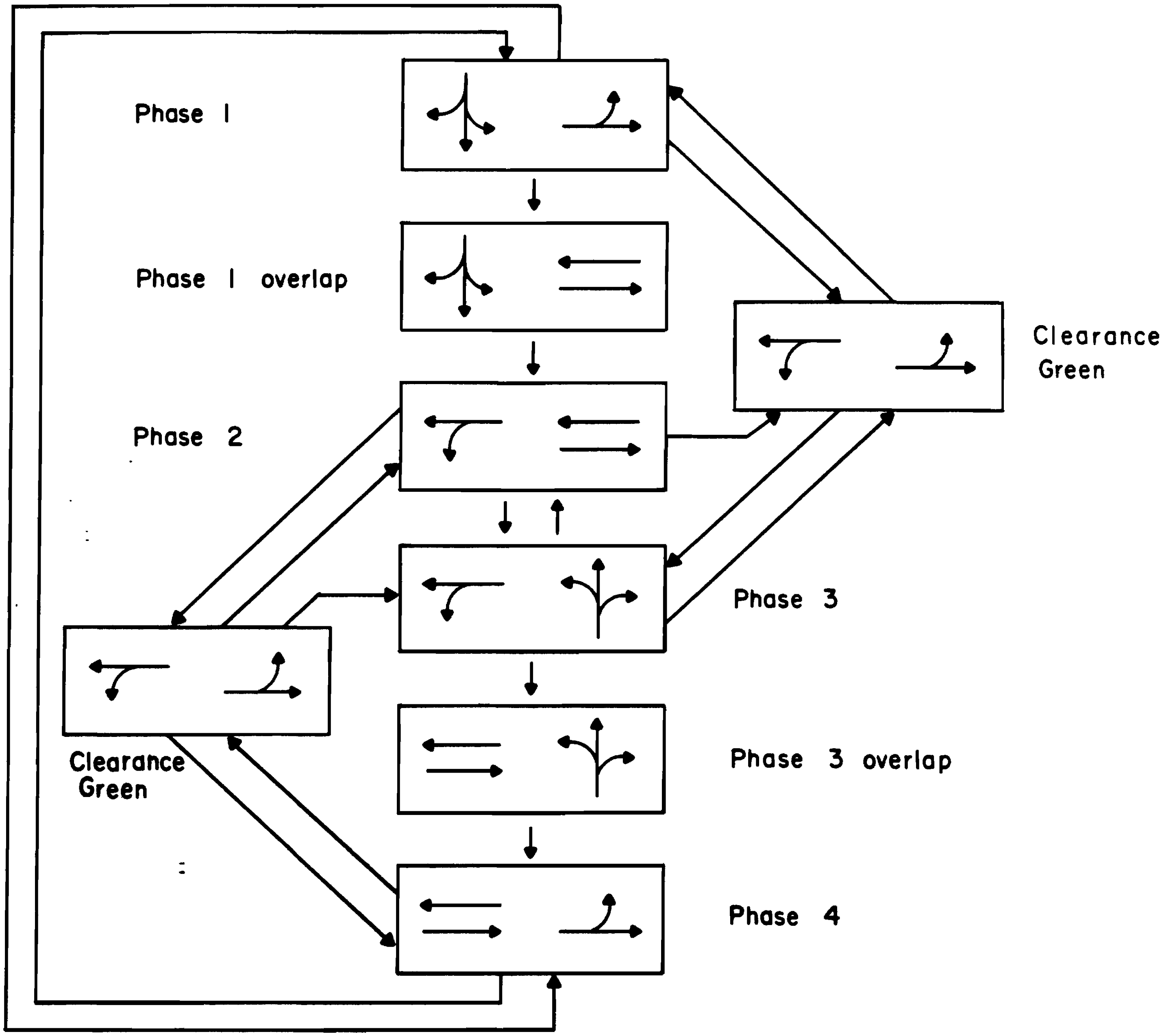


Figure 6. Four-Phase Full Traffic Actuated Diamond Interchange Phasing.

numbering is different between three-phase and four-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 an inbound, actuated cross-street phase. Note, however, that only one arterial approach initially receives the green at a time.

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

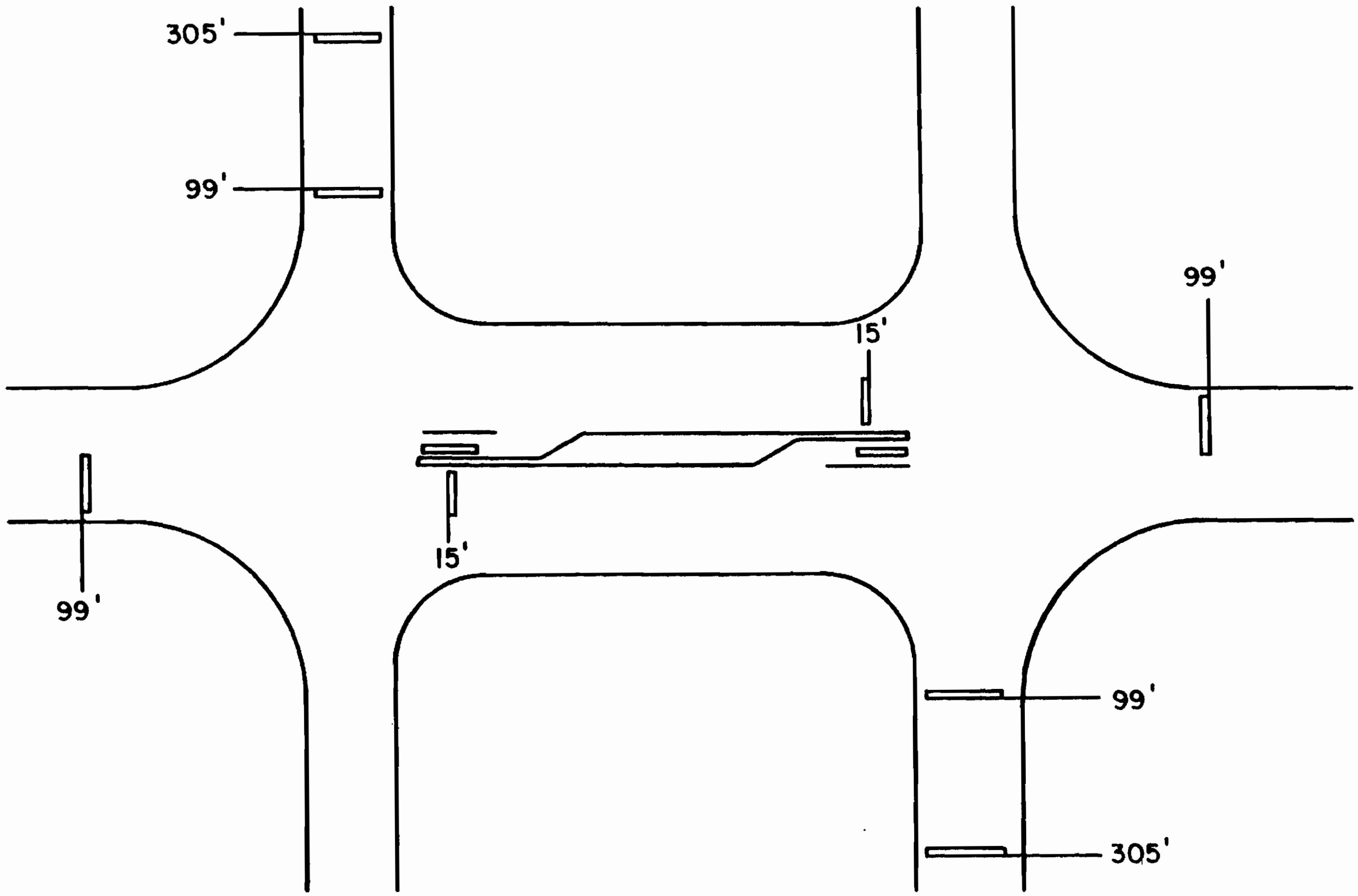
Phase 4 concludes the services of actuated phases for this type of control. Phase 4 is the arterial inbound phase and is similar to Phase 2.

Detectors

Two detector configurations were also tested for four-phase control; namely, (1) single-point detection and (2) multi-point detection. Figure 7 illustrates a typical detection plan for four-phase, single-point detection; whereas, Figure 8 presents a common detector layout for four-phase with multi-point detection. Some variation in the detection plan was made at each site to best accommodate each interchange's geometrics and approach speeds.

Due to high volumes of low speed, turning traffic observed on the cross-street inbound approaches, practically no variation in single-point and multi-point 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 feet from the stop bar, the same as three-phase. In four-phase, multi-point detection, an additional detector was placed about 50 feet 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.

The big difference in detector patterns between three-phase and four-phase control occurs on the frontage roads. Detector switching between sets of detectors was used in four-phase for both single-point and multi-point operations. Frontage road speeds often are high (40-50 mph) in the off-peak as traffic powers off the freeway toward the diamond interchange. Frontage road speeds also can be fairly high even during peak hour traffic. Consequently, at phase gap-out some traffic engineers desire to provide



Note: Not for design

Figure 7. An Illustration of Four-Phase, Single-Point Detector Layouts.

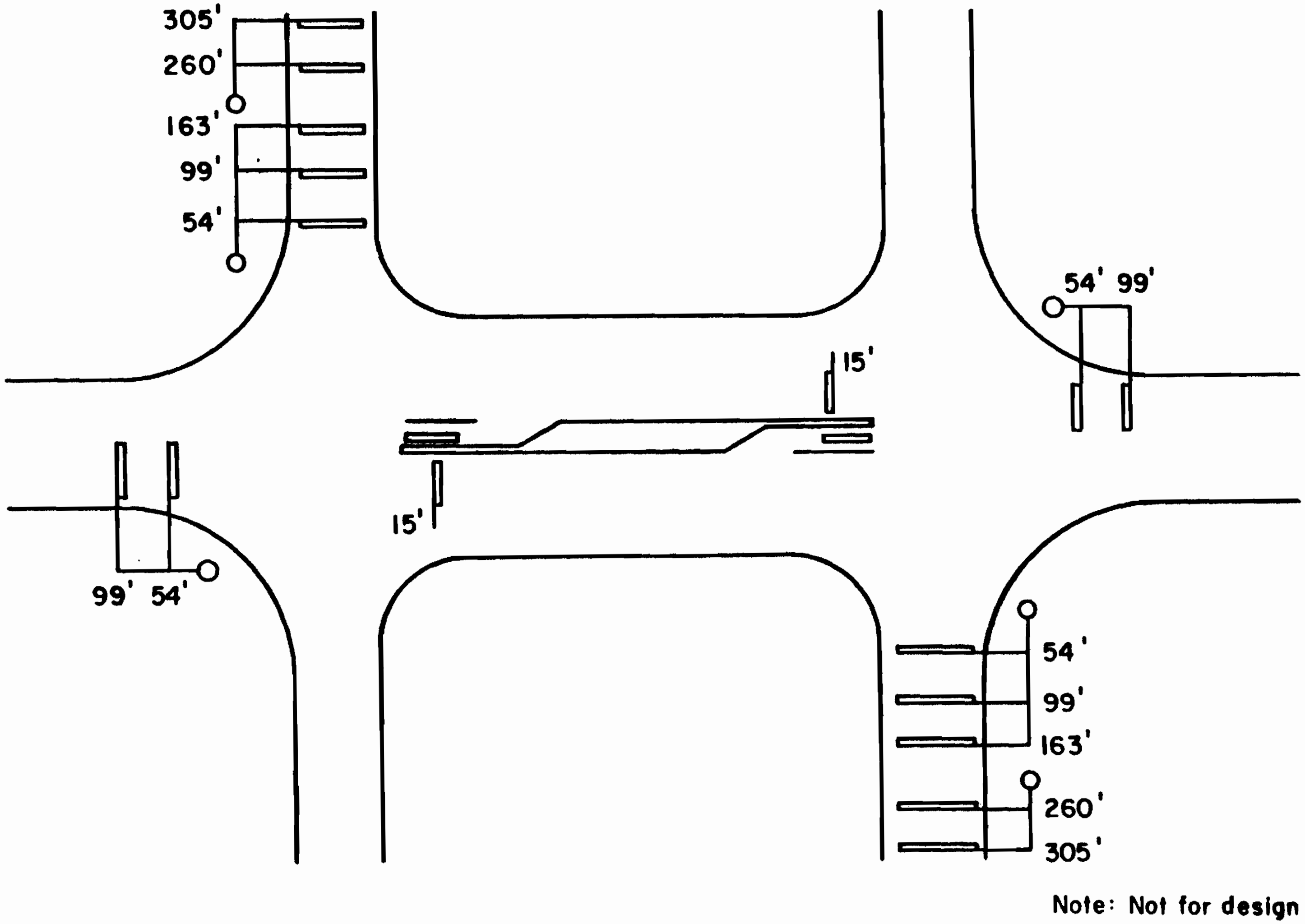


Figure 8. An Illustration of Four-Phase, Multi-Point Detector Layouts.

dilemma zone protection during the signal change interval for frontage road traffic. Operational efficiency of Phase 1 and Phase 1 overlap requires that
gap-out from Phase 1 to Phase 1 overlap (which has a fixed duration) occurs at a predefined distance (and time) upstream from the frontage road stop bar, say 7 seconds or more. Another detector is placed close to the intersection to call the phase and permit a short minimum green setting. For Phase 1 to be efficient, phase extension and gap-outs must be timed from the upstream, not downstream, detector. This control objective is attained by the controller switching from the near detector to the far detector station upon green onset, as noted in Figure 9.

Multi-point detection on the frontage roads used the five-detector Beierle system (6) shown in Figure 8. The three detectors located closer to the intersection are connected to one amplifier. These detectors protect vehicles approaching at speeds up to 40 mph. 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. These two detectors will extend the green when headways of 2.1-2.5 seconds are maintained, depending on actual speeds, and provides 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.

Detector switching is also used on the cross-street through movement detectors. These detectors selectively call Phase 2 (or 4) and extend the "clearance green" phases shown in Figure 5. At other times, they are turned off by the external logic card.

Features

Four-phase traffic actuated control is the mainstay of signal control for diamond interchanges. The phasing strategy features progression for all external inputs throughout the interior of the interchange except for frontage road U-turns. U-turning movements will not exist if interchange turnarounds

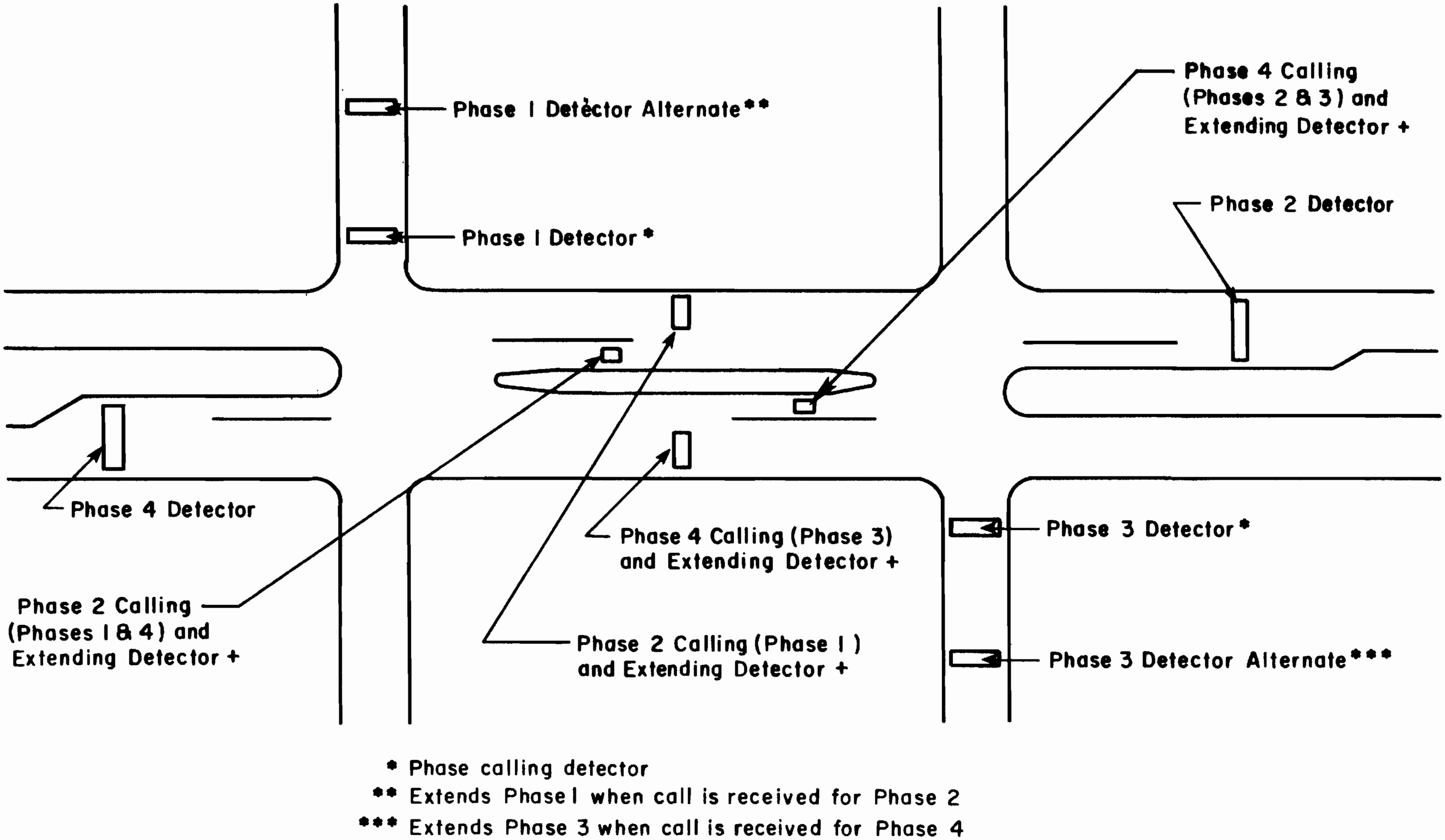


Figure 9. Detector Functions for Four-Phase Control.

are provided. Almost no vehicles are stopped within the interior of the interchange. The desirable progression features are provided at the expense of more external phases (four), longer cycles, and usually more exterior delay than occurs with three-phase control.

