TECHNICAL REPORT STANDARD TITLE PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
TX-90/970-1F		

4. Title and Subtitle
EVALUATION OF ARLINGTON, TEXAS DIAMOND INTERCHANGE STRATEGY

5. Report Date
August 1989

6. Performing Organization Code

7. Author(s)
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8. Performing Organization Report No.
Research Report 970-1F

9. Performing Organization Name and Address
Texas Transportation Institute
The Texas A&M University System
College Station, TX 77843-3135

10. Work Unit No.

11. Contract or Grant No.
Study No. 2-18-87-970

12. Sponsoring Agency Name and Address
Texas State Dept. of Highways and Public Transportation
Transportation Planning Division
P.O. Box 5051
Austin, TX 78763

13. Type of Report and Period Covered
Final - September 1986 - August 1989

14. Sponsoring Agency Code

15. Supplementary Notes
Research performed for the State of Texas.

16. Abstract

Most signalized conventional diamond interchanges in America operate in only one signal phasing sequence and this limits the efficacy of the signal system. The Texas Department of Highways and Public Transportation (SDHPT) developed by 1984 an urban diamond controller that provided two phasing sequences that produces improved efficiency and reduced traffic delays over that provided by conventional controllers. Many of these controllers have been installed in the Dallas-Ft. Worth metroplex area of which Arlington is included. Traffic engineers with the City of Arlington began to experiment with innovative control ideas to provide additional phase flexibility at signalized diamond interchanges beyond the two-sequence system. This study describes the results of their development work and the quality of traffic flow provided at three interchanges studied in Arlington during the summer of 1988 by the Texas Transportation Institute.

17. Key Words
Diamond interchange
Signalized diamond interchange
Traffic signal control
Traffic actuated control

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	35	

Form DOT F 1700.7 (8-69)

EVALUATION OF ARLINGTON, TEXAS DIAMOND INTERCHANGE STRATEGY

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Research Report 970-1F

Research Study No. 2-18-87-970
State Funded

Sponsored by
Texas State Department of Highways
and Public Transportation

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College Station, Texas 77843

August 1989

METRIC (SI*) CONVERSION FACTORS

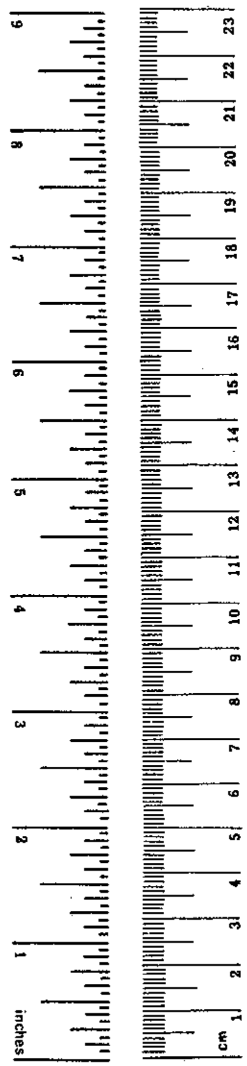
APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
AREA				
in²	square inches	645.2	millimetres squared	mm²
ft²	square feet	0.0929	metres squared	m²
yd²	square yards	0.836	metres squared	m²
mi²	square miles	2.59	kilometres squared	km²
ac	acres	0.395	hectares	ha
MASS (weight)				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
VOLUME				
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft³	cubic feet	0.0328	metres cubed	m³
yd³	cubic yards	0.0765	metres cubed	m³

NOTE: Volumes greater than 1000 L shall be shown in m³.

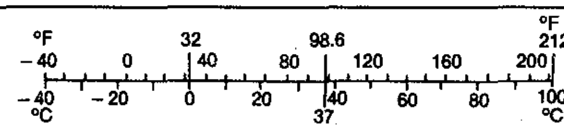
Symbol	When You Know	Multiply By	To Find	Symbol
TEMPERATURE (exact)				
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements



APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
AREA				
mm²	millimetres squared	0.0016	square inches	in²
m²	metres squared	10.764	square feet	ft²
km²	kilometres squared	0.39	square miles	mi²
ha	hectores (10 000 m²)	2.53	acres	ac
MASS (weight)				
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
VOLUME				
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m³	metres cubed	35.315	cubic feet	ft³
m³	metres cubed	1.308	cubic yards	yd³
TEMPERATURE (exact)				
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

ABSTRACT

Most signalized conventional diamond interchanges in America operate in only one signal phasing sequence and this limits the efficacy of the signal system. The Texas Department of Highways and Public Transportation (SDHPT) developed by 1984 an urban diamond controller that provided two phasing sequences that produces improved efficiency and reduced traffic delays over that provided by conventional controllers. Many of these controllers have been installed in the Dallas-Ft. Worth metroplex area of which Arlington is included. Traffic engineers with the City of Arlington began to experiment with innovative control ideas to provide additional phase flexibility at signalized diamond interchanges beyond the two-sequence system. This study describes the results of their development work and the quality of traffic flow provided at three interchanges studied in Arlington during the summer of 1988 by the Texas Transportation Institute.

KEY WORDS: Diamond interchange, Signalized diamond interchange, Traffic signal control, Traffic actuated control.

PROJECT SUMMARY

Signalized diamond interchanges are relied on to serve the traffic interchanging between high-volume urban freeways and major arterials of the local street system. Should the interchange fail to operate efficiently, traffic may not be able to rapidly depart the local street system and load onto the freeway. This condition may lead to gridlock of the local street system. Conversely, poorly operating traffic signals at freeway diamond interchanges may cause long queues to form on the exit ramps or one-way frontage roads (in Texas). These delayed vehicles may become so large that the growth of the queues may back up the freeway exit ramps and onto the freeway mainlanes causing large-scale traffic congestion on the high-volume urban freeways. The consequence of unexpected queueing on the affected freeways due to the queue back-ups are potentially significant traffic safety and operational problems. Large-scale urban-congestion could form due to the occurrence of a rear-end accident on the freeway.

Highly efficient traffic signal control is a desired goal to be provided at signalized interchanges. As most signalized interchanges in Texas are tight diamond interchanges having one-way frontage roads, the Texas State Department of Highways and Public Transportation (SDHPT) is continually striving to improve its traffic control specifications and systems for signalized diamond interchanges. This report describes a recent field evaluation conducted by the Texas Transportation Institute (TTI) of new innovative features that have been added by engineers at the City of Arlington, Texas, to the evolutionary development of SDHPT's basic traffic actuated signal control of conventional tight diamond interchanges.

Most signalized diamond interchanges operate in only one basic signal phase sequence. The most frequently used sequence is probably the "four-phase with two overlaps" strategy developed cooperatively by SDHPT and TTI about 1960. In about 1972 these same two organizations conceived and developed signalization using minicomputers whereby two different signal phasing sequences could be used at diamond interchanges. By 1984, SDHPT had further developed and installed many "urban diamond" signal control units that provided this two phase sequence capability.

Traffic engineers at the City of Arlington operated several of these controllers and began to envision ways of improving the ability to provide even further phase flexibility, perhaps as many as a dozen or so possible phase sequences each dependent upon the prevailing traffic conditions and selected on a cycle-by-cycle basis. A dozen of these new advanced phasing controllers were installed in Arlington by the summer of 1988.

The Texas Transportation Institute was requested by SDHPT and Arlington to study the operational efficiency of these controllers and to provide the following report on the study results. Three interchanges were observed in Arlington during the summer of 1988. Manual counts of traffic volume and queueing delay were recorded and evaluated. No special attempt was made to fine-tune the existing timing nor was any unusual maintenance performed. Statistical analysis of the observed data were conducted primarily

using transformed multivariable linear regression techniques. Overall, the Arlington system performed reasonably well and its features are to be commended for innovation and flexibility.

IMPLEMENTATION

The following implementation actions should be considered by SDHPT regarding the Arlington traffic-actuated diamond interchange control system:

1. The dynamic phase selection process provided by the Arlington system based on critical queue detection on each external approach to the interchange should be seriously considered for further implementation. However, design modifications should be formulated and corresponding controller timing parameters selected which minimize dual ramp queue actuations from arising, when possible.

2. Protected-plus-permitted left turns should be considered a desirable control feature on all SDHPT traffic-actuated control systems for diamond interchanges. Close monitoring of its safety effectiveness is to be encouraged, particularly for three lane approaches.

3. The optimal location and use of ramp queue detectors should be determine through analytic and simulation studies.

ACKNOWLEDGEMENTS

The authors would like to acknowledge the cooperation and assistance provided by the Department of Transportation of the City of Arlington, Texas. Specifically, Messrs R. Marshall Elizer, Jr., Director; Jack W. Loggins, Assistant Director; Ken R. Creamer, Signal Engineer, and their staff provided valuable insight and technical support to the study team. As noted in more detail in the body of the report, several new features of diamond interchange signal timing as studied in this research were developed by the City of Arlington, and we want to clearly acknowledge this point. Mr. Herman E. Haenel, Supervising Traffic Engineer V of D-18T with SDHPT in Austin, identified the desirability for this study and secured the state funding within SDHPT to support the work reported herein. Several staff members from the Traffic Operations Program of TTI helped collected the data in Arlington and to them we are grateful.

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INTRODUCTION

Problem Statement

Traffic demand has been steadily increasing in the urban centers of Texas for many years. Urban freeways are relied upon to carry a large portion of the intercity traffic. The junction of this traffic network with the adjacent local street system is a critical element to the efficiency of the overall highway transportation system. Should the interchange fail to operate efficiently, traffic may not be able to rapidly depart the local street system and load onto the freeway. This condition may lead to gridlock of the local street system. Conversely, poorly operating traffic signals at freeway diamond interchanges may cause long queues to form on the exit ramps or one-way frontage roads (in Texas). These delayed vehicles may become so large that the growth of the queues may back up the freeway exit ramps and onto the freeway mainlanes causing large-scale traffic snarls on the high-volume urban freeways.

Highly efficient traffic signal control is a consistent and commendable goal for traffic engineers to provide at signalized interchanges. As most signalized interchanges in Texas are conventional diamond interchanges of freeways having one-way frontage roads, the Texas State Department of Highways and Public Transportation (SDHPT) is continually striving to improve its traffic control specifications and systems for signalized diamond interchanges. This study describes a recent field evaluation by the Texas Transportation Institute (TTI) of new innovative features that have been added by engineers at the City of Arlington, Texas, to the evolutionary development of SDHPT's basic traffic actuated signal control of traffic at conventional urban diamond interchanges.

Study Background

Most signalized conventional diamond interchanges in America operate in only one signal phase sequence. The most frequently used sequence is probably the "four-phase with overlaps" strategy developed cooperatively by the Texas Highway Department and Texas Transportation Institute about 1960 (1). In about 1972, these same two organizations conceived and developed signalization timings that used minicomputers to control the traffic signals where different signal phasing sequences could be used at the diamond interchanges (2). Operational experience of this research system lead the research team to most frequently use one of two basic strategies for conventional diamond interchanges: either 1) three-phase control, or 2) four-phase with two overlaps as before. The widely used computer program PASSER III originally came from this research effort to operate and control signalized diamond interchanges (3).

By 1984, SDHPT had developed and installed many conventional urban "Texas Diamond" signal controller units that provided both three- and four-phase signal control (4). An extensive field study and evaluation of this effective controller was published by TTI in 1987 (5,6). Each signal phasing was noted to have its realm of more efficient traffic control, depending on interchange geometrics, traffic pattern and traffic volume level. As traffic is widely variable along a freeway and at its interchanges, a robust signal controller that can quickly and efficiently respond to a wide variety of traffic conditions is highly desired.

Three traffic control features which have recently become available are being used by innovative traffic engineers to improve signal performance. Microprocessor-based controller units provide improved timing and flexibility to implement certain classes of new strategies. Delay detectors, also microprocessor-based, provide the option of delaying calls of vehicles that might arrive on a nonprotected phase. Permissive left turning on a green ball can thereby result from these delayed calls which provides the option of operating the diamond interchange's left turn signals with the highly efficient protected/permissive phasing. Higher capacities, shorter cycles, and lower delays will result with protected/permissive left turns. With this phasing, it is also now possible to operate a diamond interchange in a "two-phase" mode in light traffic. In addition to lower delays, this strategy allows the phasing to dwell in "main street green" in light traffic, as in late nighttime operations. This condition keeps the arterial traffic moving, promotes ramp right turns to be made on red, and is believed to provide safer traffic flow. Delayed-call detectors can also be used as congestion detectors, as they can be set to ignore counts of free flowing vehicles but to quickly identify the presence of a standing queue of vehicles on an approach to a signal.

The City of Arlington, Texas, has developed an innovative traffic control strategy for signalized diamond interchanges which was evaluated in this research study. It uses all of the newly available features described above to enhance the already proficient operational qualities of SDHPT's existing three- and four-phase traffic signal controller. The essential operational features of the Arlington system have been described previously in a 1987 IMSA paper by Loggins, Renshaw, and Creamer (7).

Study Objectives

This interagency research study had as its general goal to evaluate the traffic operational performance of the new Arlington signal strategy for diamond interchanges. The study had the following specific research objectives:

1. Conduct traffic performance studies at three diamond interchanges in Arlington, Texas.

2. Evaluate the traffic operational quality of the signal strategy using traffic volume and queue counts similar to TTI Study 344 (5,6).

3. Prepare a technical memorandum which describes the study, documents the data analysis, and compares the results to Study 344 findings.

4. Provide recommendations to SDHPT regarding future operations of three-phase and four-phase control.

ARLINGTON CONTROL STRATEGY

Development

The basic operational features of the Arlington system follow as extracted from a previous publication by the developers (7). Some minor variations are implemented, depending on site specific local conditions. While minor in traffic impact when operational, their technical complexity may be considerable. This design has been used successfully at twelve different diamond interchanges within Arlington.

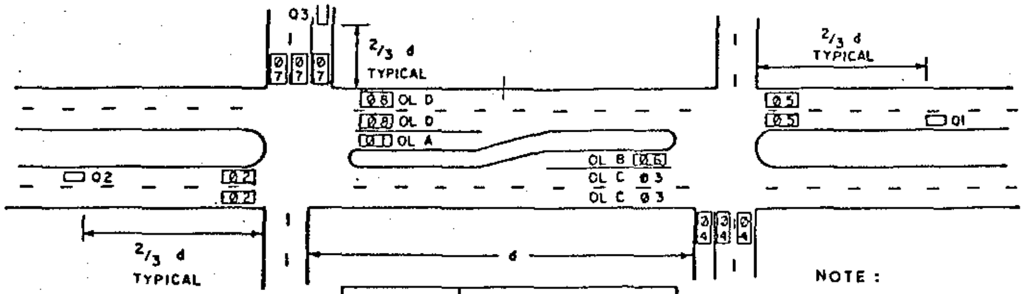
Features

Efficient isolated diamond interchange control requires that cycle lengths are kept low in order to minimize delay; yet some coordination between ramp intersections must exist in order to facilitate high traffic volume movement(s). Arlington achieves relatively short cycle lengths by minimizing service to the interior left turns and by only providing a protected left turn interval when substantial demand is present (use of protected/permitted signal heads). By serving as few phases as possible and by assigning phases and overlaps to enhance heavy traffic movements through the interchange, the phasing sequence is made dependent upon current traffic demand. This dependency produces dynamic two-, three-, or four-phase signal operation.

All of the above operational benefits require the strategic placement and application of queue detectors on the approach roadways to the interchange. The queue detector is a small (6 ft. x 20 ft.) inductive loop detector that places a delayed call to a phase (usually an interior protected left turn) only when a traffic queue on its approach location is detected for about 8 seconds or longer. The location of these detectors are dependent upon the site specific characteristics of the diamond. They are normally installed on the major exterior approaches to the interchange at a distance equalling two-thirds of the distance between the ramp (or frontage road) intersections.

Figure 1 shows typical phase assignments used at a majority of the diamond interchange locations in Arlington which presently utilize the queue detection techniques. As noted above, each specific interchange must be designed to incorporate phase and overlap assignments, signal settings, and electrical circuitry that best fits the site characteristics of the diamond and traffic volume. Shown on the phasing diagram are some alternative sequences that can be accomplished based upon the activation sequence of the queue detectors.

Condition 1 illustrates the predominant phasing for Arlington's scheme. The detectors associated with phases 1 and 6 are delay detectors which prevent premature left turn signal display and service. The actual left turn movements are served, assuming no queue detector actuation, by the permitted interval and, should there be left turn delay, the protected arrow will be activated only after the delay timer has expired. Phase 2 is always placed on vehicle recall to insure sufficient green time for vehicles to clear each ramp intersection during light



OVERLAP	PHASES ASSIGNED TO OVERLAP
A	1,8
B	3,6
C	1,2,3,5,6
D	1,2,5,6,8

NOTE :

Ø 1,3,6, and 8 are for timing only when queue detector is activated . No detector is used on 3 and 8 , Ø 1 and 6 can time it's own phase .

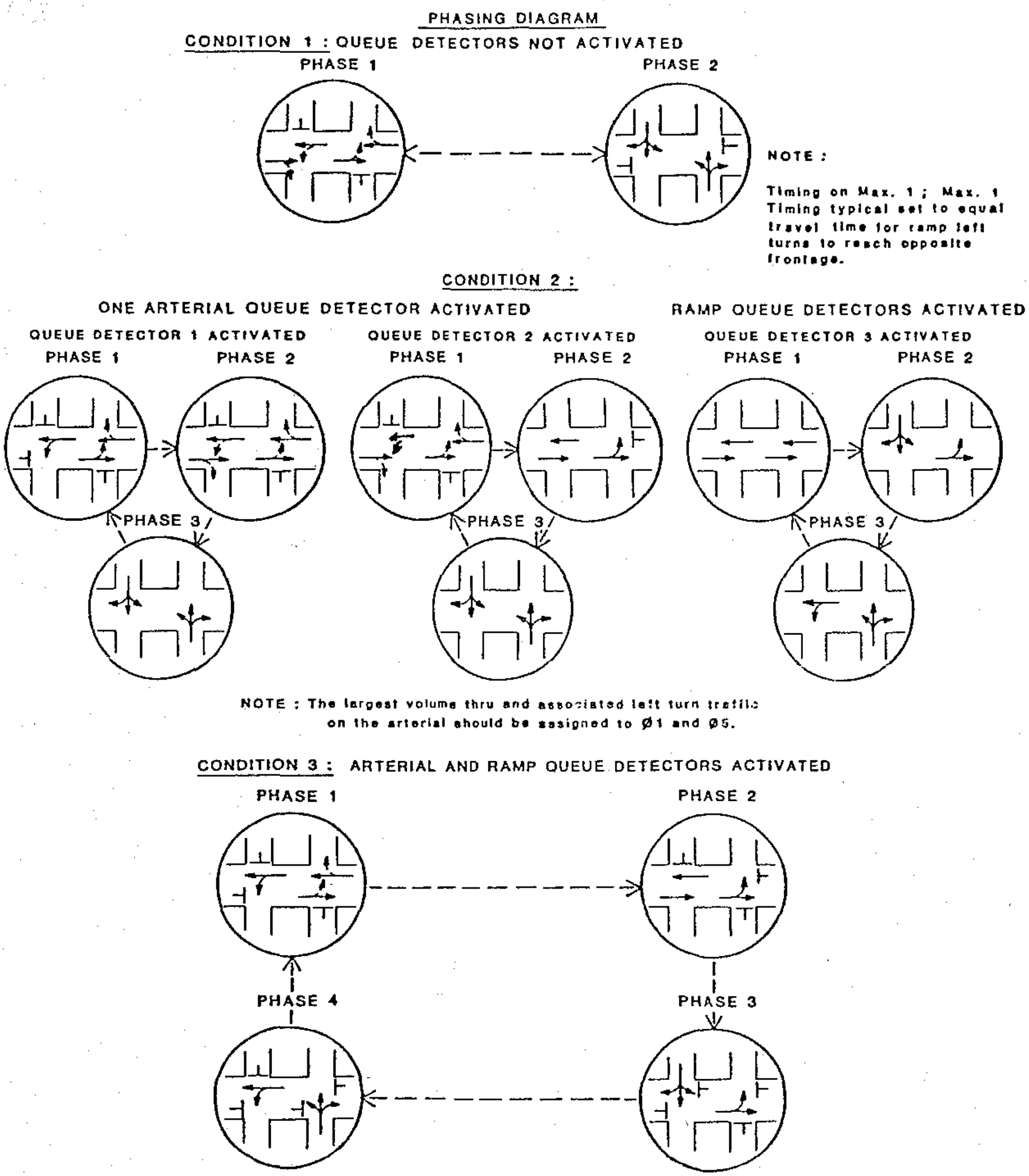


Figure 1. Arlington Diamond Interchange Control Strategy.

traffic conditions. The Max 1 timing for the phase is set to limit simultaneous ramp flow such that the existing storage between the ramp intersections is not exhausted.