Perusal of Figure 2 for three-phase and Figure 6 for four-phase illustrates these phase relationships. We find that for three-phase:

$$C = G_1 + G_{1A} + G_2 + G_{2A} + G_3$$

and for four-phase:

$$C = G_1 + G_{1o} + G_2 + G_3 + G_{3o} + G_4$$

where G_i is a phase time and C is the cycle length. Note that there are five phases, having fixed-time change intervals in "three-phase", and six phases having fixed-time change intervals in "four-phase". Adding the six change intervals and two overlaps, there are eight intervals in the four-phase cycle that have a fixed duration. Thus, longer cycles tend to arise in four-phase due to the sequential nature of each major input flow and the large number of fixed intervals in the cycle. As the interchange becomes wider, the tendency increases for actuated control to produce longer cycles and greater delay.

With the exception of the very unusual case of no left turn bays, no turnarounds and very high U-turn volumes from the frontage roads, the control performance of four-phase, however, is generally not critically sensitive to the threat of "grid-lock" at high volumes or poor geometrics, as no input demands are potentially blocked by other movements. Progression and platoon clear-out within the interchange are typically provided for all movements at the expense of longer cycles. However, increasingly longer queues on the frontage roads or cross street may become a problem if they back into a freeway off-ramp or intersection.

III. RESEARCH PLAN

INTRODUCTION

The research approach was formulated by SDHPT and TTI at the inception of the study. Both groups believed that direct field observations of actual traffic flow and real control system performance were desired for this study. The financial resources available to the study limited the number of variables and sites that could be studied, however.

As the cost for installing detectors in the field and the cost of data analysis became better defined following a preliminary study conducted in Ft. Worth just prior to beginning this project, the final scope of research was narrowed to assessing the effects of the following three variables:

1. type of control phasing,
2. type of detector pattern, and
3. effects of geometrics.

Effects of signal settings were deleted since a full study of this parameter would have required a costly duplication of all field studies.

A total of four interchanges were planned for field study. Each interchange was selected to provide variation in intersection separation distance. All interchanges had continuous one-way frontage road operations and were adaptable to three-phase and four-phase control. The scope of study limited field observations to only one day per type of signal control system studied at each interchange.

Technical Advisory Panel

A technical advisory panel was formed early in Project 344 to guide the study and to provide contacts for selecting interchanges and implementing controlled research studies in the field. A total of 22 SDHPT and city personnel actively participated in the Technical Advisory Panel. SDHPT districts in Ft. Worth, Dallas, Houston, San Antonio and Abilene were represented. In addition, representative from the cities of Ft. Worth, Dallas, Irving, Houston and Abilene provided urban municipal expertise. A complete list of panel members was noted on page v. The cities of Mesquite and Carrollton provided support to related phases of this research effort.

Site Selection

Following discussions with and inputs from the Technical Advisory Panel, a list of potential interchange sites were obtained for possible study. For convenience of the research team and other practical considerations, most of these sites were located in the Ft. Worth and Dallas metropolitan area.

The research team and SDHPT representatives personally visited each of the candidate sites, reviewed signal design plans and discussed the attributes of each potential location. The following list of four interchanges were selected for study:

1. I.H. 20 at South Drive, Ft. Worth,
2. I.H. 20 at Green Oaks, Arlington,
3. S.H. 121 at Beach, Ft. Worth, and
4. S.H. 183 at MacArthur, Irving.

All four interchanges could provide three-phase and four-phase control with existing equipment. However four-phase control tested used a special NEMA 4-phase controller that had to be temporarily installed to provide single-point and multi-point (The Beierle Method (6)) detection. Three-phase control used the existing controller units.

INTERCHANGE CHARACTERISTICS

The four sites offered a typical variety of geometric and traffic patterns. Some geometric commonality was also present. All interchanges provided continuous, one-way frontage road operations in a suburban environment. None were located downtown, for example. All interchanges were presently traffic actuated with each city having some experience with three-phase and four-phase control.

A summary of selected diamond interchange attributes is given in Table 1. The schematic layout of Beach, Green Oaks and MacArthur were similar. All three had turnaround lanes on both sides. However, MacArthur was a fairly small interchange, Beach mrlerately sized, and Green Oaks was a large interchange. Interchange lengths (distance along the cross street) ranged from 278 to 470 feet. South Drive was a very small interchange. It 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.

TABLE 1. INTERCHANGE SITE CHARACTERISTICS.

Interchange Cross-street Name	Dimensions Curb - to - Curb Outside	Dimensions Curb - to - Curb Inside	Queue Storage Distance	Turnaround Lanes Present	Left Turn Lane
South	232	160	150	No	No
MacArthur	278	220	200	Yes	Yes
Beach	382	310	290	Yes	Yes
Green Oaks	470	396	360	Yes	Yes

DATA COLLECTED

The data collection plan was developed from the experiences of earlier Study 344 work (5), the guidance provided by the Technical Advisory Panel, and significant supplemental financial and implementation support provided primarily by District 2 of SDHPT in Ft. Worth. Study protocol was influenced by practical considerations of minimization of impacts on existing traffic flow at critical urban interchanges.

The data collected at each site contained three types of measures: (1) traffic demand variables, (2) interchange control and geometric attributes, and (3) 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-minute time interval as being the time base for study. Each 15-minute 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-minute 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. Timelapse© 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-minute study period was identified. These six "critical" volumes, three at each intersection, were then tallied (added together) to form an "interchange total critical volume" for each study interval. That is:

$$VT = V_{1c} + V_{2c} + V_{3c} + V_{4c} + V_{5c} + V_{6c}$$

where

VT = interchange total critical volume, vphpl

V_{ic} = critical volume on approach i, vphpl

Subscripts 1, 3 and 5 relate to the three approach legs on one intersection;

whereas, subscripts 2, 4 and 6 relate to the corresponding movements on the other intersection. V_{3c} and V_{4c} 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 both as a dependent variable and as an independent variable at various stages of the analysis process. Cycle length for actuated 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 (1) initial green, (2) gap extension and (3) maximum green for each phase, together with other factors. An average cycle length over each 15-minute period was determined by averaging samples of 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 (7), in terms of stopped delay per vehicle. Stopped delay per vehicle on an approach serving an arrival flow of "v" vehicles per hour is:

$$d = \frac{Q \cdot T}{V \cdot T} = \frac{Q}{V}$$

where

d = stopped delay, sec/veh,

Q = average number of vehicles stopped in queue at signal during the study interval, veh,

V = approach flow, veh/sec, and

T = study interval, sec.

To obtain a strong statistical model, this study observed stopped queues (the only kind normally measured) at an intersection each 15 seconds and averaged these 60 (15 x 4) samples over 15-minute periods to obtain mean stopped queues per 15-minute periods. Queues were observed for each approach lane. Maximum queue or average queue per lane could then be determined.

Maximum queues per lane per approach were determined during data reduction. Denote each maximum (critical) queue per lane per approach as Q_i.

Total interchange queue was then derived from the six approaches similar to total input volume. Total interchange critical queue is equal to

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

where

QT = total interchange critical queue, veh/lane

Q_{ci} = maximum queue per lane on approach i, veh/lane

Total interchange critical queue is used as the traffic control system performance measure of operational efficiency. Comparisons between system design attributes can be effectively made at the same total volume levels. Equation 2, however, 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 four interchanges were conducted at the locations and times noted in Table 2. Data were collected from Tuesday through Friday during the Spring and Summer of 1984. A typical TTI field study team was composed of eight field observers plus one study supervisor.

Factorial Design

A two-by-two factorial design was tested on each of the interchanges. Two phasings (three-phase and four-phase) and two detector patterns (single-point and multi-point) were studied. Each of the four resulting system combinations (phasing-by-detector pattern) was studied one day. A summary of the study design and schedule is presented in Table 2.

Study Periods

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. - 9:00 a.m. followed by a breakfast break. A two-hour study of off-peak and noon-hour traffic began at 11:00 a.m. and lasted until 1:00 p.m. Several

TABLE 2. OVERALL RESEARCH STUDY SCHEDULE.

Diamond Interchange	City Location	Study Date	Control Phasing	Detector Pattern
I.H. 20 at South	Ft. Worth	4-24-84	4	Single
		4-25-84	4	Multiple
		4-26-84	3	Single
		4-27-84	3	Multiple
S.H. 183 at MacArthur	Irving	5-15-84	4	Single
		5-16-84	4	Multiple
		5-17-84	3	Single
		5-18-84	3	Multiple
I.H. 20 at Green Oaks	Arlington	7-10-84	4	Single
		7-11-84	4	Multiple
		7-12-84	3	Multiple
		7-13-84	3	Single
S.H. 121 at Beach	Ft. Worth	7-24-84	4	Multiple
		7-25-84	4	Single
		7-26-84	3	Single
		7-27-84	3	Multiple

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-minute study intervals were obtained by all staff synchronizing their watches before each study. The study plan thus provided five hours of observation time per day with four data points per hour for a total of twenty (5 x 4 = 20) data points obtained per system configuration per interchange.

Implementation

An extensive amount of field preparation and logistical effort were required to test actual controller performance at real-world interchanges using each detector configuration. This approach required major commitments of labor and equipment by SDHPT. At some interchanges, over 15 new detectors had to be installed. Modifications to detector wiring and hook-up were required before and after each test.

Four-phase control tested at all interchanges was provided by a standard four-phase standard NEMA controller with added SDHPT external logic cards. The controller was routinely brought from Austin and installed for each study. The existing controller would be removed on Monday and the NEMA controller installed and tested Monday night and early Tuesday morning. The existing controller (always a three- and, four-phase Crouse-Hinds DM 800 eight-phase controller with special internal programming) provided the three-phase control tested on Thursday and Friday. Signal control was returned to the pre-existing normal state on Friday evening following completion of the study. Under the best of working conditions, this complex interchanging of controllers and detector configurations was a difficult job.

Problems

As it turned out, one of the study sites (SH 183 at MacArthur) did not perform up to standards expected for three-phase control and for one of the two four-phase studies. Existing evidence suggests that two critical call and extension detectors may have been accidently switched in the complex task of rapidly wiring controllers to detectors. Consequently, most of the data collected at MacArthur could not be used as planned. See page 47 for additional information.

DATA REDUCTION

Three levels of data reduction were performed. A brief description of these activities follows.

Field Reduction

All manually recorded queue and turning movement counts were routinely logged in 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.

Manual Processing

A considerable quantity of data had to be manually reduced in the office by staff personnel. Queue counts, in particular, required a lot of time. Queue counts were being recorded on scribble pads at six approaches by lane each 15 seconds. This sampling rate results in about 1,000 queue samples for all lanes each 15-minute 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.

Computer Processing

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 run on the data to further check for coding errors. Following a final perusal of the data sets, data analysis began.

DATA ANALYSIS

The reduced data were analyzed using statistical analysis techniques. Statistical Analysis System (SAS) 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 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 subsequently presented.

Basic Summary and Descriptive Statistics

The following descriptive statistics are presented in quantitative or graphical form as appropriate:

- measures of central tendency such as mean and median,
- measures of dispersion such as variance, range and percentile, and
- frequency distribution.

Regression Models

Regression models were used to evaluate factors affecting diamond interchange operations for different signal phasings and detector configurations. Regression models are useful for the following reasons:

1. To detect the significance of models and relationships characterizing diamond interchange operation such as queue vs. volume, cycle vs volume, and queue vs. cycle.
2. To obtain the expected value of variables affecting diamond interchange operation such as cycle length.
3. To examine the functional effects of traffic and geometric attributes affecting diamond interchange operation such as left turn volume and internal queue storage length.

General Linear Hypothesis Testing

Hypothesis testing was performed to evaluate the statistical significance of independent variables and the significant difference in diamond interchange operation between different signal phasings and detector configurations. Hypothesis testing is useful for the following reasons:

1. To detect the significance of independent variables and their interactions affecting diamond interchange operation such as internal volume, left turn volume, and left turn volume over internal volume.
2. To detect any significant difference between different signal phasings (three-phase vs. four-phase) or detector configurations

(single-point vs. multi-point detector plans).

The primary variables characterizing diamond interchange operation are traffic volume, queue and cycle length. Further geometric characteristics of a diamond interchange will also affect its operation.

Traffic Variables

Interchange traffic volume was separated by its external and internal flow. Further, left turn volume within the internal flow was analyzed. The interaction variables between these flows were also examined. Following is the summary of traffic variables analyzed in the study.

1. External volume: Sum of four external approach critical lane volumes.
2. Internal volume: Sum of two internal approach critical lane volumes, internal left turns plus internal throughs.
3. Interchange volume: Sum of external and internal volumes.
4. Internal left turn volume: Left turn critical lane volume within internal volume.
5. Ratio of internal to external volume (RIE): Characterization of relative sensitivity of internal volume given external volume.
6. Ratio of internal left turn to internal volume (RILI): Characterization of relative sensitivity of internal left turn volume given internal volume.
7. Ratio of internal left turn to external volume (RILE): Characterization of relative sensitivity of internal left turn volume given external volume and representation of interaction between RIE and RILI (i.e., RIE x RILI = RILE).

Geometric Variables

Inernal storage length was analyzed to represent the effect of internal geometric characteristics on diamond interchange operation including the possible spillover effect onto external approaches.

Interaction of Traffic and Geometric Variables

Following is the summary of interaction of traffic and geometric variables examined.

1. Cycle length: Characterization of combined processor of interchange traffic, geometric, and signal control variables.
2. Maximum internal critical lane volume standardized by its queue storage length: Characterization of interaction between internal traffic and its geometric conditions (i.e., max (Int 5, Int 6) / (SL/20)).
3. Maximum internal left turn lane volume standardized by its storage length: Characterization of interaction between internal left turn traffic and its geometric conditions (i.e., max (IL 5, IL 6)/(SL/20).

Evaluation Processes

The set of models tested was evaluated to select the best representation of interchange operational characteristics observed for different signal phasings and detector configurations. Recall that the objective of this study is to develop guidelines on when and where different phasing arrangements and detector configurations are beneficial in reducing delay. Consistency of independent variables in characterizing different systems is an important criterion in the evaluation process. These evaluations were made to determine the advantages and disadvantages of a particular operating system on an identical set of variables throughout the systems evaluated.

IV. FIELD STUDY RESULTS

Presentation of field study results follows. Characterization of traffic observed at each interchange will introduce the field observation results. Cycle length and traffic delay findings are then presented. Queue characteristics observed for different phasings are illustrated. These field study results will be presented by interchange and operational system.

GENERAL CHARACTERISTICS

Traffic Volume

Traffic counts per lane were made at the six intersection approaches to each interchange. Total approach critical lane volumes were obtained for 15-minute time periods and expanded to equivalent hourly flow rates. These 15-minute volumes are the basic volume measure used in this study.

Table 3 presents the range of total volumes observed at the four interchanges. The interchanges are sequenced according to rank of highest observed volume. Total volume is the sum total of the six approaches' expanded critical lane volumes. Volumes were similar among the four control systems tested at each interchange. Maximum total critical lane volume ranged from 1940 vehicles at South Drive to 2,596 vehicles at Beach. Maximum volumes were consistently about twice minimum values.

The observed traffic volume characteristics indicate that comparisons of operational systems at each interchange can be performed at a relatively stable and common background of traffic volume. Further, Table 3 reveals that the four interchanges provide a consistent range of traffic volumes such that any sensitivity of the operational systems to traffic volume can be detected.

Traffic Patterns

Traffic patterns at the interchanges are characterized by two parameters. The first one is the sum of traffic volume at internal stations. The second is the sum of internal left turning traffic at all internal stations. These two parameters appear to adequately characterize the observed traffic patterns.

Table 4 presents the range of observed internal critical volumes and left turn volumes at the four interchanges. It is seen that the four interchanges

TABLE 3. RANKING OF FOUR INTERCHANGES BY HIGHEST TOTAL HOURLY CRITICAL LANE VOLUME.