Condition 2 displays the phasing for activation of a queue detector on the arterial street. Queue detector #1, when activated, places a call on phase 1 and the left turn phase is extended by its associated pedestrian time to assure that the platoon reaches the phase 1 vehicle detector prior to the expiration of the gap timing. Also shown is the activation of a queue detector on the ramp approach. When queue detector 3 is activated, a relay is enabled which locks a vehicle call on phase 3. This call is present as long as phase 7 is active. Unlike the other conditions, the queue detector call activates the Max II timer. This allows for longer service to the ramp approaches to clear out the queue. Phase 3's "on" output also places a vehicle call on phase 8 to assure termination of phase 7 and timely service of phases 4 and 8. Both of these conditions will basically yield a three-phase cycle sequence.

The sequencing shown in condition 3 exhibits the activation of a queue detector both on the ramp and the arterial street. When this situation occurs, the cycle sequence appears to operate as four-phase.

EXPERIMENTAL PLAN

The scope of the research funding limited the size of the study to only one day at each of three interchanges. Manual recording of operational performance was used. Following manual data reduction, statistical analysis was performed using microcomputers. Results of these analyses follow. Comparisons to earlier Study 344 research (5,6) on diamond interchanges are provided as appropriate.

Interchange Characteristics

The three diamond interchanges studied are noted in Table 1. They provided some variety in geometrics and environment. These interchanges were selected, however, primarily because of their expected variations in traffic flow among them by time of day and directional loading as confirmed by subsequent data analysis. All three interchanges had one-way frontage roads as commonly provided in Texas cities.

TABLE 1. INTERCHANGE CHARACTERISTICS IN ARLINGTON, TEXAS

Interchange Cross Street File Name		Number of Cross Street Thru Lanes	Dimensions (ft) Curb-to-Curb Inside-to-Inside	Turnaround Lanes Present	Left Turn Lanes	Left Turn Phase
Avenue H	@ SH 360	2	235	Yes	Yes	P+P
Six Flags	@ SH 360	3	190	Yes	Yes	PRO
Green Oaks	@ IH 20	2	400	Yes	Yes	P+P

Each interchange was located along a section of freeway having frontage roads. As noted in Table 1, each interchange also had separate left turn lanes for each interior left turn movement. Turnaround (or U-turn) lanes were also provided for each frontage road and exit ramp approach. Protected left turns only (PRO) were provided at Six Flags; whereas, protected-plus-permitted (P+P) left turns were provided at Avenue H and Green Oaks. The Green Oaks interchange had protected left turns only phasing when Study 344 was conducted a few years earlier (5,6). Details of geometrics, signal phasing and controller settings are given in the Appendix.

Study Periods

The scope of the research funding limited study to one day for each site. Study days were on Tuesday, May 31, 1988, at Six Flags; Wednesday, June 1, 1988, at Avenue H; and the following Thursday June 2, 1988, at Green Oaks. Study times were also scheduled to provide six hours of data per day. Scheduled times were 7-9 a.m. to cover the morning peak, 11 a.m.-1 p.m. to cover the midday traffic, and from 4-6 p.m. to study the evening rush. Study times were planned to begin slightly in advance of the rush periods to obtain buildup traffic conditions.

Observed traffic data included traffic volumes, stopped vehicle queue counts, and cycle lengths. These data were always summarized to 15-minute samples which were assumed to be independent data points. Since at least 6 hours of data were always obtained each day for each interchange studied, a total of 24 data points were recorded for each interchange each day, 6 hours x four 15-minute sample periods per hour. Due to seasonal spring showers that frequent Texas at that time of the year, some modifications were made in the time schedule because of inclement weather.

Traffic Volumes

Traffic volume was used as the primary input variable. Traffic volume data were collected manually using Time-lapse recorders supplemented by assistant recorders. Volume counts were recorded by lane for each of the three input approach legs to each side of the interchange, including both the exterior and interior approaches. The critical (or maximum) volume by lane was noted for each approach for each 15-minute period. These six "critical" volumes, each expressed in vehicles per hour per lane (vphpl), were then totaled to produce and "total interchange" critical lane volume for each study interchange. That is

$$V = V1c + V2c + V3c + V4c + V5c + V6c \qquad (1)$$

where V is the total interchange critical lane volume, vphpl, and V1c through V6c are the critical lane volumes in vphpl on approaches 1 through 6. Subscripts 1, 2, and 3 refer to the three approach legs on one intersection; whereas, subscripts 4, 5, and 6 relate to the corresponding approaches of the other intersection of the signalized diamond interchange.

The statistical analysis software provided the option to automatically identify the critical (maximum) lane volumes for each approach. Total interchange summaries were readily developed by this statistical system. Data bases were initially developed for each interchange and later merged for composite analysis as necessary.

Figure 2 shows plots of total critical lane volumes observed for each of the three interchanges by study period. Again, the total interchange volume, V, is expressed in flow rates of vphpl observed over the 15-minute study intervals shown. No adjustment for heavy vehicles (trucks) was made, although Six Flags was observed to have relatively heavy truck traffic during the study. Each interchange is noted to have different demand characteristics. As the name suggests, Six Flags is located at the entrance to a regional amusement park and its peaking occurs in the late afternoon as visitors begin to heavily use the park. As can be seen in Figure 2, no data was collected at Avenue H during the morning rush hours due to rain showers that occurred at the site.

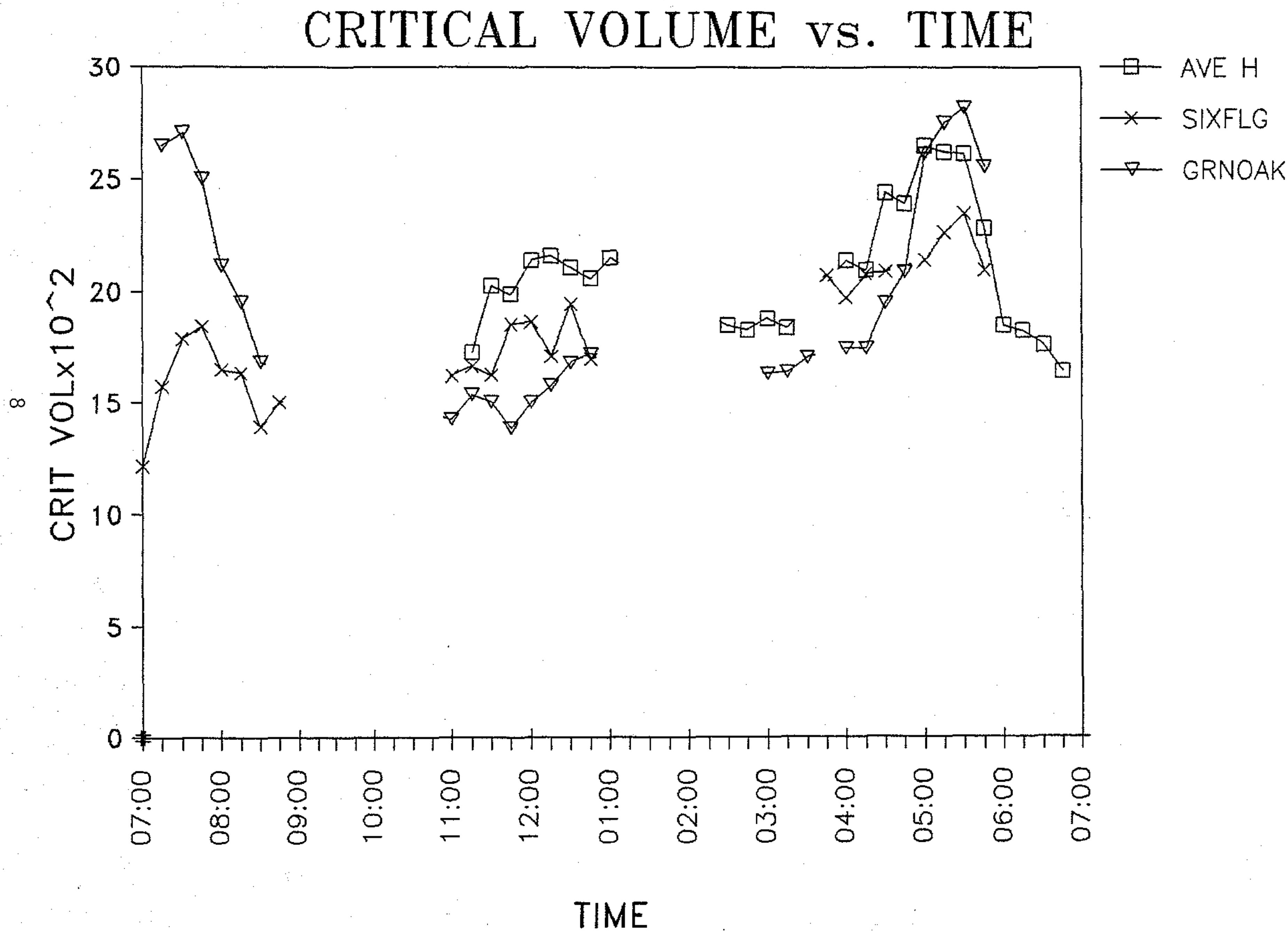


Figure 2. Critical Volume Versus Time.