Rank	Interchange Location	Operational System [a]	Total Interchange Critical Lane Volume Per Hour	
			Highest	Lowest
1	Beach	3S	2596	1184
		3M	2160	1344
		4S	2492	1272
		4M	2460	1204
2	Green Oak	3S	2352	1248
		3M	2304	1204
		4S	2436	1228
		4M	2348	1276
3	South Drive	3S	1940	1080
		3M	2000	1076
		4S	1980	1140
		4M	2004	1052
4	MacArthur	3S	2436	1244
		3M	2176	1432
		4S	2276	1232
		4M	2476	1420

a: 3S = Three-phase, Single-point detection
3M = Three-phase, Multi-point detection
4S = Four-phase, Single-point detection
4M = Four-phase, Multi-point detection

TABLE 4. OBSERVED INTERNAL AND LEFT TURN VOLUME PER HOUR.

Interchange Location	Operational System	Internal Critical Volume per Hour		Internal Left Turn Volume per Hour	
		Highest	Lowest	Highest	Lowest
Beach	3S	1084	444	412	244
	3M	828	464	440	168
	4S	1076	496	388	176
	4M	1000	480	360	216
Green Oak	3S	924	440	924	332
	3M	892	408	892	308
	4S	952	396	952	264
	4M	972	416	972	416
South Drive	3S	532	256	532	248
	3M	556	248	556	232
	4S	492	236	492	228
	4M	532	232	532	232
MacArthur	3S	1364	688	1084	156
	3M	996	588	684	436
	4S	1084	548	704	436
	4M	1148	616	740	492

exhibited significant differences in their respective traffic patterns, which is very desirable for determining the sensitivity of operational signal systems to different traffic patterns.

Cycle Length

Cycle lengths which varied from cycle to cycle were manually observed at the interchanges. The cycle lengths varied because of the variation in demand during the extension features of the actuated phases. Average cycle lengths were determined for the 15-minute time periods of study.

Table 5 presents the range of interchange cycle lengths observed at the four interchanges by operational system. It is seen that three-phase systems experienced shorter cycle lengths than four-phase systems for the same traffic volume levels. It is further noted that multi-point detector systems experienced shorter cycle lengths than single-point detector systems. These results are in harmony with expected cycle lengths recognizing the principal differences in operational control and detector configurations. Gap settings also impact cycle length in actuated control. Four-phase, single-point systems by their very nature are most susceptible to any deviation in the quality of fine-tuning.

Traffic Delay

Traffic delays were observed at each of the six intersection approaches to each interchange. The number of stopped vehicles were counted every 15 seconds during a 15-minute time period. The critical queue per approach was taken as the maximum queue observed on one of the approach lanes. The sum of queues observed during 15 minutes was divided by the number of observations. Thus, the total interchange traffic delay is the sum of the number of vehicles observed to be stopped on all six critical lanes, one observation for each of the six stations of the interchange. Observed totals are averaged over each 15-minute study period.

Table 6 presents the range of traffic delay in terms of the average number of vehicles stopped every 15 seconds on the six approaches' critical-queue lanes at the four interchanges. Total traffic delay ranged from 2.2 to 26.6 vehicles stopped on the six critical approach lanes at the interchanges.

TABLE 5. CYCLE LENGTHS OBSERVED AT INTERCHANGES.

Interchange Location	Operational System	Cycle Length (s)	
		Highest	Lowest
Beach	3S	64	39
	3M	49	35
	4S	119	70
	4M	101	54
Green Oak	3S	60	44
	3M	57	40
	4S	100	62
	4M	90	56
South Drive	3S	50	35
	3M	49	35
	4S	90	65
	4M	87	47
MacArthur*	3S	102	53
	3M	77	47
	4S	149	75
	4M	91	57

*Study deleted.

TABLE 6. TOTAL INTERCHANGE TRAFFIC ON SIX CRITICAL APPROACH LANES OBSERVED AT INTERCHANGES.

Interchange Location	Operational System	Total Queue	
		Highest	Lowest
Beach	3S	9.1	2.8
	3M	6.7	2.8
	4S	14.5	4.7
	4M	14.4	3.1
Green Oak	3S	11.4	3.4
	3M	10.3	3.6
	4S	11.4	3.9
	4M	14.0	4.0
South Drive	3S	7.0	2.2
	3M	7.9	2.9
	4S	18.2	4.5
	4M	11.4	2.6
MacArthur*	3S	26.6	3.1
	3M	16.3	3.7
	4S	18.9	4.1
	4M	12.0	4.6

*Study deleted.

Approach And Interchange Queues

It was noted in the previous discussion that the number of stopped vehicles were 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. Observers at the four "external" stations on the arterial street and frontage roads recorded the number of stopped vehicles for "external" traffic while observers at the two stations between the signals recorded the number of stopped vehicles of "internal" traffic.

Table 7 and Figure 10 present a summary of mean queue characteristics observed at the external and internal stations of the interchanges. They reveal distinct queue characteristics at the diamond interchanges as follows:

1. Internal queue was small regardless of the control system employed for the conditions observed. Specifically, the size of internal queue (i.e., less than 1.0) is insignificant compared to the external queue (i.e., more than 5.0) at diamond interchanges.

External queue dominated stopping characteristics. Specifically, over 86 percent of an interchange traffic queue was generated at the external stations while the remaining queue of less than 14 percent was observed at the internal stations. Three-phase had more internal queue; whereas, four-phase more external queue.

OBSERVATIONAL PERFORMANCE DATA

Critical Queue vs. Critical Volume

Figures 11 through 14 show the critical queue vs. critical volume data observed at each diamond interchange. These figures indicate the following characteristics:

1. Queue increases curvilinearly as volume increases.
2. Little difference in queue performance exists between single and multi-point detection for 3-phase control.
3. Substantial differences in queue performance exist between single and multi-point detection for 4-phase control.
4. Three-phase control experiences less queue, in general, than 4-phase when only critical volume is considered.

TABLE 7. AVERAGE TRAFFIC QUEUE CHARACTERISTICS BY OPERATIONAL SYSTEMS.

Interchange Location	Operational System	Mean Internal Queue	Mean External Queue	Total Interchange Queue
Beach	3S	0.4	4.6	5.0
	3M	0.3	4.3	4.6
	4S	0.1	8.6	8.7
	4M	0.1	7.2	7.3
Green Oak	3S	0.8	5.1	5.9
	3M	0.1	4.9	5.0
	4S	0.3	6.9	7.2
	4M	0.9	6.5	7.4
South Drive	3S	0.5	3.8	4.3
	3M	0.5	4.5	5.0
	4S	0.1	7.8	7.9
	4M	0.1	5.6	5.7
MacArthur*	3S	2.9	7.2	10.1
	3M	1.8	6.8	8.6
	4S	0.1	10.2	10.3
	4M	0.1	7.6	7.7
Mean	3S	1.2	5.2	6.3
	3M	0.7	5.1	5.8
	4S	0.2	8.4	8.6
	4M	0.3	6.7	7.0

*Study deleted.

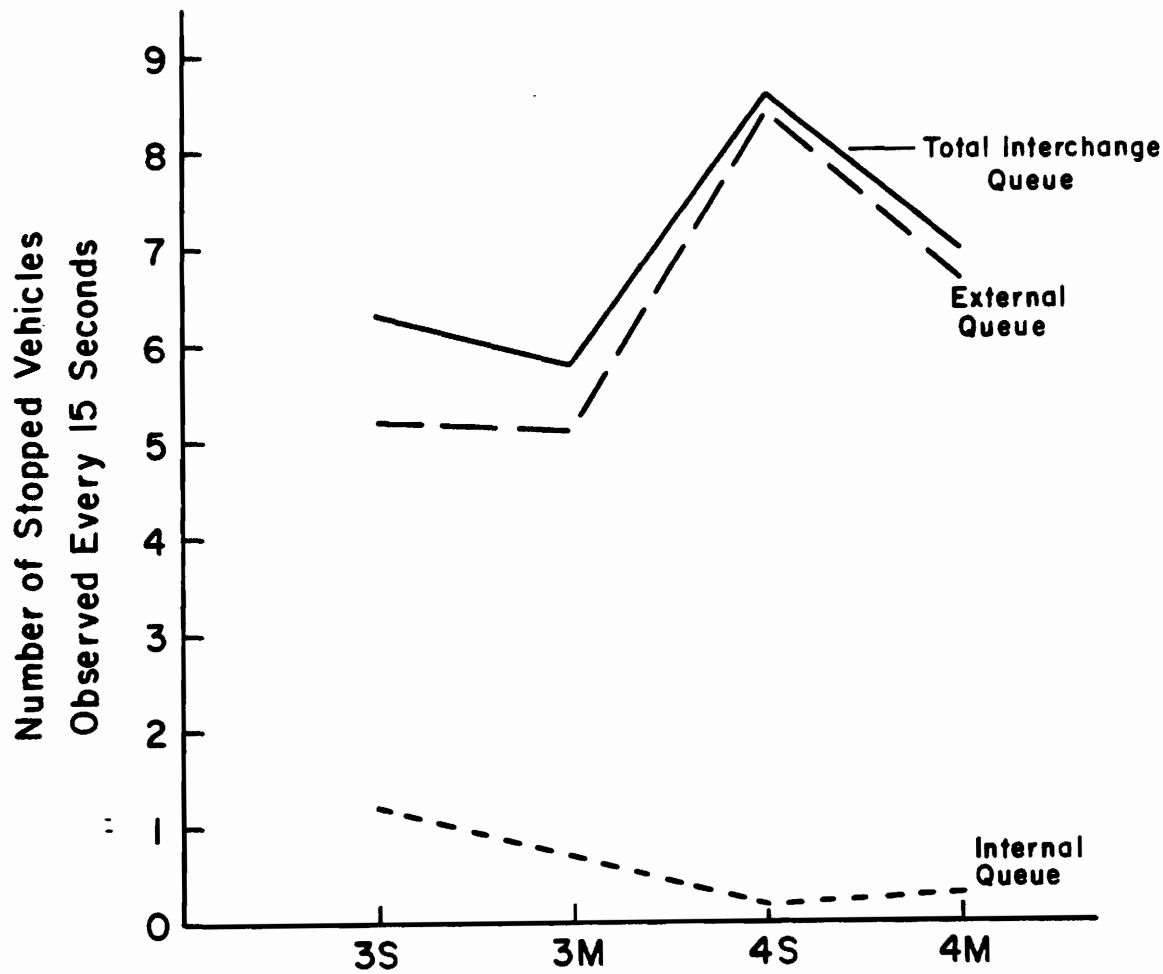


Figure 10. Mean Internal, External, and Total Queue at Diamond Interchanges.

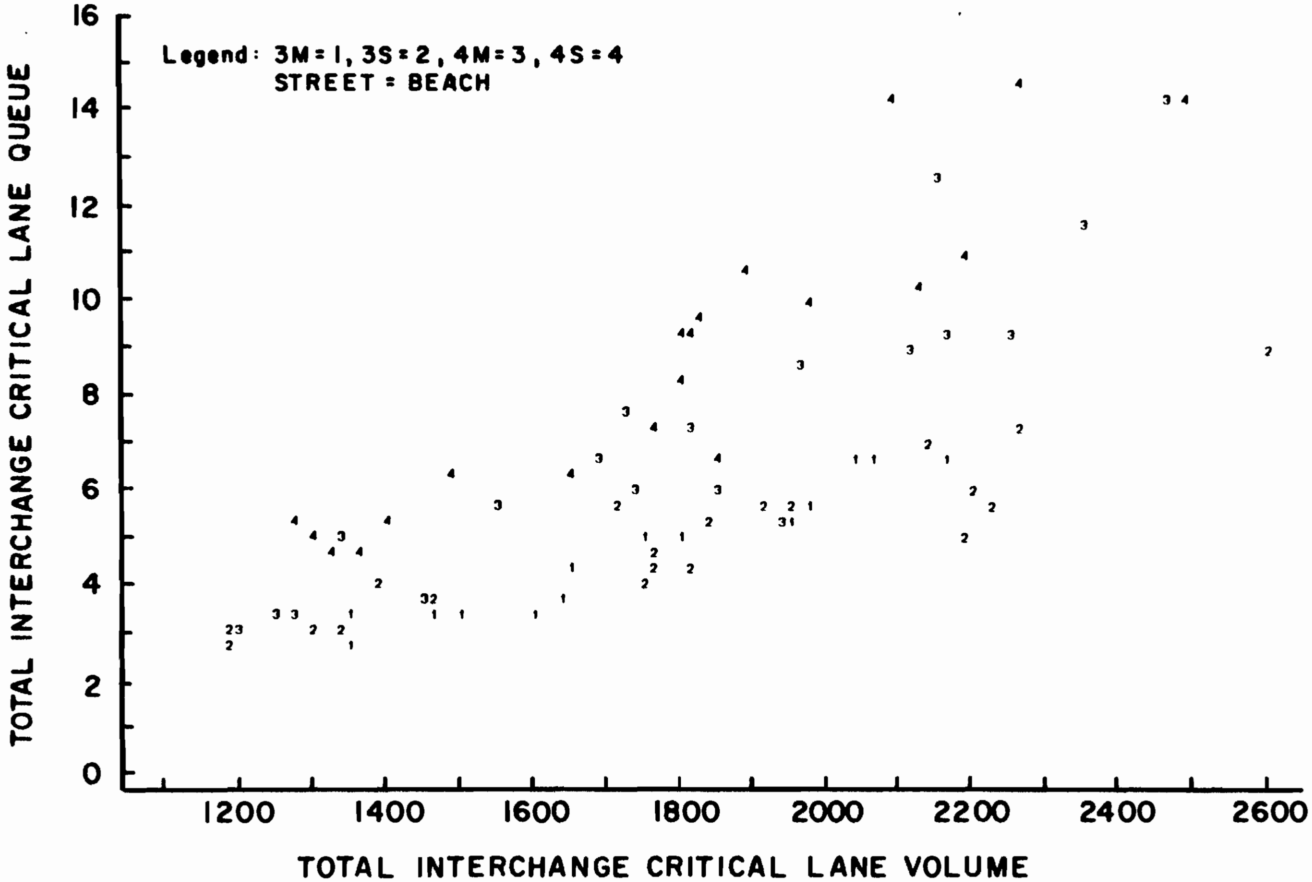


Figure 11. Observed Field Data on Critical Queue vs. Critical Volume at Beach.

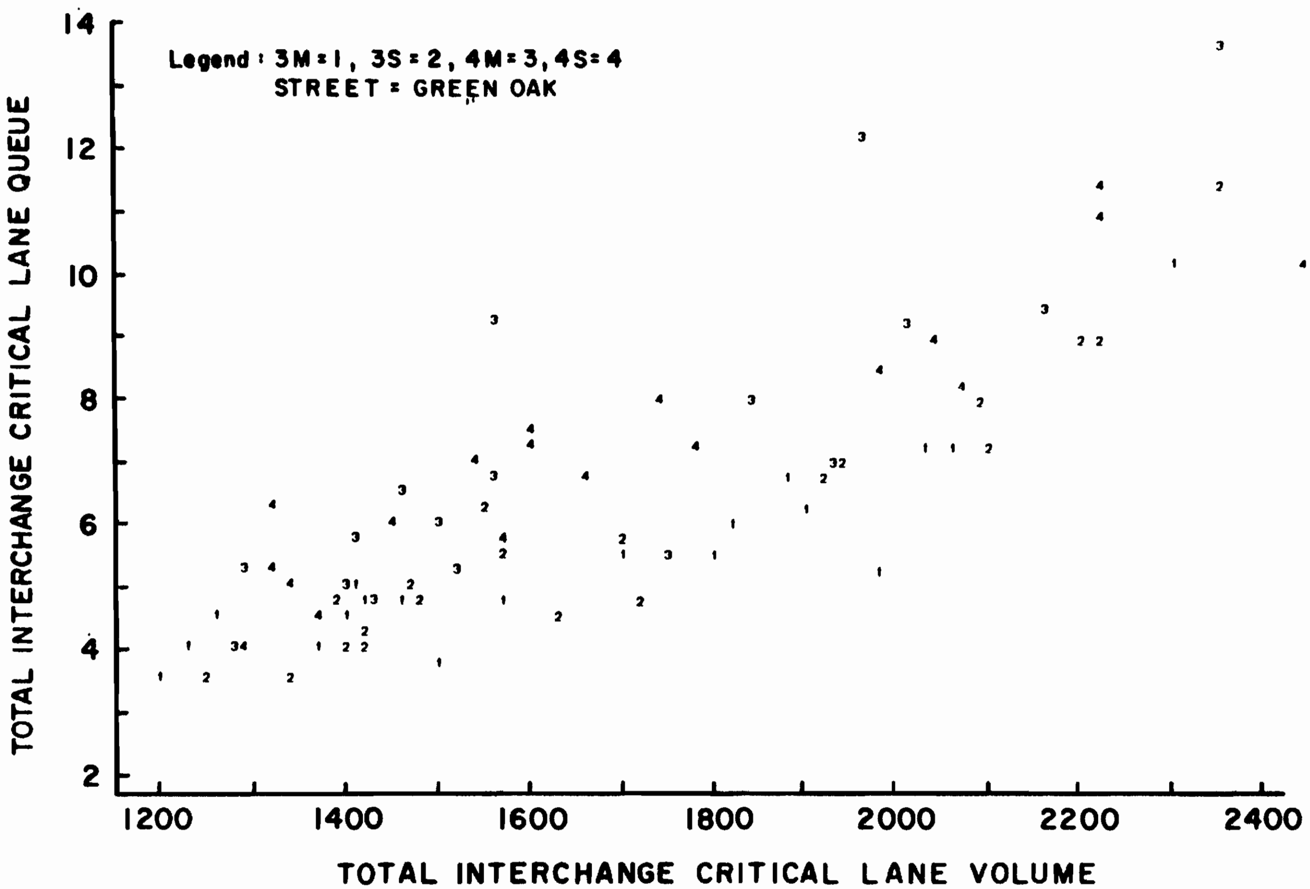


Figure 12. Observed Field Data on Critical Queue vs. Critical Volume at Green Oak.

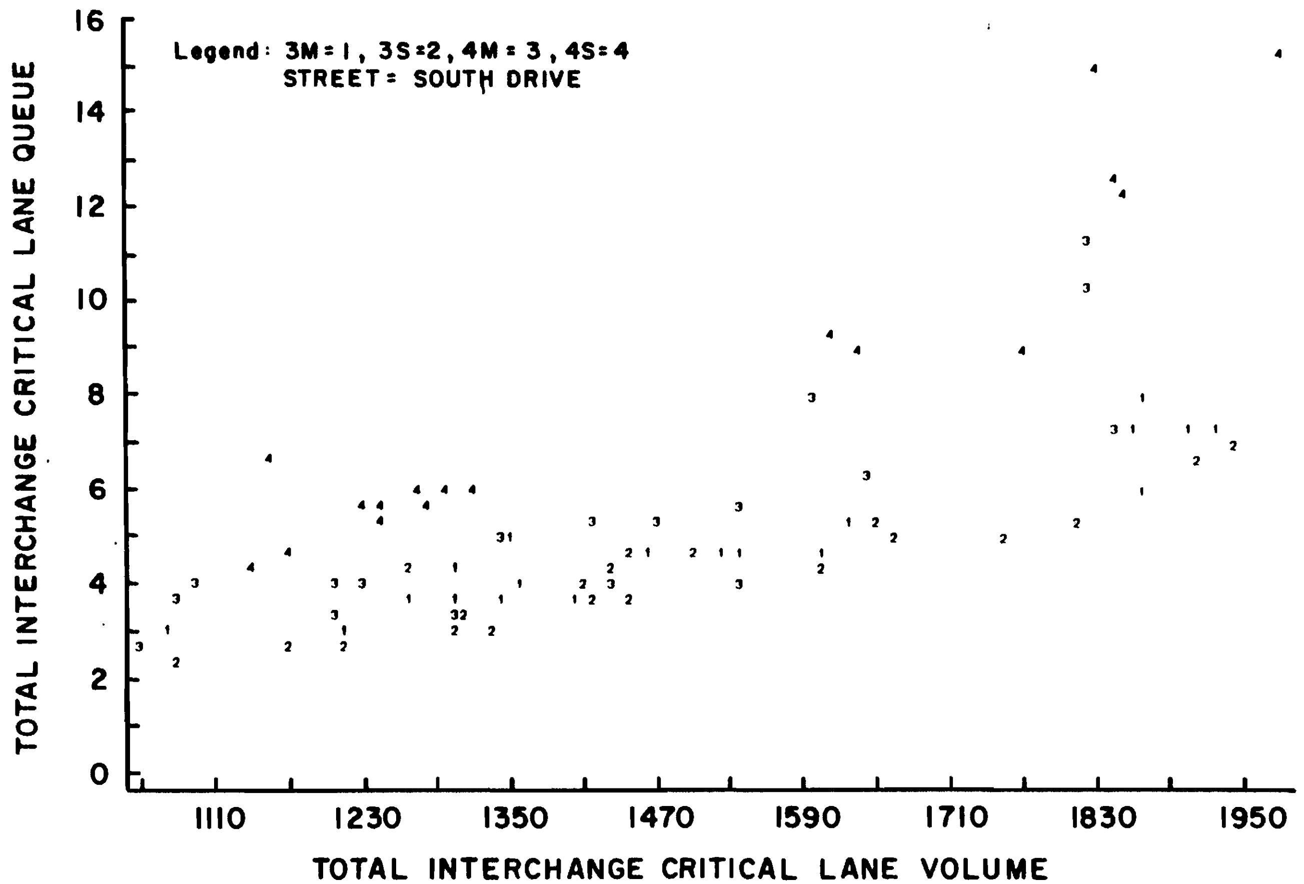


Figure 13. Observed Field Data on Critical Queue vs. Critical Volume at South Drive.

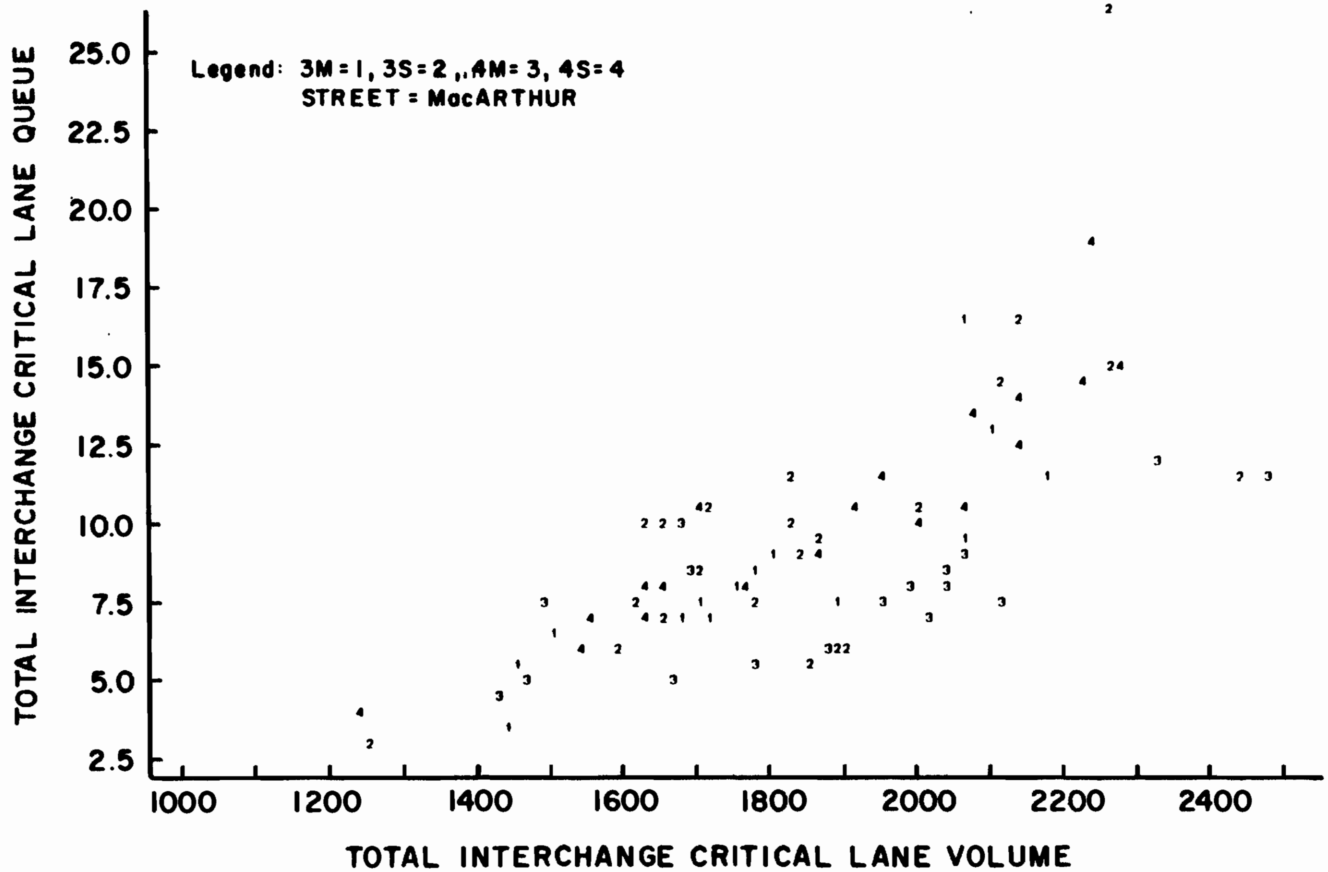


Figure 14. Observed Field Data on Critical Queue vs. Critical Volume at MacArthur.

Cycle Length vs. Critical Volume

Figures 15 through 18 show the cycle length vs. critical volume data observed at each diamond interchange. These figures suggest the following characteristics:

1. Cycle length increases either linearly or curvilinearly as critical volume increases.
2. Little difference in cycle length exists between single and multi-point detection for 3-phase control.
3. Substantial differences in cycle length exist between single and multi-point detection for 4-phase control.
4. Three-phase control provides a shorter cycle length, in general, than does 4-phase when only critical volume is considered.
5. Observed cycle lengths at MacArthur appear to be inconsistent with those of the other interchanges in the 3-phase control system, particularly 3-phase single-point detection.

Critical Queue vs. Cycle Length

Figures 19 through 22 show critical queue vs. cycle length data observed at each diamond interchange. These figures to reveal the following aspects:

1. Queue increases linearly or curvilinearly as cycle length increases.
2. Little change in cycle length is needed for 3-phase control to produce identical queue delay with single- and multi-point detection.
3. Substantial differences in cycle length are required for 4-phase control to produce nearly identical queue performance with single- and multi-point detection.
4. Identical queue performance would arise when 3-phase control operates at a longer cycle length than 4-phase control.
5. Since cycle length is not fixed in actuated control but varies with volume, no comparison should be made on queue performance given for a cycle length independent of volume.

DISCUSSION OF FIELD STUDY RESULTS

The previous study results appear to indicate that the performance data obtained from the field studies are reasonable for each diamond interchange control system and are consistent with the expected performance. For example,

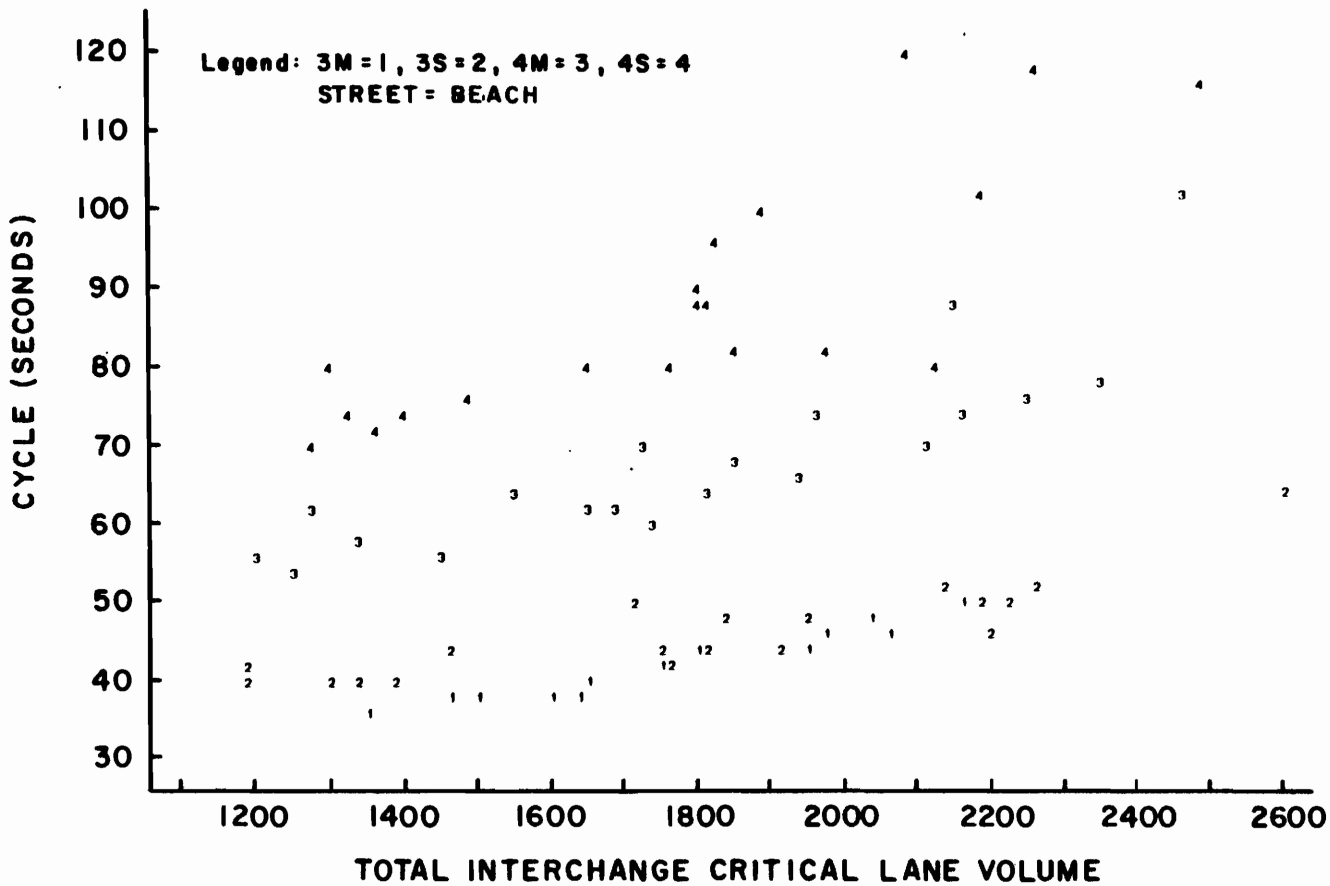


Figure 15. Observed Field Data on Cycle Length vs. Critical Volume at Beach.

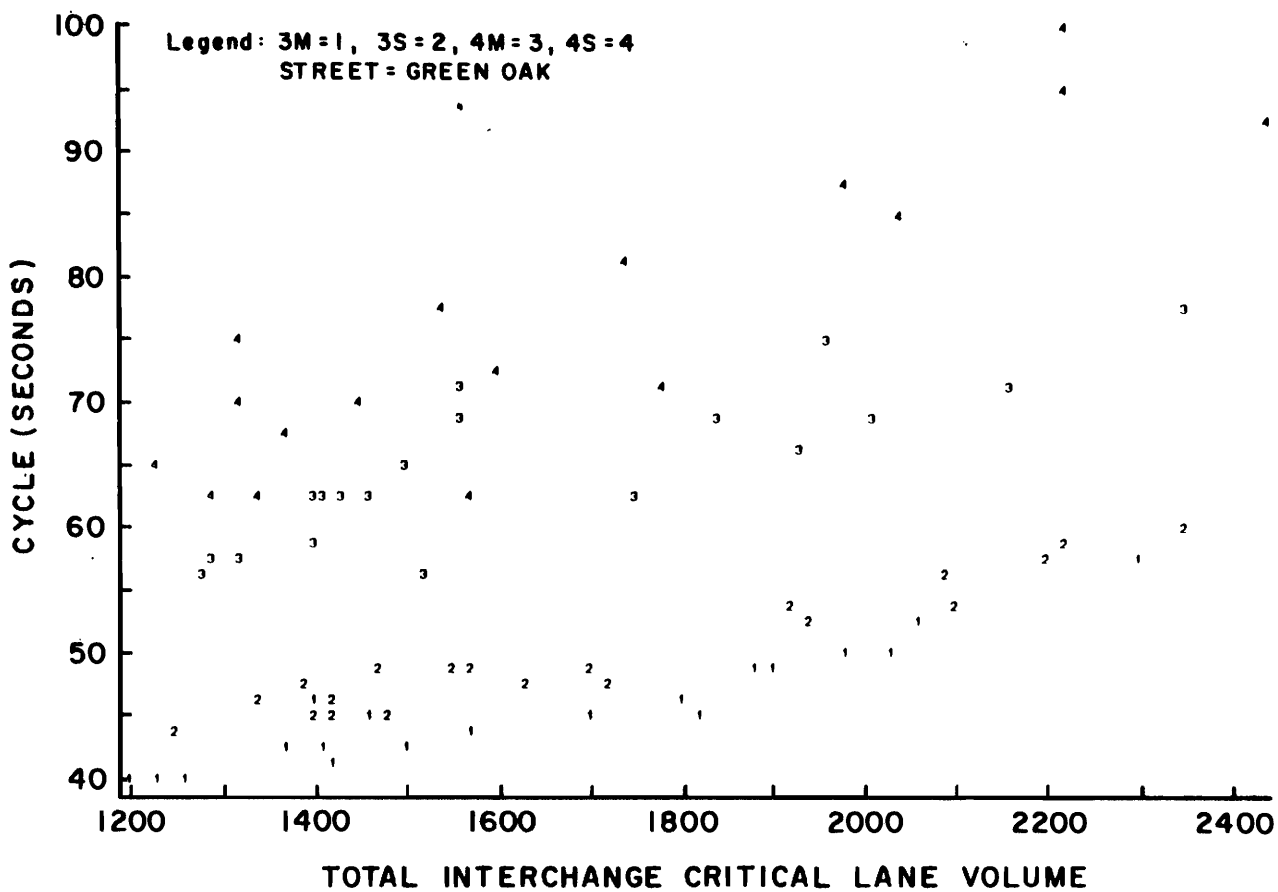


Figure 16. Observed Field Data on Cycle Length vs. Critical Volume at Green Oak.