Cycle Length

An average cycle length was recorded for each 15-minute study period by a study observer recording the start of the inbound arterial phase on recall for the actuated system. As the traffic control system was actuated, the cycle length is only suggestive of the control efficiency and traffic delay that might be occurring. Unlike pretimed control, the time of each cycle length for basic actuated control depends on short-term traffic volumes, number of signal phases in a cycle, and traffic controller settings of (a) initial green, (b) gap extension, and (c) maximum green time for each phase, together with other system design factors. Specific details of the controller settings and detector operations are given in the Appendix for each interchange.

Figure 3 presents observed average cycle times over time for the three interchanges. Cycle times at Avenue H are noted to be very sensitive to conditions compared to the other interchanges. As will be noted again in later analysis, the longer cycle times were observed in the field to be due in part to the frequent occurrence of split frontage road/ramp phasing rather than the more efficient single phase for both frontage roads. Cycle times at Six Flags tended to be longer than observed for Green Oaks, undoubtedly caused by Six Flags having "protected only" left turn operation as compared to protected-plus-permitted operation at Green Oaks.

Queue Delay

The 1985 Highway Capacity Manual (8) defines traffic signal efficiency in terms of average stopped delay per vehicle. Average stopped delay per vehicle on an approach serving an average arrival flow of "v" vehicles per second is:

$$d = q/v \qquad (2)$$

where

- d = average stopped delay per vehicle, sec/veh
- q = average number of vehicles stopped in queue at an interchange approach during the study interval, veh
- v = average approach flow during the study interval, veh/sec

Equation 2 shows that for a given flow rate, v, counting the number of vehicles stopped over a study time interval and from that count, determining the average number of vehicles stopped per unit time is directly related to, and essentially equivalent to, determining the average stopped delay from delay measurements made on the individual vehicles. The only requirement is that queue comparisons have to be made at the same volume levels. This comparison methodology was used to make the following queueing study.

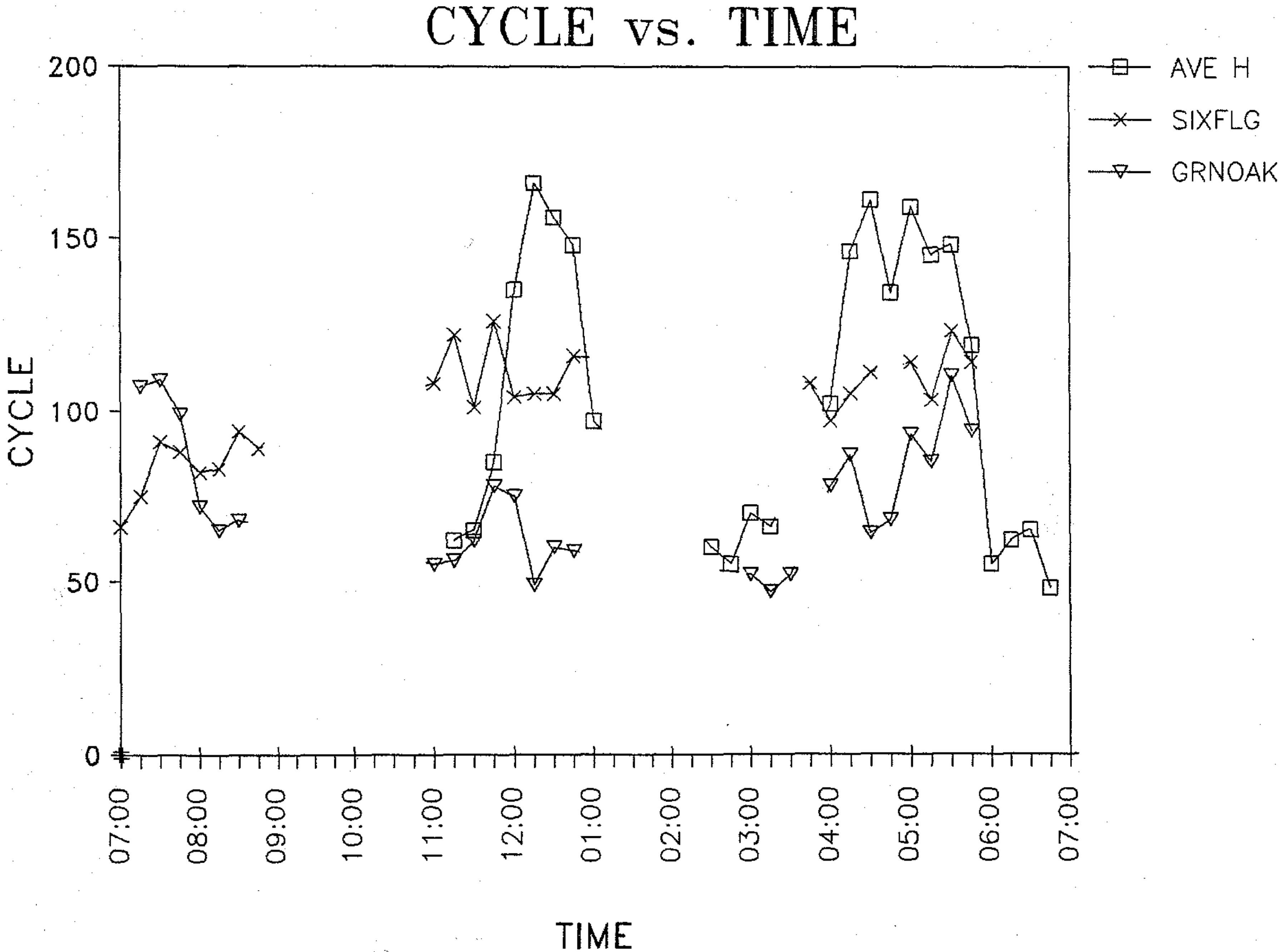


Figure 3. Cycle Versus Time.

Interchange Queue

Total interchange critical queue was selected as the primary traffic control system measure of operational efficiency. Total interchange queue was derived from the six approaches similar to that of total input volume. Observational counts of the number of vehicles stopped in each lane for each approach were recorded every 15 sec. Averages by lane per approach were then determined over each of the 60 (4/min x 15 min) samples for each respective 15-minute period. The maximum average queue per lane per approach for each interval was then identified during data reduction. Each critical (or maximum) queue per lane per approach is denoted by "ci".

Total interchange critical queue for a 15-minute study interval is equal to

$$Q = Q1c + Q2c + Q3c + Q4c + Q5c + Q6c \qquad (3)$$

where Q is the total interchange critical queue, veh/lane, and Q1c through Q6c are the maximum queue lengths per lane in veh/lane, averaged over 15 minutes, on approaches 1 through 6 respectively.

Comparisons among interchange operations can be made at the same total volume levels. However, Equation 2 indicates that comparisons of observed queues among different interchanges cannot be made at different total volume levels because queueing and coverage stopped delay per vehicle increase with increasing volume. Consequently, a case having higher total interchange queue could have arisen because of higher total input volumes, not due to a less efficient interchange design or control system.

Figure 4 provides plots of derived total interchange queue over the study times for the three interchanges evaluated. Total queue (the number on vehicles stopped on the six critical lanes on the average per study interval) is seen to respond with time (and related traffic demand) as expected.

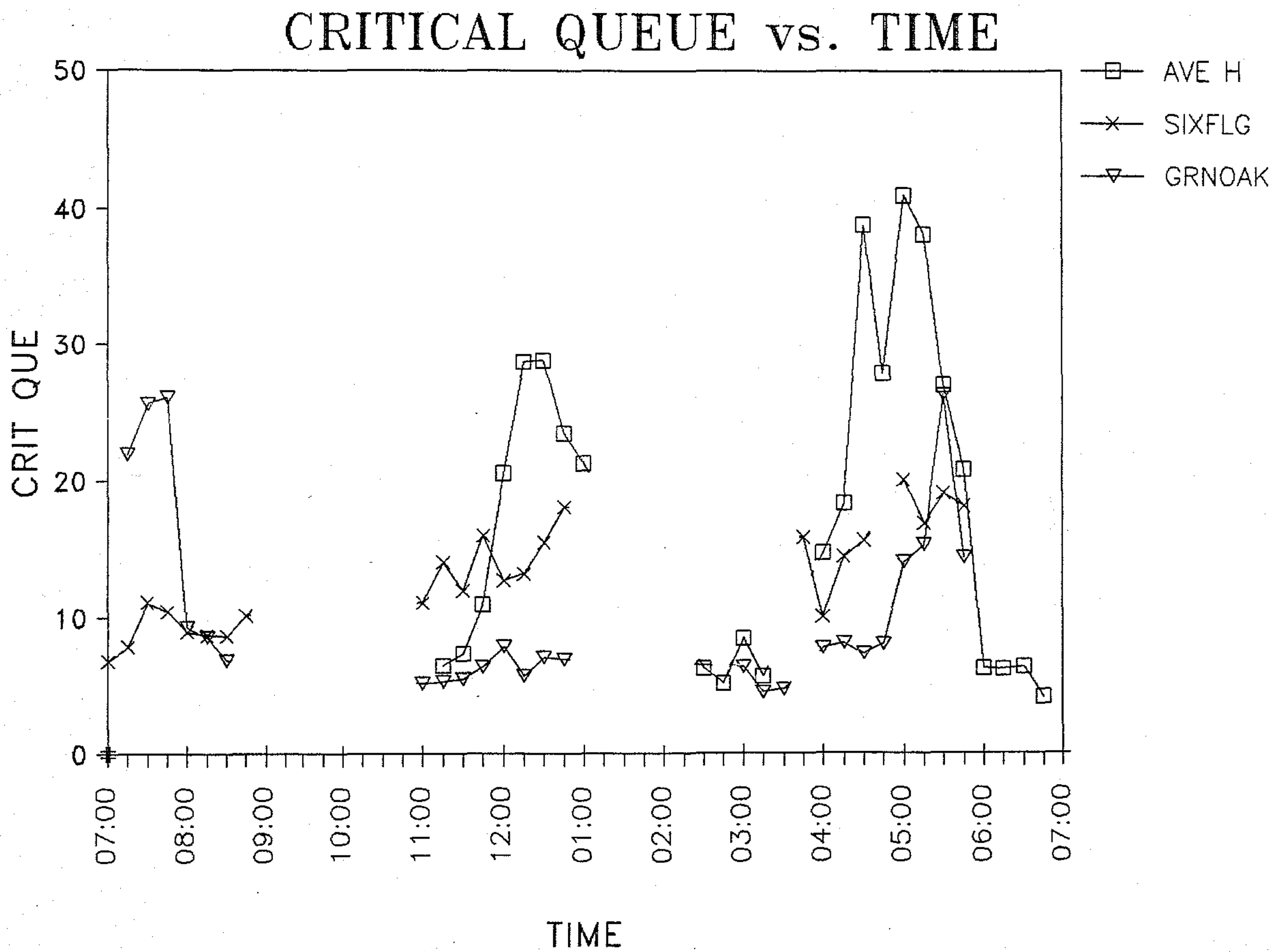


Figure 4. Critical Queue Versus Time.