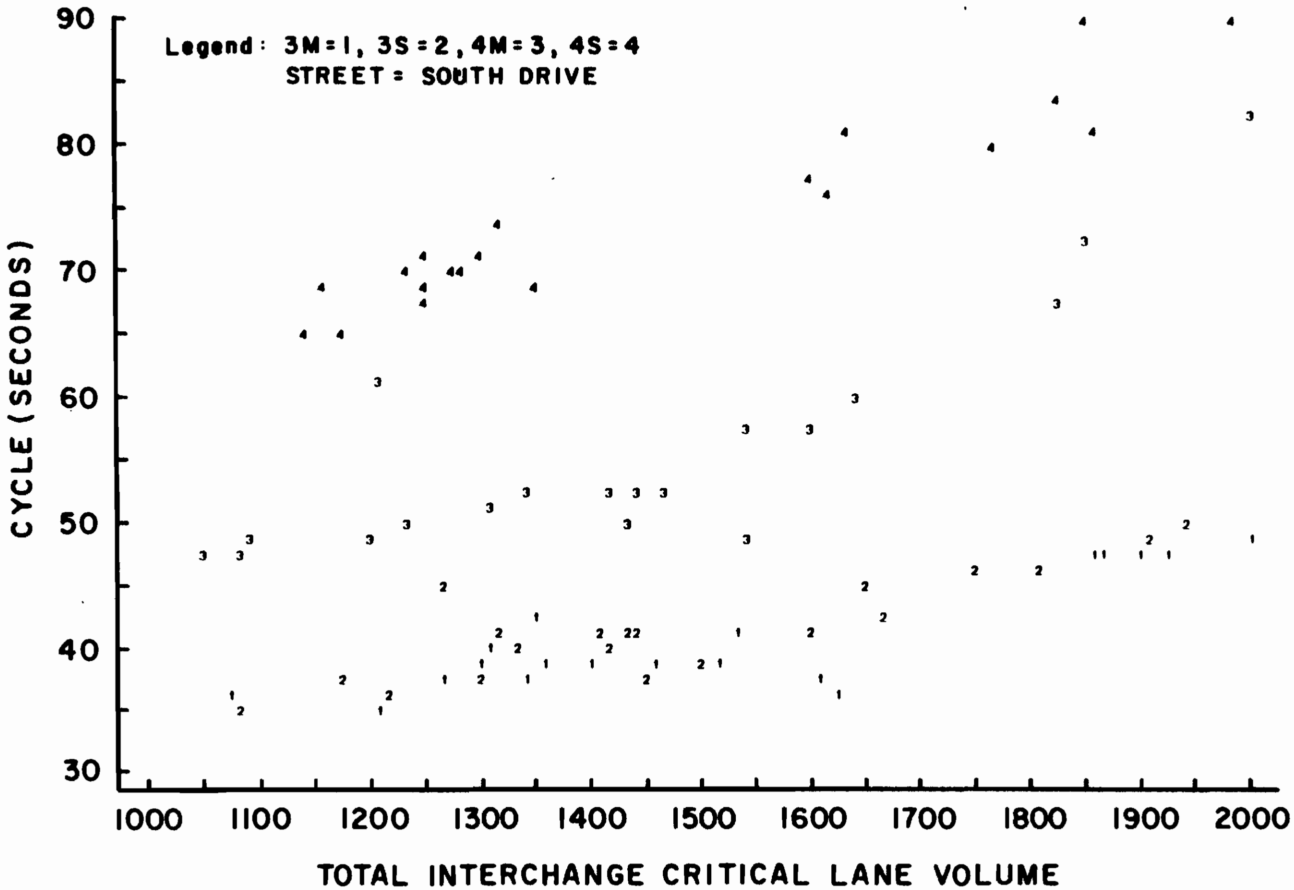


Figure 17. Observed Field Data on Cycle Length vs. Critical Volume at South Drive.

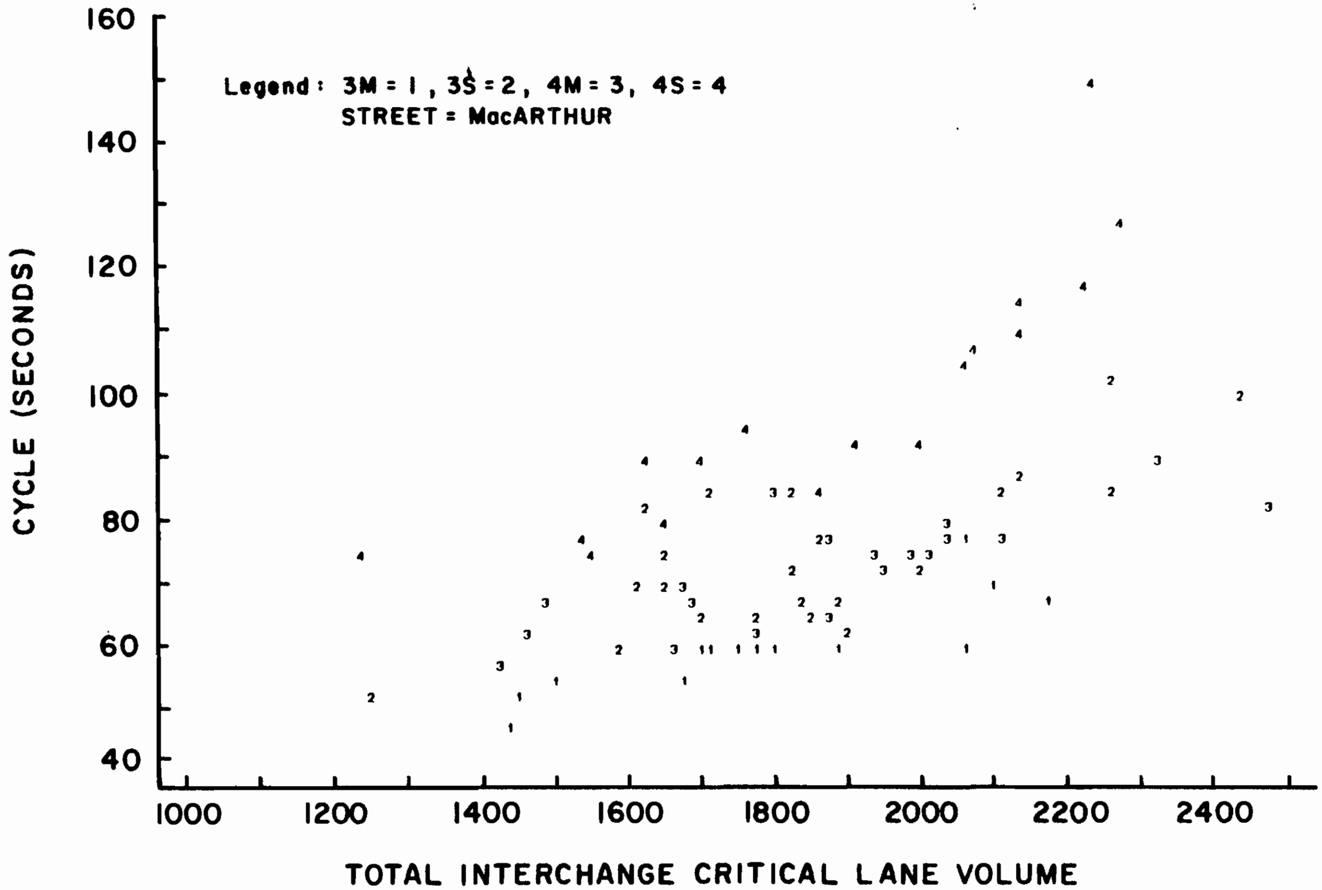


Figure 18. Observed Field Data on Cycle Length vs. Critical Volume at MacArthur.

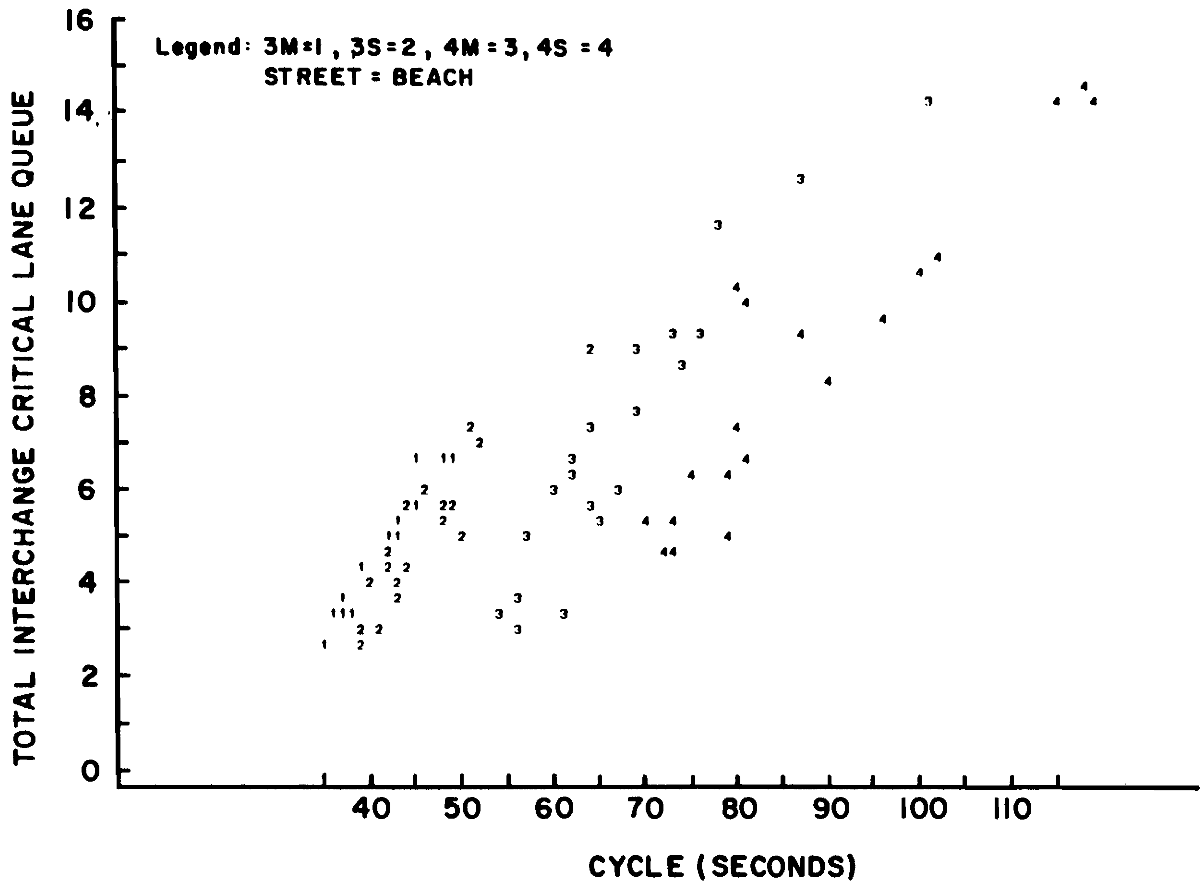


Figure 19. Observed Field Data on Critical Queue vs. Cycle Length at Beach.

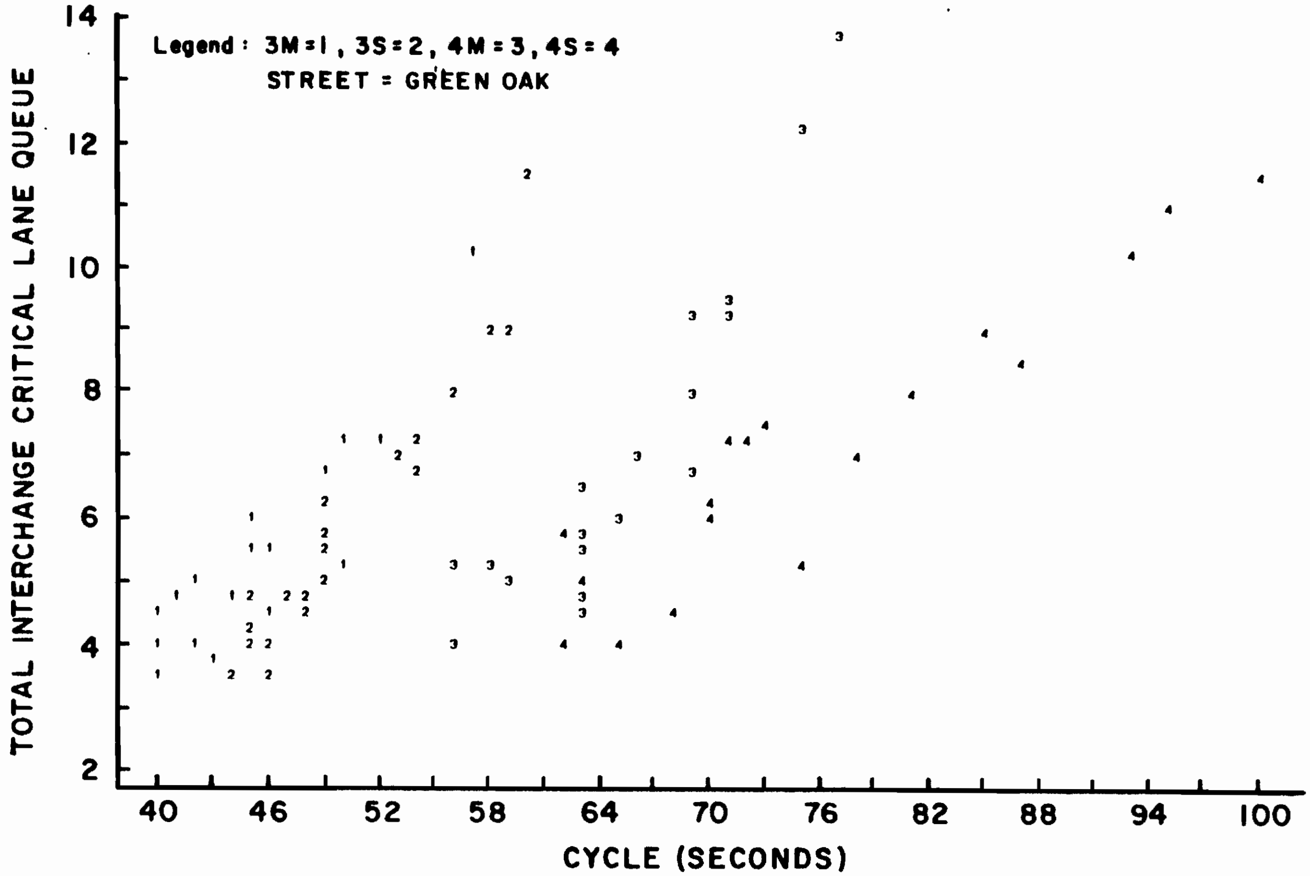


Figure 20. Observed Field Data on Critical Queue vs. Cycle Length at Green Oak.

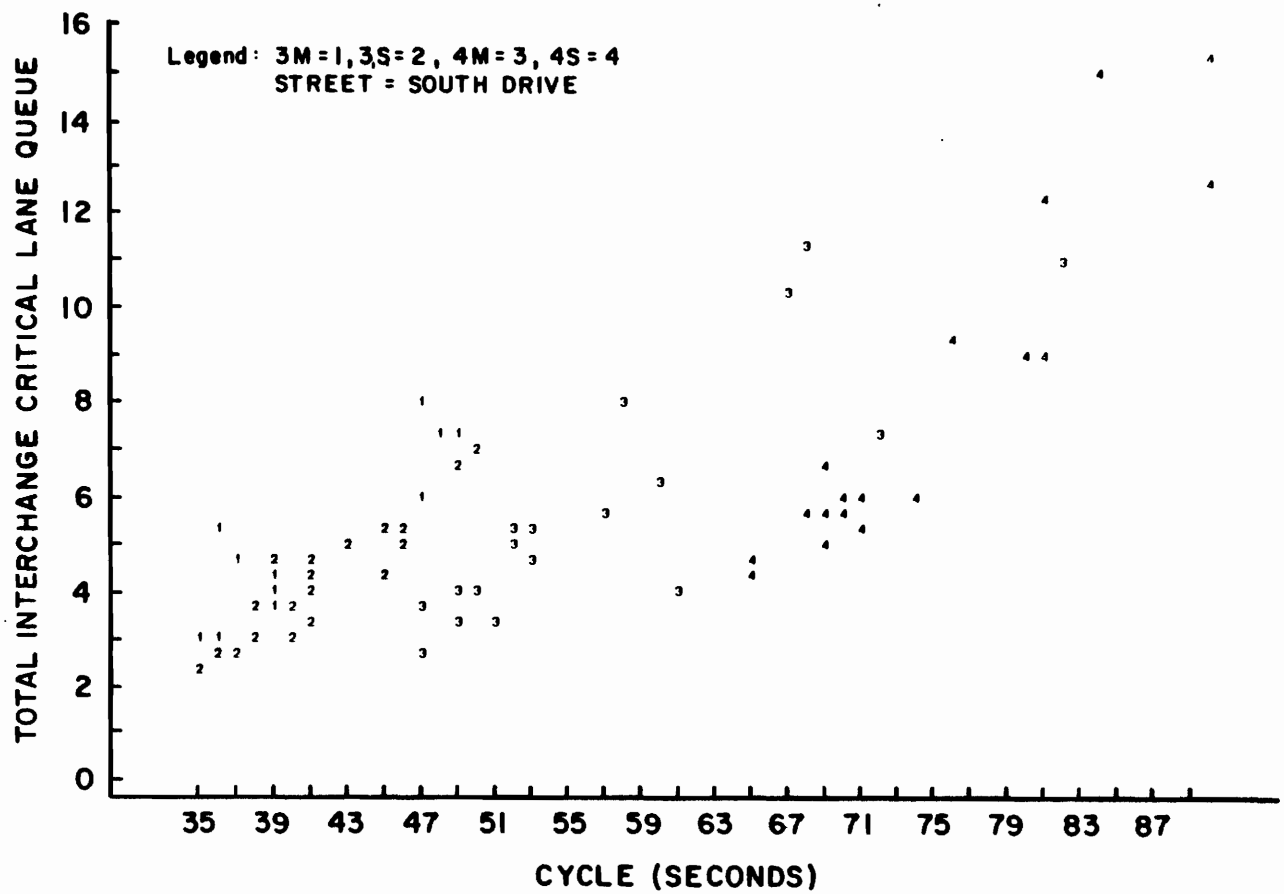


Figure 21. Observed Field Data on Critical Queue vs. Cycle Length at South Drive.