STUDY RESULTS

Introduction

Statistical regression analyses were performed on the interchange data sets to develop predictive models of each interchange's operational performance. The micro version of the Statistical Analysis System, Micro SAS 6.02, was used to develop the regression models. Two basic model relationships were desired. One was the cycle length that results for a given total interchange critical volume. The other was the total critical queue (delay) that results for a given total interchange critical volume. Plots of these regression results will be provided for the three interchanges followed by plots which add Study 344 findings (5) to the previous plots. Study 344 findings are based on multi-point detector strategies for three-phase and four-phase signal control, since the Arlington system also uses two sets of detectors on each approach to an interchange.

Cycle Length Versus Volume

Linear relationships were developed to predict average cycle time as related to total interchange critical lane volumes. Figure 5 shows the results of this modeling effort for the three interchanges. The derived models were:

$$C = 148.52 + 116.56(V/1000) + 37.29RILCVE; \quad R^{**}2 = 0.67 \text{ Ave H} \quad (4)$$
$$C = 43.26 + 35.61(V/1000) - 13.94RILCVE; \quad R^{**}2 = 0.38 \text{ Six Flags} \quad (5)$$
$$C = -0.48 + 32.98(V/1000) + 21.06RILCVE; \quad R^{**}2 = 0.69 \text{ Grn Oaks} \quad (6)$$

where C is the cycle length in seconds, V is the sum of the critical lane volumes at the interchange in vphpl and RILCVE is the internal left turn volumes per sum of external critical volumes, as in Study 344. An average RILCVE of 0.4 was used to generate all of the following graphs for cycle length.

A perusal of Figure 5 shows several relationships. As expected, cycle time increases with increasing demand volume for the actuated control systems. Green Oaks had the shortest cycle times which were about 30 seconds less than Six Flags over all ranges of volumes. Recall that Green Oaks had permitted/protected left turns whereas Six Flags only had protected left turns which probably accounted for its consistently longer cycle lengths. One can only speculate about the anomalous performance of Avenue H. While nothing seemed unusual at the site during operations, the signal phasing did seem to be "kicking in" split frontage road phasing a lot (producing a resulting inefficient four-phase timing). Consequentially, cycle lengths were observed to be running longer than expected.

Figure 6 compares Figure 5 results to those obtained for interchanges in the Dallas/Ft. Worth area in Study 344 (herein designated as "344") for three-phase and four-phase control and multi-point detection. In Study 344 no benefits of permitted left turns were available to shorten the cycle for a given demand volume. Green Oaks and Study 344 four-phase generated about the same cycle times. Three-phase produced clearly the shorter cycle

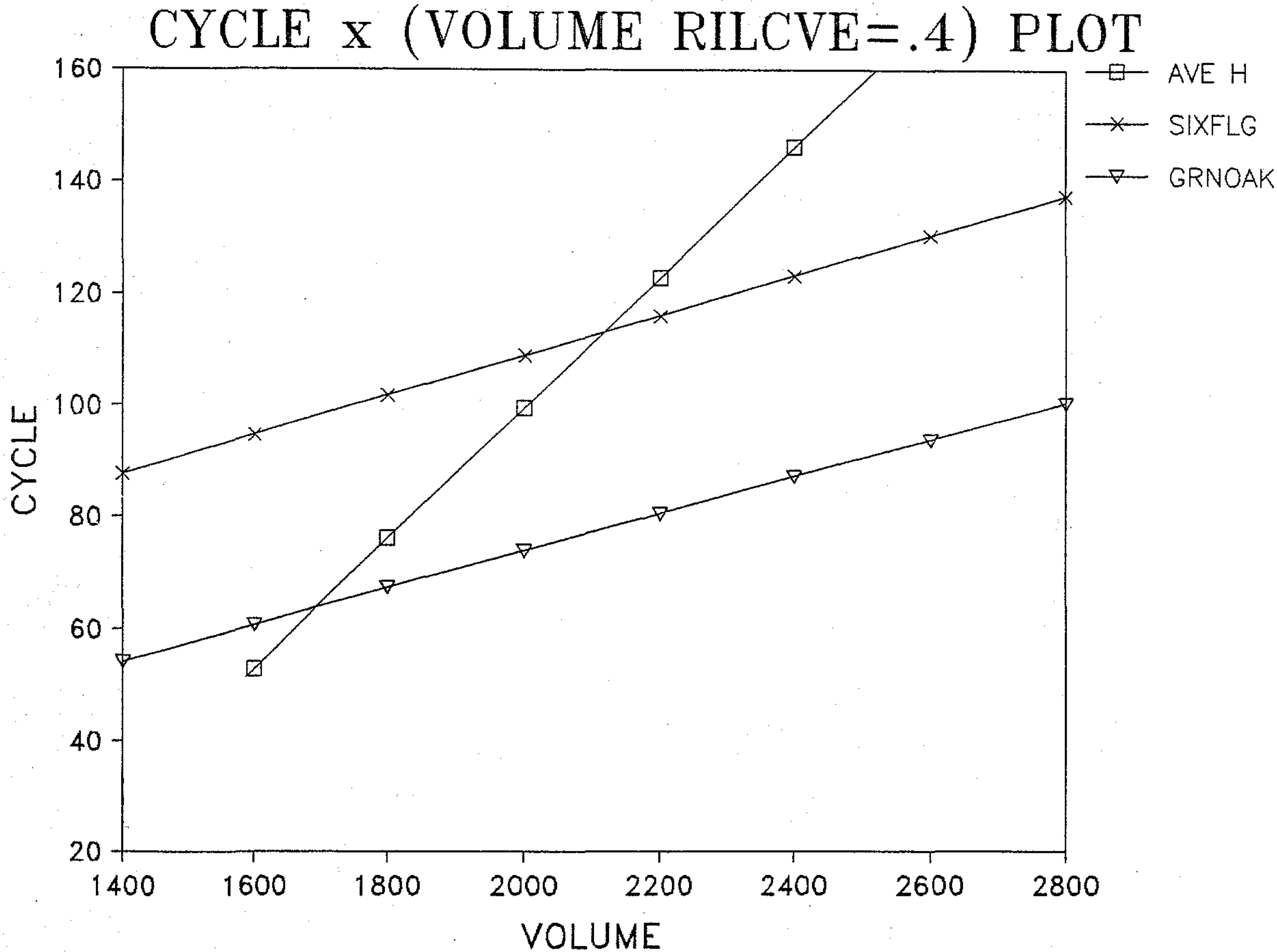


Figure 5. Cycle Versus Critical Volume Plots.