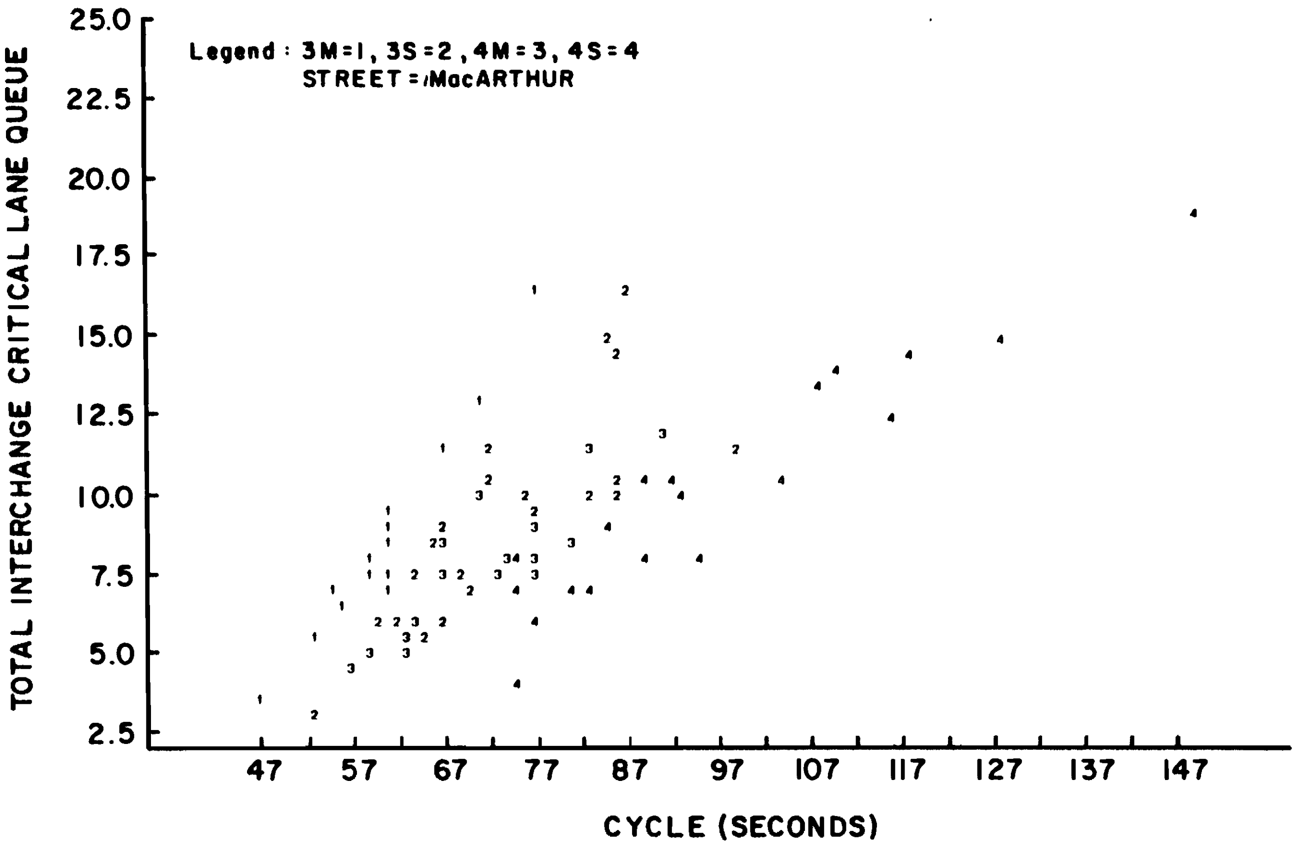


Figure 22. Observed Field Data on Critical Queue vs. Cycle Length at MacArthur.

multi-point detection was expected to result in a shorter cycle length than that of single-point detection. Further, it is well known that as cycle length increases, queue increases. In addition, due to the separate phase given each frontage road in four-phase control, the cycle length for four-phase control was expected to be longer than that for three-phase control.

All interchanges, except MacArthur interchange revealed a consistent pattern in queue and cycle length characteristics given critical volume. However, the MacArthur interchange revealed an inconsistent pattern in most queue and cycle length characteristics. This appears to be due to an inadvertent detector wiring error discussed previously.

In order to develop application guidelines for diamond interchange signal systems, it is desired to pool all relevant data to determine the effects of different interchange geometric and traffic patterns. Since the MacArthur interchange revealed a pattern apparently inconsistent with the other three interchanges, a statistical test was performed to evaluate if the MacArthur data could also be pooled with the other data sets.

A generalized linear model test was performed to see if the MacArthur data set is similar or quite different from the other three interchanges. The test results showed that MacArthur data is quite different from the other three interchanges in three of the four systems observed. Specifically, the tests revealed that MacArthur data cannot be pooled together except for the four-phase multi-point detection plan. Since three systems observed for MacArthur interchange were different from the other three interchanges, the MacArthur data were completely excluded from subsequent analysis.

The data obtained from the other three interchanges were pooled together to evaluate performance characteristics among four alternative diamond interchange control schemes.

V. ASSESSMENT OF TRAFFIC SIGNAL PHASING AND DETECTOR CONFIGURATION

The assessment of traffic signal phasing and detector configuration at diamond interchanges involves several key questions as follows:

1. Given an interchange, which combination of signal phasing and detector configuration results in superior performance?
2. Given a signal phasing plan, are there any differences in performance between different detection schemes? Further, if there is any difference, which detection scheme provides better performance?
3. Given a detection scheme, are there any differences in performance between different phasing plans? Further, if there is any difference, which phasing plan provides better performance? In addition, how sensitive is this performance to traffic and geometric characteristics at an interchange?

The observed general performance characteristics of four alternative diamond interchange control systems will introduce the assessment. These performance characteristics will be represented by a series of models or graphs illustrating relationships such as cycle vs. critical volume, critical queue vs. cycle, critical queue vs. critical volume and traffic pattern, and critical queue vs. others. Subsequently, alternative control systems, given either phasing plan or detection scheme, will be presented to illustrate performance differences. Some other interchange geometric and traffic characteristics that appeared to affect interchange performance were also evaluated and will be presented accordingly. In the following sections, the four signal control systems are denoted as follows:

3S = 3-phase, single-point detection

3M = 3-phase, multi-point detection

4S = 4-phase, single-point detection

4M = 4-phase, multi-point detection

CYCLE LENGTH VS. CRITICAL VOLUME

To understand the effect of diamond interchange control alternatives on cycle length, the four alternative control schemes were evaluated to determine the cycle that they would be expected to operate given critical volume at the diamond interchange. The models developed were as follows:

3S, $C = 21.8 + 14.4\ (VT/1000)$, $R^2 = 0.68$

3M $C = 20.8 + 13.5\ (VT/1000)$, $R^2 = 0.64$

4S, $C = 27.7 + 31.7\ (VT/1000)$, $R^2 = 0.72$

4M, $C = 21.5 + 25.4\ (VT/1000)$, $R^2 = 0.73$

where

C = cycle length, seconds

VT = sum of critical lane volumes at the interchange, vphpl

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

3S, $C = 14.5 + 14.4\ (VT/1000) + 20.1\ RILCVE$, $R^2 = 0.80$

3M, $C = 15.9 + 12.9\ (VT/1000) + 15.8\ RILCVE$, $R^2 = 0.76$

4S, $C = 38.7 + 32.3\ (VT/1000) - 33.8\ RILCVE$, $R^2 = 0.79$

4M, $C = 16.9 + 25.8\ (VT/1000) + 11.4\ RILCVE$, $R^2 = 0.75$

where

RILCVE = Internal left turn volumes/sum of external critical volumes. Figure 23 illustrates the relationship found between cycle length and critical volume using RILCVE = 0.4, the mean of the field studies. Figure 23 shows that cycle length increases in the order of 3-phase multi-, 3-phase single, 4-phase multi- and 4-phase single-point detection plans. Several observations determined from Figure 23 are as follows:

1. Three-phase, multi-point detection produces the shortest cycle length given traffic conditions.
2. Four-phase, single-point detection generates the longest cycle length given traffic conditions.
3. Three-phase produces shorter cycles than does four-phase control.
4. Three-phase, multi-point detection has little advantage in cycle length when compared to three-phase, single-point detection.
5. Four-phase, multi-point detection provides substantial reduction in cycle length as compared to four-phase single-point. The reduction is more significant as traffic volume increases.

CRITICAL QUEUE VS. CYCLE LENGTH

The relationship between queue and cycle length examined the sensitivity of cycle length on queue. The models developed were as follows:

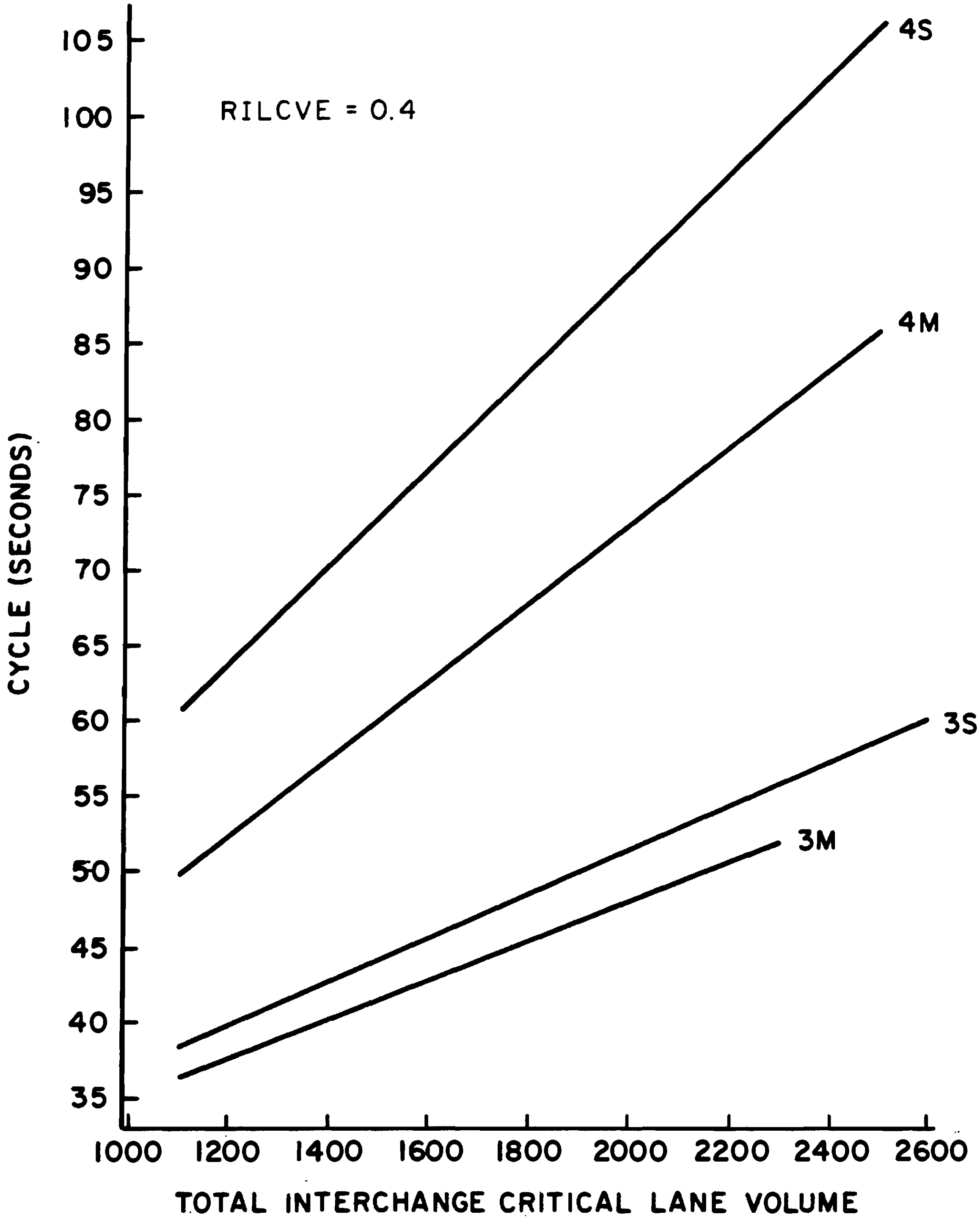


Figure 23. Relationship Between Cycle Length and Critical Volume.

3S, $QT = \text{Exp}\ (-0.77 + 0.051\ C)$, $R^2 = 0.83$

3M, $QT = \text{Exp}\ (-0.65 + 0.052\ C)$, $R^2 = 0.79$

4S, $QT = \text{Exp}\ (0.17 + 0.023\ C)$, $R^2 = 0.70$

4M, $QT = \text{Exp}\ (-0.37 + 0.035\ C)$, $R^2 = 0.75$

where

QT = Sum of critical lane queues at the interchange.

The high R^2 found from the models illustrate strong linear relationships between queue and cycle length.

Figure 24 illustrates the relationship between queue and cycle length for the four alternative control schemes. It shows that different cycle lengths are associated with identical queue for the four control schemes. Specifically, several observations can be drawn from the graph as follows:

1. Three-phase, multi-point control is associated with the shortest cycle length to generate equal queue among alternatives.
2. Four-phase, single-point control is associated with the longest cycle length to generate equal queue among alternatives.
3. Three-phase control is associated with shorter cycle length than four-phase to generate equal queue between these two phasing plans.

No comparison of queue should be made based on a given cycle length because the control systems are actuated and the traffic volume processed during a given cycle length is quite different between alternative control systems.

CRITICAL QUEUE VS. CRITICAL VOLUME

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

3S, $QT = \text{Exp}\ (0.111 + 0.87\ (VT/1000)$, $R^2 = 0.79$

3M, $QT = \text{Exp}\ (0.202 + 0.85\ (VT/1000)$, $R^2 = 0.74$

4S, $QT = \text{Exp}\ (0.560 + 0.88\ (VT/1000)$, $R^2 = 0.74$

4M, $QT = \text{Exp}\ (0.084 + 1.06\ (VT/1000)$, $R^2 = 0.79$

Figure 25 illustrates the relationship found between critical queue and critical volume. Several observations can be derived from the figure as follows:

1. There is no significant difference in queue performance between three-phase, single-point and multi-point detection given traffic volume at an interchange.