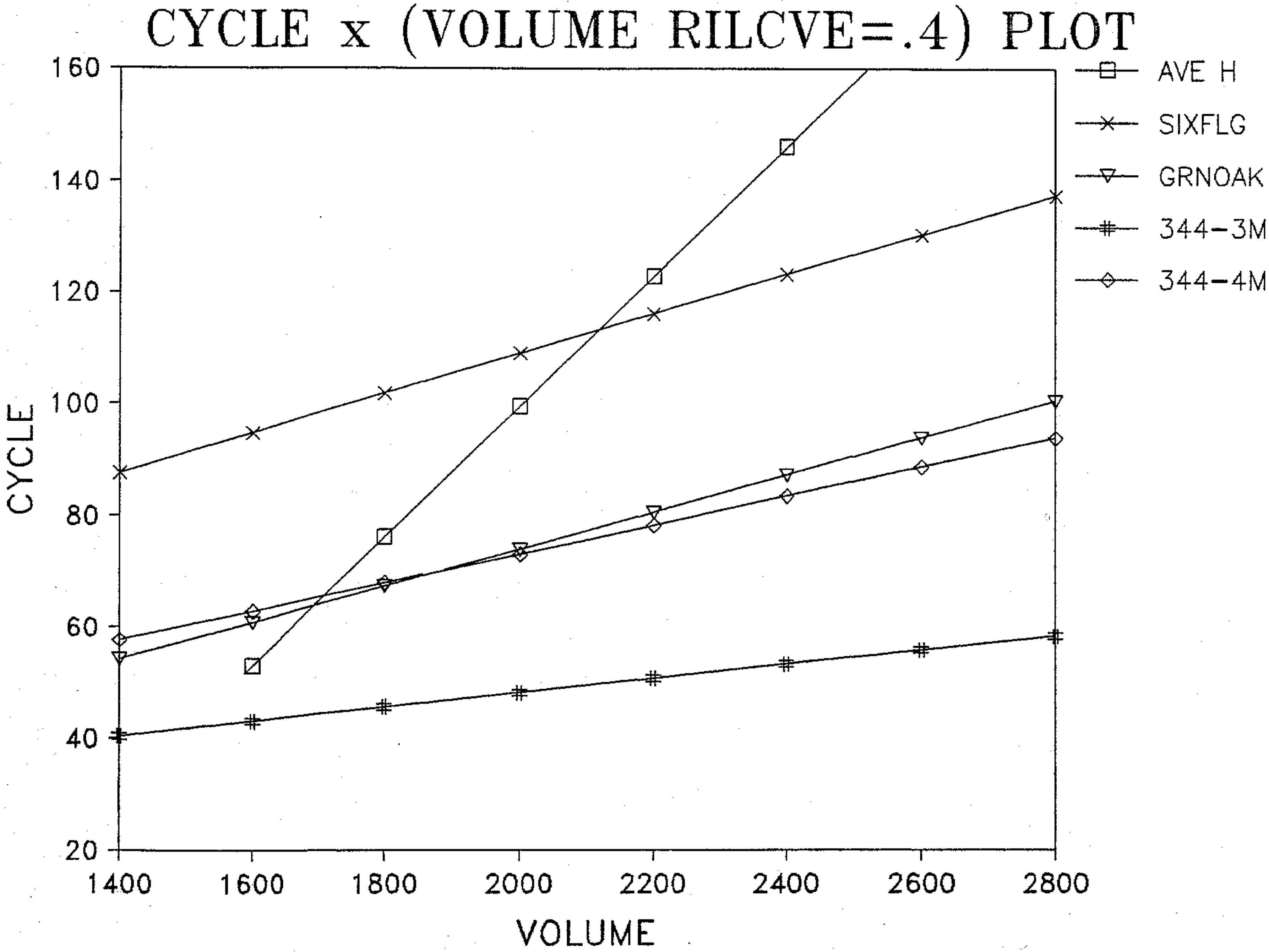


Figure 6. Cycle Versus Volumes Versus Study 344.

times. In general, the Study 344 control systems provided shorter cycle times even with the limitation of no permissive left turn phasing.

Queue Delay Versus Volume

Exponential relationships were developed between total interchange queue delay and critical lane volume for each of the three interchanges in Arlington using transformation regression techniques. Figure 7 depicts the results of this modelling effort. The three equations developed were:

$$Q=\text{EXP}[-1.83 + 2.42(V/1000) - 0.67\text{RILCVI}]; \quad R{**}2 = 0.82 \quad \text{Ave H} \qquad (7)$$

$$Q=\text{EXP}[+0.47 + 0.43(V/1000) + 1.76\text{RILCVI}]; \quad R{**}2 = 0.78 \quad \text{Six Flags} \qquad (8)$$

$$Q=\text{EXP}[-0.62 + 1.17(V/1000) - 0.67\text{RILCVI}]; \quad R{**}2 = 0.87 \quad \text{Grn Oaks} \qquad (9)$$

where Q is the total interchange critical lane queue veh/lane, V is the total interchange critical lane volume vphpl, and RILCVI is the internal left turns per sum of critical lane volumes, as in Study 344.

The results of Figure 7 continue to show the same relative trends of the earlier cycle time analysis. Green Oaks generally had lower delays than did Six Flags for the same volume in the low to moderate range. At the higher volume levels, however, the queue delay results of Green Oaks are noted to approach those at Six Flags. These high-volume results are consistent with the idea that protected-plus-permitted left turns lose much of their capacity at high-volume levels and begin to perform much like protected-only operations. Avenue H seems to have reached its functional capacity at a total volume of about 2000 vph as delays for protect-plus-permitted left turn operation (as compared to Green Oaks) became excessive above this volume.

The Study 344 model results for three-phase and four-phase are added to the above in Figure 8. Traffic performance at Green Oaks is observed to be slightly better than Study 344 three-phase. The improved operating range again is likely due to the benefits of protected-plus-permitted left turn operation at Green Oaks. These benefits are minimal at high-volume levels. However, Study 344's three-phase produced less queue delay than occurred at Six Flags or Avenue H. Four-phase performed about the same as the Six Flags control system.

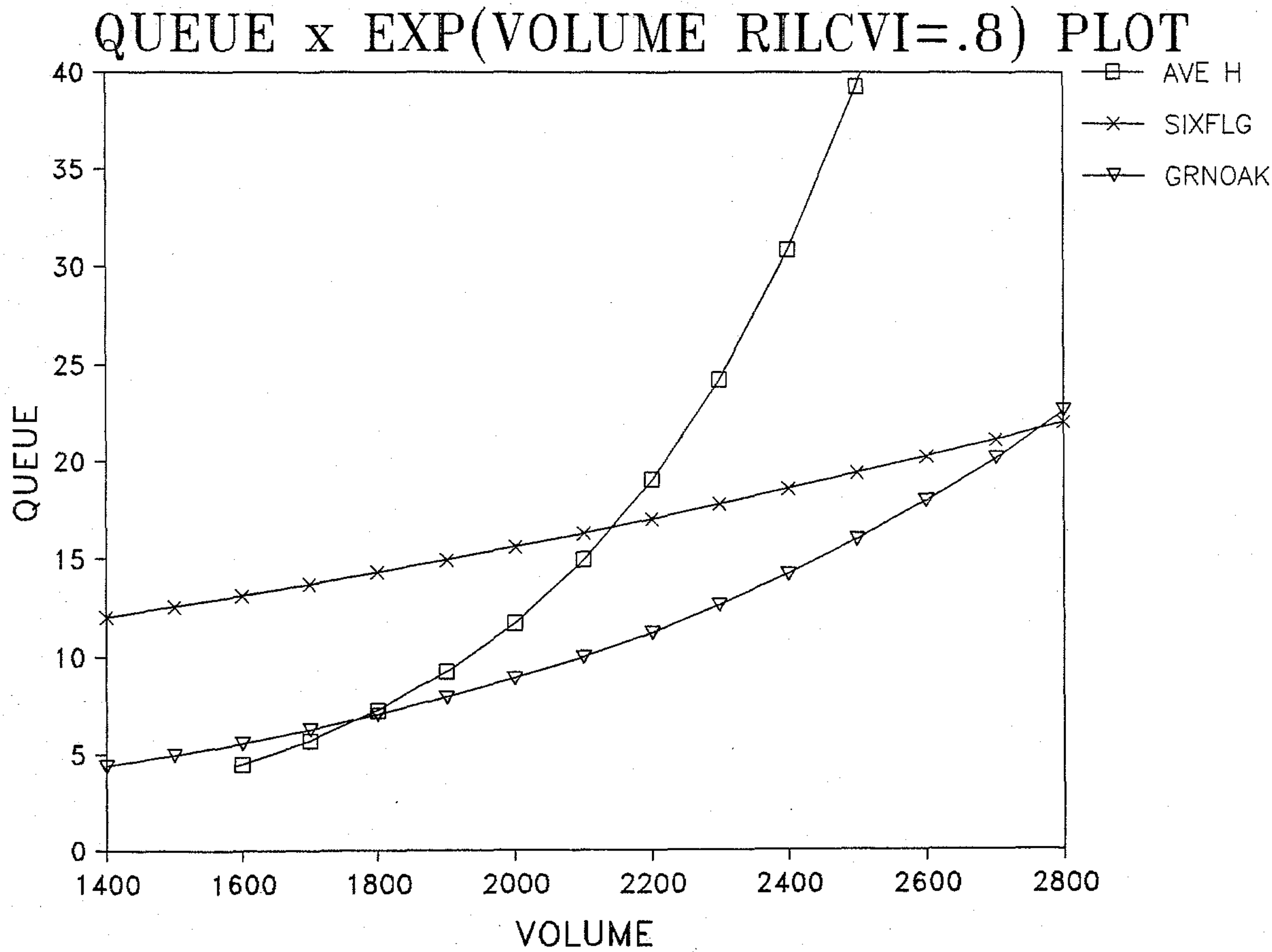


Figure 7. Queue Versus Critical Volume Plots.

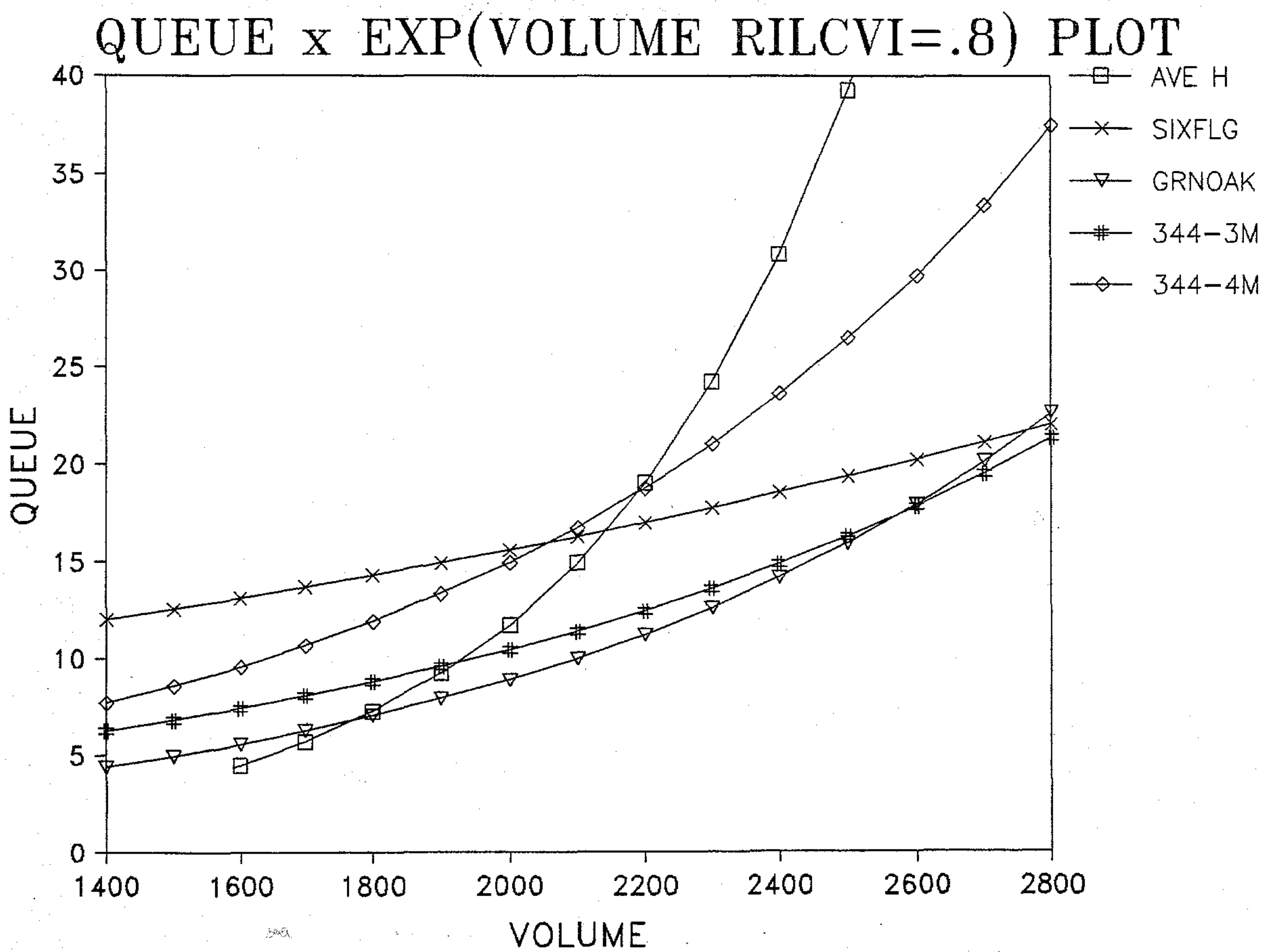


Figure 8. Queue Versus Volumes Versus Study 344.

STUDY FINDINGS

The Arlington system provides several desirable features for diamond interchange control. It generally provides a short cycle length in light-to-moderate traffic providing the interior left turns an opportunity to turn on a "permitted" green ball phase. Its ramp and arterial queue detectors provide additional inputs which can be used to modify controller timings and phase sequence. The new system at Green Oaks appeared to operate very well.

This limited study did reveal that drivers adapt easily to variable phase sequencing. No unusual operational problems were noted in the field due to the dynamic phase sequence selection process provided by the Arlington system.

Observations taken from Avenue H and a few afternoon rush hour cycles at Green Oaks reveal how sensitive cycle length is to the simultaneous occurrence of long ramp queues (i.e., actuation of the frontage road/ramp queue detectors). When both frontage road queue detectors are occupied, a four-phase sequence is generated. This simple four-phase sequence is operationally inefficient. These "explosive" cycle conditions generate longer queues and heavy delays for the volume level on which the Arlington system then appears to further feed upon the phase sequence's own inefficiency. These conditions were observed to occur at Avenue H during the midday and afternoon study periods. In addition, these "explosive conditions" tend to occur at the higher-volume levels wherein the capacity of the permitted left turn phases are minimal. As noted at Green Oaks, this capacity reduction tends to increase queueing and delays. The combination of these factors, together with some other unknown factors, contributed heavily to the poor performance observed at Six Flags for total interchange volumes exceeding 2000 vphpl.

Predicted performance of SDHPT's "Texas Diamond" three-phase and four-phase controller seems to compare favorably with the Arlington design, especially since the Study 344 Texas Diamond design did not have the more efficient protected-plus-permitted left turn phasing installed when study 344 observations were made. The three-phase system seems to be especially effective in the volume range studied.

RECOMMENDATIONS

The following recommendations are offered for consideration by SDHPT regarding the findings from the Arlington traffic-actuated diamond interchange control system and future applications to SDHPT systems:

1. The dynamic phase selection process of the Arlington system based on critical queue detection should be seriously considered for further implementation. However, design modifications should be formulated and corresponding controller timing parameters selected which minimize dual ramp queue actuations where possible. When both ramp queue detectors become occupied, the optimal four-phase sequence should be implemented until both queue detectors clear. Arlington has proposed a lead-lag ramp/frontage-road phasing (as at high-type intersections having concurrent dual-ring timing with lead-lag phasing) which may provide the desired higher performance.

2. Protected-plus-permitted left turns should be considered a standard control feature on all SDHPT traffic-actuated control systems for diamond interchanges. Its use in three-phase control should be encouraged. Its use with four-phase should be studied to determine its optimal application. General application guidelines should be developed for all cases. There are concerns that protected-plus-permitted left turn operations should not be implemented where the opposing approach has three thru lanes of traffic, for example as at Six Flags where protected left turns only had to be reinstalled due to safety problems with protected-plus-permitted operations.

3. The optimal use of ramp queue detectors should be determined through analytic and simulation studies.

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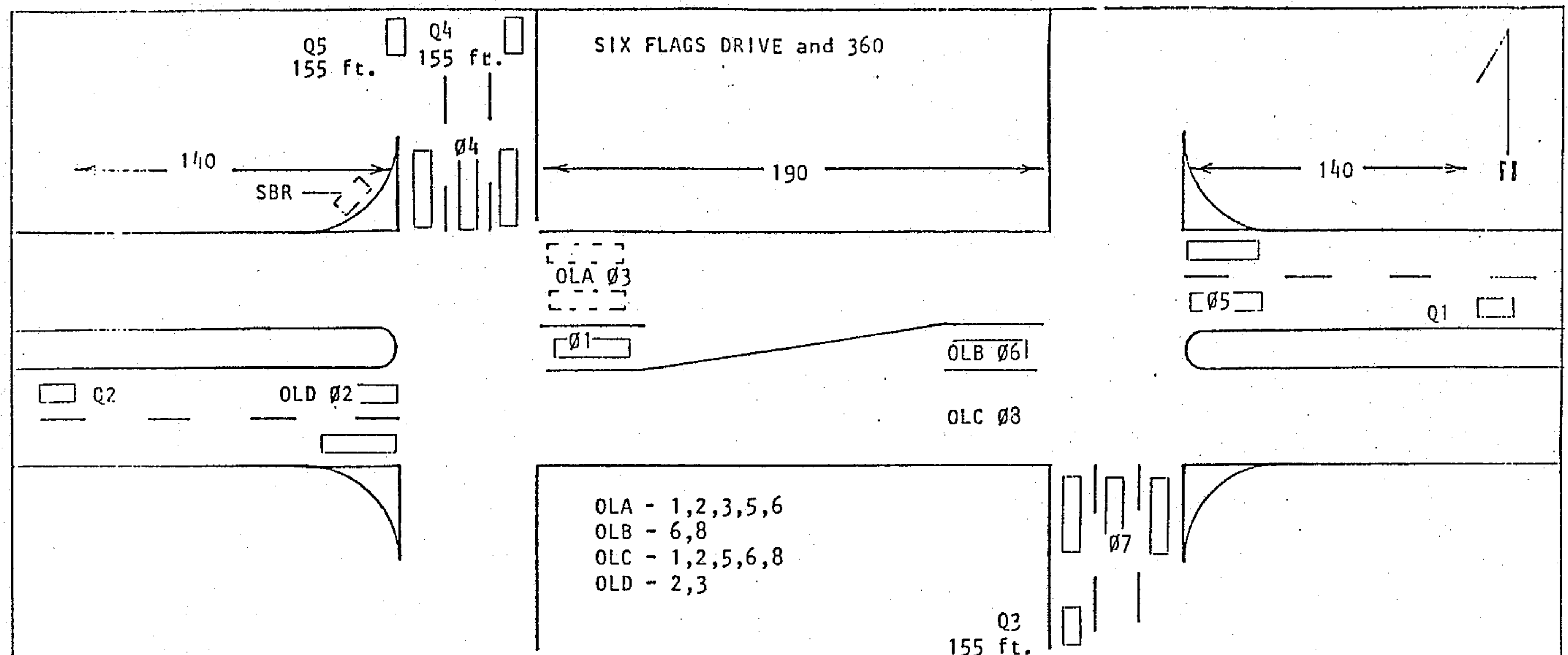
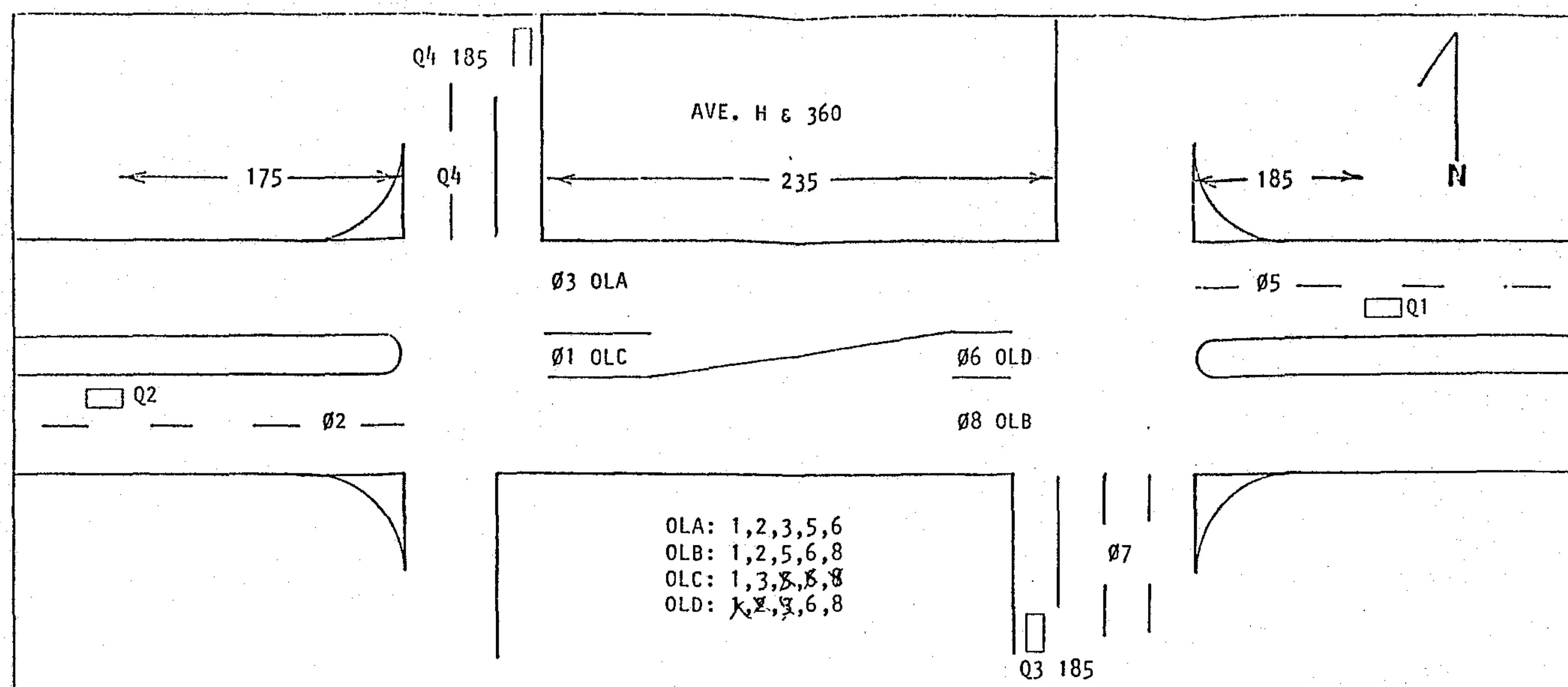
APPENDIX