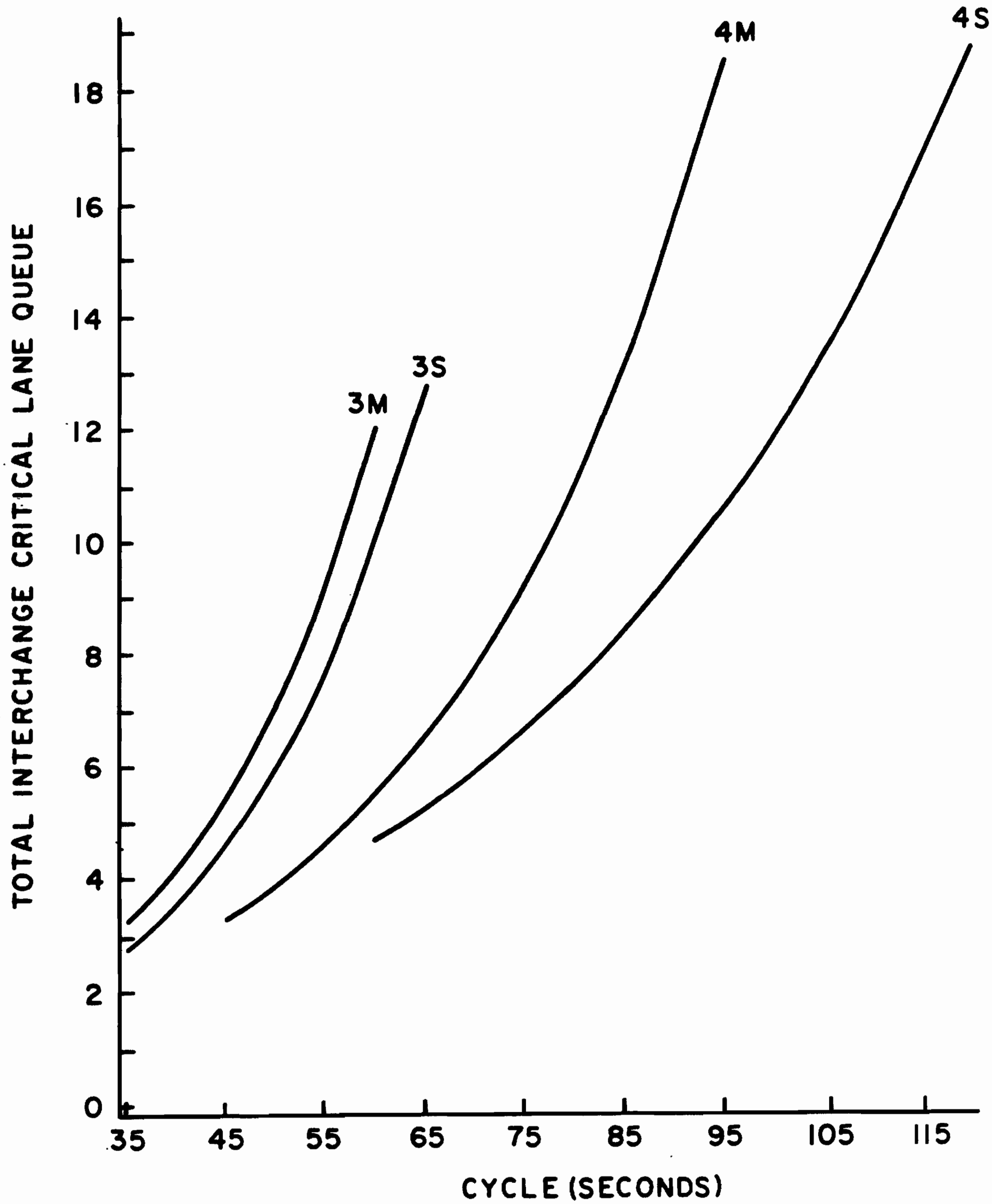


Figure 24. Relationship Between Critical Queue and Cycle Length. (Note: Cycle is the response variable produced by the existing queue).

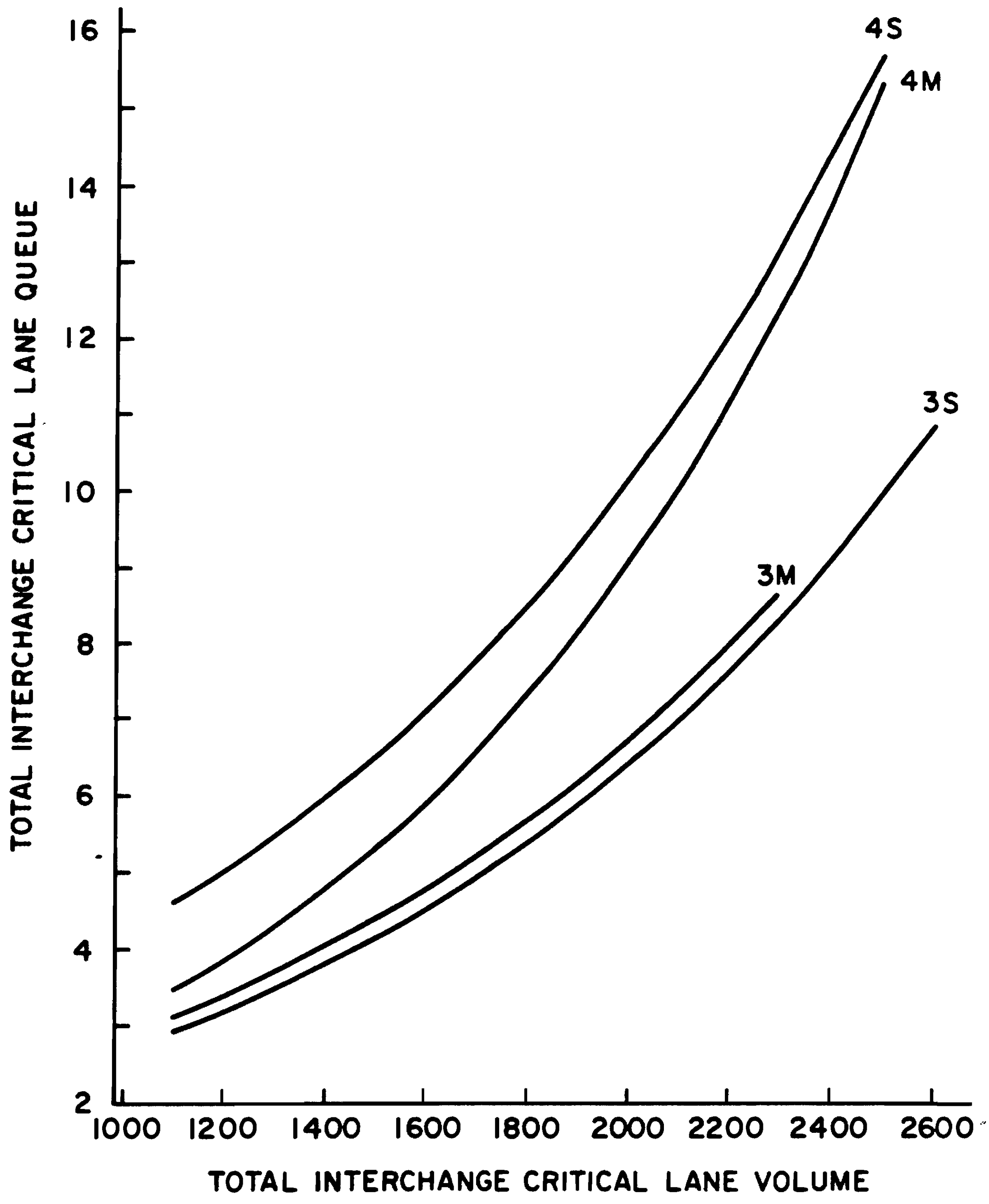


Figure 25. Relationship Between Critical Queue and Critical Volume.

2. Three-phase control produced less delay than four-phase control given traffic volume at an interchange.
3. Four-phase, single-point system generated the highest delay among other alternative control schemes for a given traffic volume.

CRITICAL QUEUE VS. CRITICAL VOLUME AND TRAFFIC PATTERN

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 tested. The best models found were as follows:

3S, QT = Exp (-0.33 + 0.976 (VT/1000) + 0.35 RILCVI), $R^2 = 0.84$

3M, QT = Exp (-0.35 + 0.938 (VT/1000) + 0.50 RILCVI), $R^2 = 0.89$

4S, QT = Exp (0.33 + 0.943 (VT/1000) + 0.17 RILCVI), $R^2 = 0.76$

4M, QT = Exp (-0.40 + 1.185 (VT/1000) + 0.36 RILCVI), $R^2 = 0.84$

where

RILCVI = Internal left turn/sum of critical internal lane volumes.

Figure 26 illustrates the effect of traffic volume and traffic pattern at an interchange on traffic delay experienced, using the mean RILCVI = 0.8 observed in the field studies. It shows that the queue performance using average RILCVI is similar to the one observed between queue and traffic volume. It is noted, however, that the additional variable of RILCVI increased the prediction of fit to the observed data by providing a higher R^2 and a lower mean square error.

CRITICAL QUEUE VS. ALL OTHERS

Total interchange queue was examined as a function of traffic volume, cycle length, the interaction of volume and cycle length and traffic pattern. The best functional model found was as follows:

Q = f(VT, C, VTC, and RILCVI)

where

VTC = Interaction of traffic volume and cycle length (that is, VT x C).

The above model improved predicted fit only marginally compared to the model of traffic volume and traffic pattern shown previously. Since improvement is marginal and since cycle length would be input to the model as

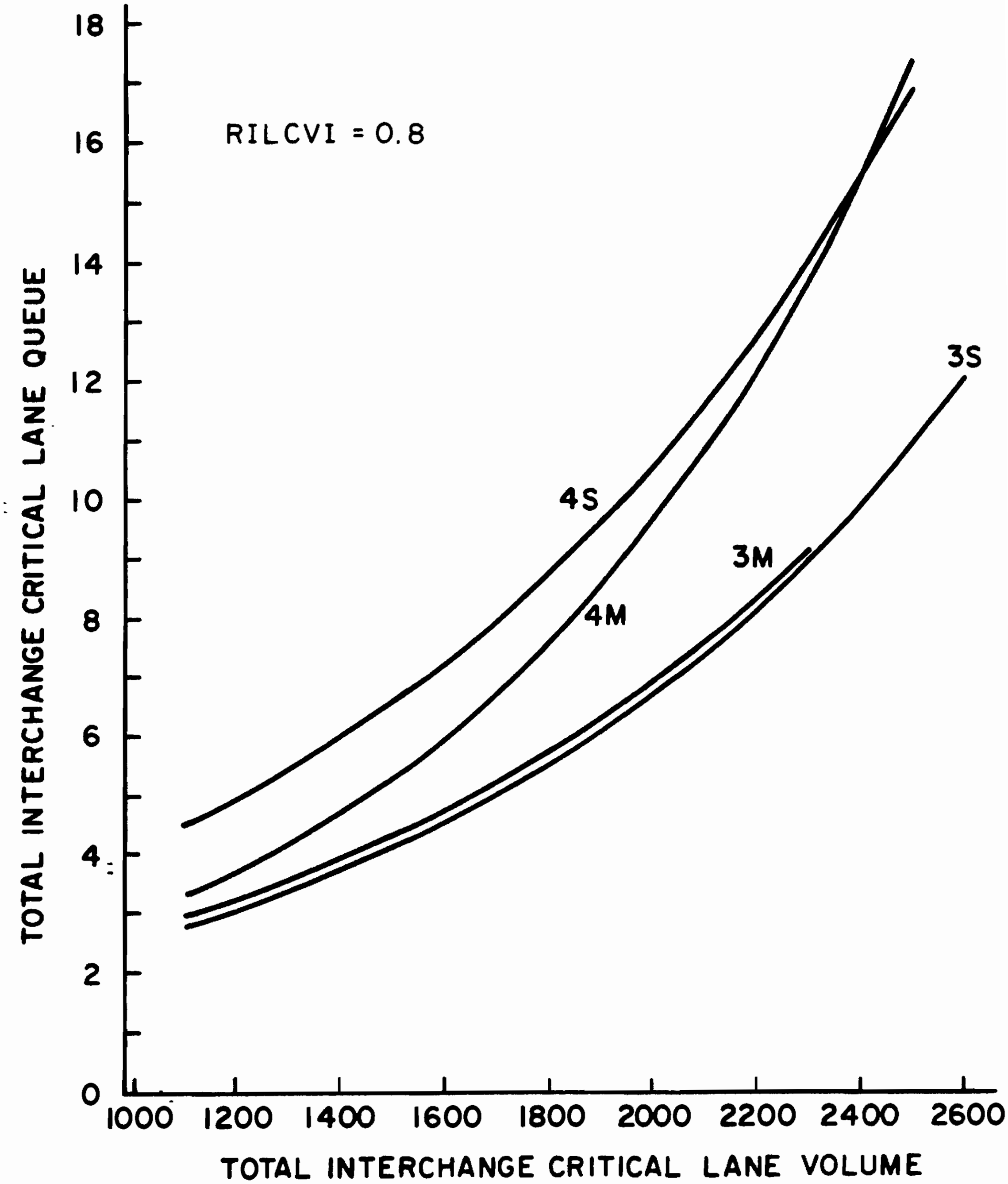


Figure 26. Relationship Between Critical Queue vs. Critical Volume and Traffic Pattern for RILCVI of 0.8.

a function of volume due to having a different cycle length at a given volume for different control systems, this detailed model structure was not pursued any further.

GEOMETRIC EFFECTS ON OPERATION

In addition to traffic volume, the effects of diamond interchange geometry on traffic operations were analyzed. Several variables previously used for defining geometric characteristics and their interaction with traffic patterns at an interchange were tested.

The best functional model for all control systems was as follows:

Q = f(c,VT,MILSL)

where

MILSL = maximum internal critical lane volume standardized by its storage length. (i.e., max (Int 5, Int6)/(SL/20)).

The model specifically illustrates the sensitivity of traffic operations to diamond interchange storage length.

EVALUATION OF DETECTOR CONFIGURATION GIVEN PHASING

Three-Phase Control

Figure 27 illustrates the queue performance characteristics between single-point and multi-point detection for three-phase control. Traffic pattern given in terms of RILCVI is shown at 0.4 and 1.0. It is seen from the figure that there appears to be no significant difference between single-point and multi-point detection for three-phase control at a given traffic volume and traffic pattern.

A general linear test was performed to evaluate if queue performance between single-point and multi-point detection for three-phase control is statistically different. Table 8 shows the results of the test. No significant difference in queue performance was detected between single-point and multi-point detection for three-phase control.

Considering the costs of constructing and maintaining multi-point detection and the apparent lack of substantial advantage in queue performance for three-phase multi-point detection, it appears to be cost-effective to use single-point detection for three-phase control at diamond interchanges.

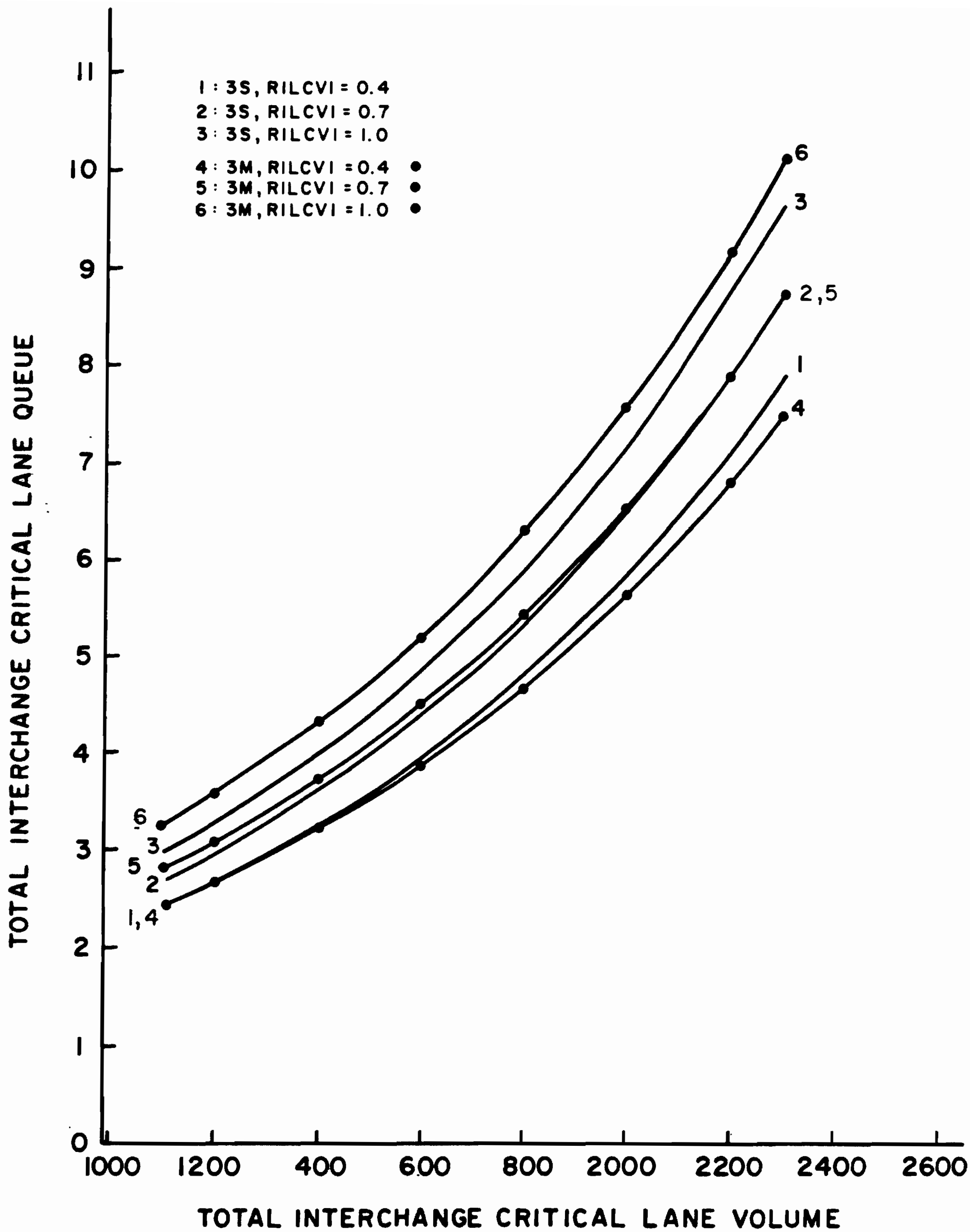


Figure 27. Queue Performance Charateristics Between Single and Multi-Point Detection for Three-Phase Control.

Table 8. HYPOTHESIS TESTING OF THREE-PHASE SINGLE- AND MULTI-POINT DETECTION.