Geometric, Signal Phasing, And Controller Setting Details.



1. Phase 2 on min. recall.
2. Q1 places ped call on phase 1 ____ second delay.
3. Q2 places ped call on phase 6 ____ second delay.
4. Q3 places ped call on phase 3 ____ second delay.
5. Q4 places ped call on phase 8 ____ second delay.
6. Q5 enables Max. 11 and SBR detector. Circuit shown on separate page ____ second delay.
7. 03 loops operational only after Q3 activation, circuit shown on separate page.
8. 03 or 08 ped call enables max. 11.
9. 01 delay detector ____ second delay.
10. 0 6 delay detector ____ second delay.



1. Ø2 ON MIN. RECALL 15 SECOND INITIAL & DUAL ENTRY ON Ø3
2. Q1 PLACES PED. CALL ON Ø1 & Ø5 8 SECOND DELAY
3. Q2 PLACES PED. CALL ON Ø2 & Ø6 8 SECOND DELAY
4. Q3 PLACES VEHICLE CALL ON Ø3 8 SECOND DELAY
5. Ø3 ACTIVATION ENABLES A DETECTOR SWITCHING CIRCUIT (SHOWN ON SEPERATE PAGE) MAX II CALLED ALSO
6. CLOCK USED TO PLACE A CALL ON Ø8 UPON Q3 ACTIVATION DURING PEAK (ALSO SHOWN ON SEPERATE PAGE) 7:30 - 8:30am & 4 - 6:30pm
7. Q4 PLACES CALL ON Ø8 NOT ~~USED AT THIS TIME~~
8. NBR HAS A DELAY DETECTOR 10 SECOND DELAY

Six Flags Dr. & 360

SIGNAL MAINTENANCE RECORD

TURN ON DATE:

PHASE		INT.	VEH. EXT.	MAX I	MAX II	VEH. CLR	ALL RED	MAX. INT.	TBR	TTR	MIN. EXT.	RCL / MEM.	TEMP. RCL
1	WBL	4	2.0	45	45	4.0	.5	.			.	L	
2	OLD - CB	10	1.5	40	40	4.0	1.0	.			.	NL/VR	
3	OLA - WB	6	2.0	35	60	4.0	.–	.			.	NL	
4	SB	6	0.8	25	60	4.0	1.0	.			.	NL	
5	WB	.0	2.0	38	38	4.0	.5	.			.	L	
6	OLB - EBL	4	1.0	15	20	4.0	.–	.			.	NL	
7	NB	6	0.8	22	60	4.0	1.0	.			.	NL	
8	OLC - EB	6	1.0	40	30	4.0	.–	.			.	NL	

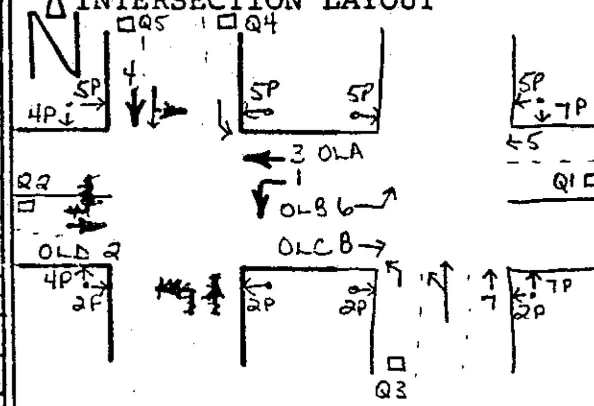
COMPUTER HARDWARE TIMES

PH	PHASES	G.G.	CLR
A			
B			
C			
D			

SPECIAL INSTRUCTIONS

CLOCK PLACES PT L :ALL PH 6 7am - 9:30am 3:30pm - 7pm

INTERSECTION LAYOUT



Ø	WALK	D'WALK
1	10	5
2	6	10
3	10	10
4	6	10
5	6	10
6	10	1
7	6	10
8	6	6

OLA 1,2,3,5,6

OLB 6,8

OLC 1,2,5,6,8

OLD 2,3

LAMAR : 360	SIGNAL MAINTENANCE RECORD	TURN ON DATE: 11-15-76

	PHASE	INT.	VEH. EXT.	MAX I	MAX II	VEH. CLR	ALL RED	MAX. INT.	TBR	TTR	MIN. EXT.	RCL MEM.	TEMP. RCL
1	WBL OLC	2	1.0	40	40	4.0	1.0	.			.	NL	
2	EB	15	1.2	35	35	4.0	1.0	.			.	VR/NL	
3	WB OLA	6	.5	22	60	4.0	1.0	.			.	NL	
4	SB	2	1.2	40	40	4.0	1.0	.			.	NL	
5	WB	6	1.2	40	40	4.0	1.0	.			.	NL	
6	EBL OLD	2	.8	35	35	4.0	1.0	.			.	NL	
7	NB	2	1.0	27	60	4.0	1.0	.			.	NL	
8	EB OLC	1	1.0	02	02	4.0	1.0	.			.	NL	

COMPUTER HARDWARE TIMES

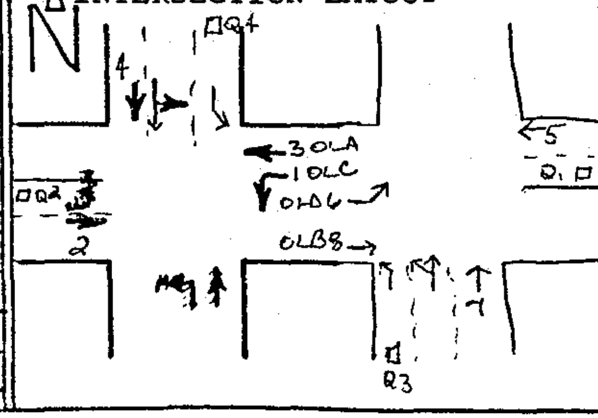
PH	PHASES	G.G.	CLR
A			
B			
C			
D			

SPECIAL INSTRUCTIONS

Ø3 dual entry

Clock places Ø3 v.c. when Ø3 is on 730-830am & 4-6:30pm

INTERSECTION LAYOUT



Ø	WALK	D'WALK
1	20	0
2	20	0
5	20	0
6	20	0

OLA 1,2,3,5,6

OLB 1,2,5,6,8

OLC 1,3

OLD 6,8

I20 & GREEN OAKS	SIGNAL MAINTENANCE RECORD	TURN ON DATE:

PHASE		INT.	VEH. EXT.	MAX I	MAX II	VEH. CLR	ALL RED	MAX. INT.	TBR	TTR	MIN. EXT.	RCL MEM.	TEMP. RCL
1	SBL OLB	4	.5	40	50	4.0	.5	.			.	NL	
2	NB	14	1.5	35	40	4.0	.5	.			.	12	
3	SB OLA	6	1.0	30	30	4.0	.5	.			.	NL	
4	EB	6	1.0	37	30	4.0	.5	.			.	NL	
5	SB	10	1.0	35	45	4.0	.5	.			.	NL	
6	WBL OLD	6	.5	20	20	4.0	.5	.			.	NL	
7	WB	6	1.0	37	35	4.0	.5	.			.	NL	
8	NB OLC	1	.1	20	20	[illegible]	.0	.			.	NL	

COMPUTER HARDWARE TIMES

PH	PHASES	G.G.	CLR
A			
B			
C			
D			-

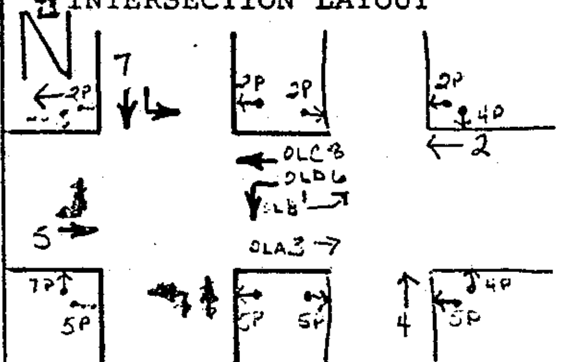
SPECIAL INSTRUCTIONS

SF#2 Ø3&7 [illegible] / Peak 13&5 For [illegible]

SF#2 Ø6 Ped [illegible] AM Peak

2&5 [illegible] Peak

INTERSECTION LAYOUT



Ø	WALK	D'WALK
1	10	5
2	6	8
3	10	5
4	8	14
5	6	8
6	10	5
7	8	14
8	10	5

OLA 1 2 [illegible]

OLB [illegible]

OLC [illegible]

OLD 6 5