Model	SSE	d.f.
3S	1.102	57
3M	0.519	51
Sum of 3S and 3M	1.621	108
Pooled 3S and 3M	1.704	111

H_0: Two regression lines for three-phase, single- and multi-point detection plans are identical, i.e., queue for 3S = queue for 3M.

H_1: Two regression lines for three-phase, single- and multi-point detection plans are different, i.e., queue for 3S = queue for 3M.

Test Statistic:

$$F^* = \frac{\text{SSE (3S and 3M)} - [\text{SSE(3S)+SSE(3M)}]}{\text{d.f. (3S and 3M)} - [\text{d.f.(3S)+d.f.(3M)}]} \quad \frac{\text{SSE(3S)+SSE(3M)}}{\text{d.f.(3S)+d.f.(3M)}}$$

$$= \frac{1.704 - 1.621}{111 - 108} \quad \frac{1.621}{108}$$

$$= 1.84$$

Critical F_c value $F_{\alpha=0.05}(1-\alpha/2=0.975;\ 3,\ 108) = 3.25$

Since $F^* < F_c$, the null hypothesis is accepted and it is concluded that two regression lines for three-phase, single- and multiple-point detection plans are statistically identical.

Four-Phase Control

Figure 28 illustrates the queue performance characteristics derived for single-point and multi-point detection for four-phase control. Traffic pattern is also depicted at 0.4 and 1.0 values of RILCVI. It is seen from the figure that multi-point detection for four-phase control generated lower delay except when heavy traffic flow together with heavy internal left turns exist at an interchange.

Considering the general advantages of multi-point detection for most traffic conditions, it appears to be delay-effective to use multi-point detection for four-phase control at diamond interchanges, particularly those having high-speed, high volume frontage roads.

EVALUATION OF PHASING GIVEN DETECTION

Single-Point Detection

Figure 29 illustrates the queue performance characteristics of three- and four-phase control for single-point detection. Traffic pattern is described at RILCVI values of 0.4 and 1.0. It is seen from the figure that three-phase control produces lower delay than four-phase control at a given traffic volume and traffic pattern when single-point detection is used at diamond interchanges. Thus, it is delay-effective to use three-phase control if single-point detection is used at diamond interchanges.

Multi-point Detection

Figure 30 illustrates the queue performance characteristics of three- and four-phase control for multi-point detection. Traffic pattern as given by RILCVI values of 0.4 and 1.0 are shown. It is seen from the figure that three-phase control generates lower delay than four-phase control at a given traffic volume and traffic pattern when multi-point detection is used at diamond interchanges. Thus, it is delay-effective to use three-phase control if multi-point detection is operating at diamond interchanges.

SUMMARY CHARACTERIZATION OF ALTERNATIVE SIGNAL PHASING AND DETECTION PLANS

Following is a summary of the characteristics found from field data analysis regarding traffic operational performances among alternative phasing

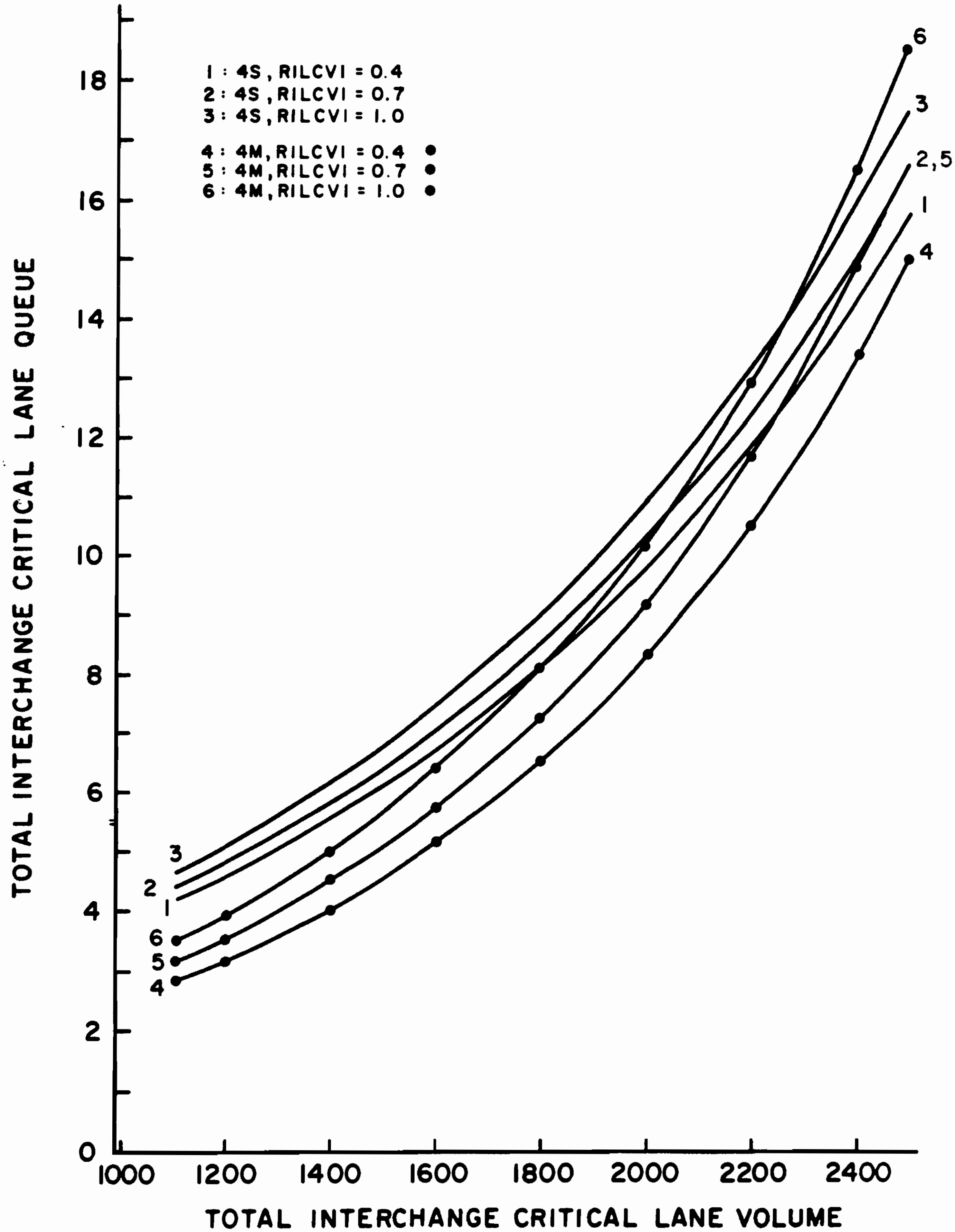


Figure 28. Queue Performance Characteristics Between Single- and Multi-Point Detection for Four-Phase Control.

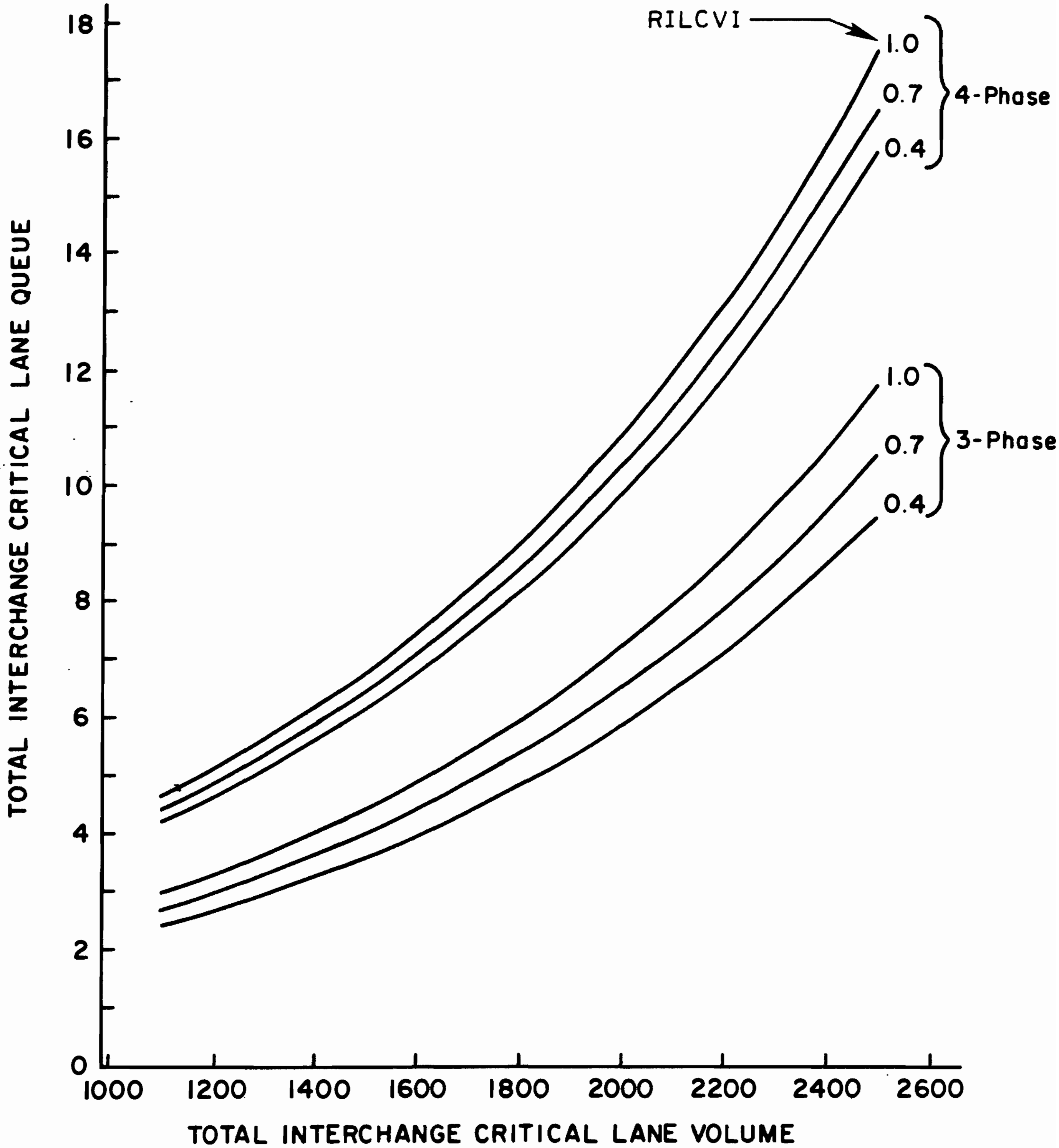


Figure 29. Queue Performance Charateristics Between Three- and Four-Phase for Single-Point Detection.

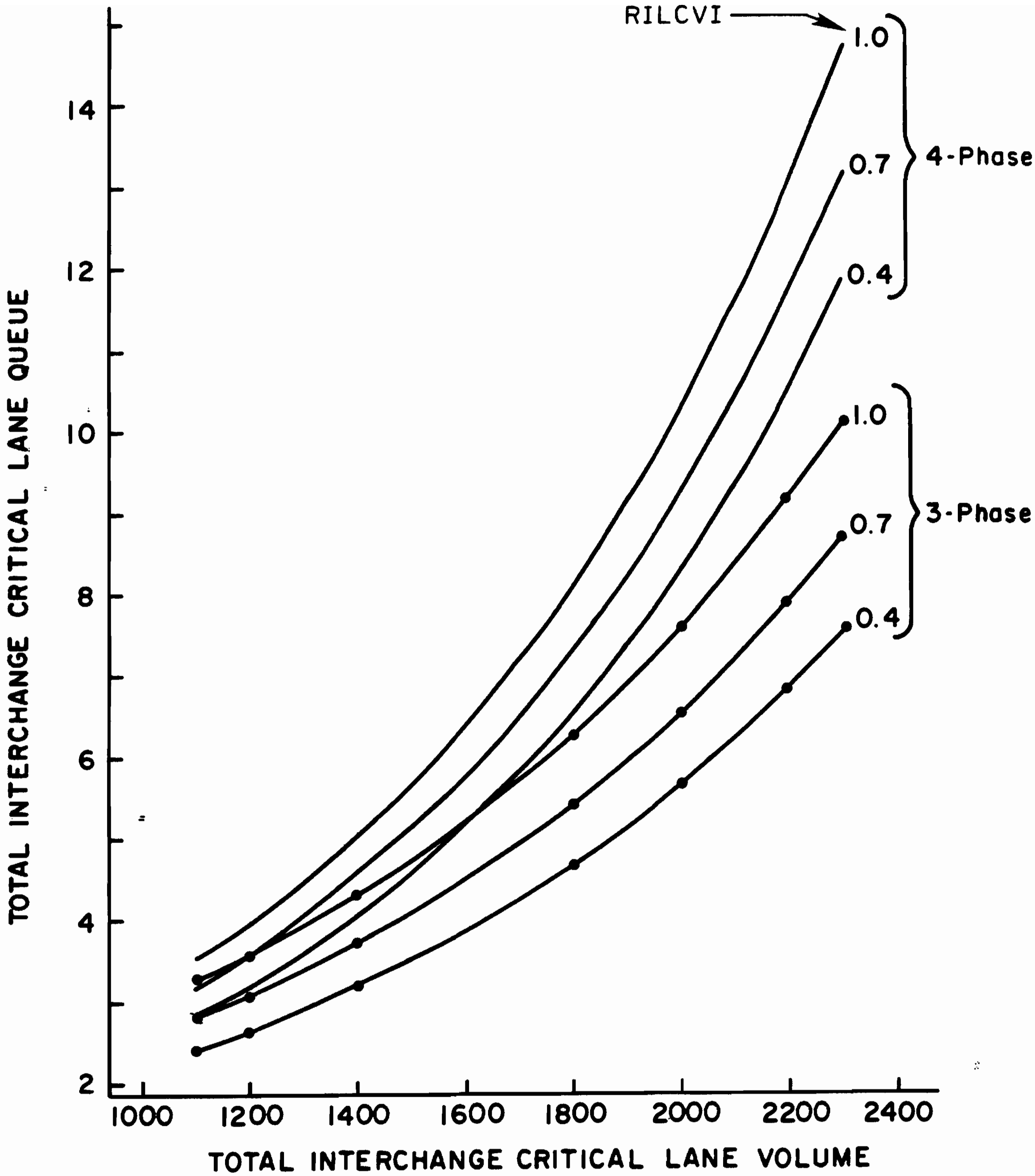


Figure 30. Queue Performance Characteristics Between Three- and Four- Phase for Multi-Point Detection.

and detection schemes.

For a given traffic volume and traffic pattern, cycle length increases in the order of three-phase, single-point; three-phase, multi-point; four-phase, multi-point; and four-phase, single-point detection. Since delay at diamond interchanges generally increases as cycle length increases, the four-phase single-point detection is the least favorable system among alternative control schemes based on overall delay. There is no significant difference in cycle length and queue performance between three-phase single- and multi-point detection. Thus, three-phase single-point detection is the most cost-effective among alternative control schemes. Four-phase control generates longer cycle lengths and subsequently more delay than three-phase control at most diamond interchanges when interchange lock-up does not occur. However, if four-phase control is used, then multi-point detection is delay-effective since it generates shorter cycle length and subsequently less delay than single-point detection.

VI. CONCLUSIONS AND RECOMMENDATIONS

This study has examined the operational performance of traffic actuated signalized diamond interchange control systems. Basic traffic actuated controller units were employed. All interchanges were operated isolated from all other intersections or interchanges. None of the interchanges were 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 within the study. They apply within the volume levels measured, traffic patterns experienced and operational environment of one-way frontage roads using basic actuated signal control.

1. Shorter cycle lengths are, in general, a desirable attribute for isolated interchange control. Phase terminations should be "snappy", with prompt termination becoming more critical as volume increases.
2. Queue delays increase as cycle length increases (above some minimum delay cycle length) for both three-phase and four-phase control.
3. Four-phase control characteristically operates at a longer cycle length than does three-phase for a given traffic volume.
4. Three-phase control usually produces less overall queueing delay than does 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.
5. 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 where there is a high proportion of through flow, either on the frontage roads and/or cross street. In most cases, three-phase requires the use of relatively short cycle times with wider interchanges permitting better phase flexibility and smoother flow.
6. 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.

7. Single-point detection produces, in general, longer cycle lengths than does multi-point detection. The trend toward longer cycle times for single-point detection is greater for four-phase than for three-phase control. Multi-point detection also can become susceptible to producing long cycle lengths under some heavy volume conditions.
8. Single-point detection is the more cost-effective three-phase detection system.
9. Multi-point detection is the more delay-effective four-phase detection system.
10. Multi-point detection should require less retuning than single-point detection as traffic patterns change if a suitable multi-point detection design, such as Beierle's system (6), is used.
11. Efficient and safe traffic flow at diamond interchanges is directly related to traffic dynamics and interchange geometrics for both three-phase and four-phase control.

RECOMMENDATIONS

The following recommendations are offered for consideration and possible implementation by SDHPT based on the results of this study. These recommendations apply to situations where 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 feet 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. Multi-point 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 as viable alternative when any of the following isolated interchange control conditions exist:

a) When there is a high percentage of pull-through traffic on the frontage roads; or

b) when the interchange has sufficient internal queue storage capacity to store traffic without locking-up; 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 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 density timing may be desired to minimize phase max-out even for multi-point detection.

6. 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 and/or frontage roads would be an additional attractive feature (8).

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