Notice: ATRC published two versions of this report. The difference in the two versions is that Appendix C (ADOT Operating Policy #11 is dated 1981 in one, 1983 in the other. Both are included here.

ARIZONA DEPARTMENT OF TRANSPORTATION

REPORT NUMBER: FHWA/AZ 85/192

LEFT TURN SIGNAL WARRANTS FOR ARIZONA

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NOTICE

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16. Abstract

A warrant was developed to choose the appropriate type of left turn signal phasing: permissive, exclusive/permissive, or exclusive.

Time-lapse photography was used to observe volume and delay data at a total of six arterial-arterial signalized intersections in the Phoenix metropolitan area. From the time-lapse film, data on volume, number of vehicles stopping, total delay, average delay per stopped vehicle, and average delay for all vehicles was obtained for each turning movement.

The effect of the type of left turn signal phasing on left turn delay and through delay was analyzed. A three year history of Accident rates for the three types of left turn phasing were also reviewed.

The developed warrant chooses the type of left turn phasing based on left turn volume, opposing volume, number of opposing lanes, cycle length, approach speed, sight distance restrictions, and accident history.

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Throughout the conduct of the research, a number of organizations contributed to the project. The project staff wishes to recognize the assistance of those organizations.

- Arizona Transportation Research Center, Arizona Department of Transportation
- Traffic Engineering Section, Highway Division, Arizona Department of Transportation
- Traffic Engineering Department, City of Phoenix
- Traffic Engineering Department, City of Scottsdale
- Traffic Engineering Division, City of Tempe
- Traffic Engineering Department, City of Mesa

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SI (METRIC) UNIT CONVERSION FACTORS

The material contained in this report is presented in terms of English units. The following factors may be used to convert the measures used in this report to the International System of Units (SI):

1 mile per hour (mph) = 1.6093 kilometer per hour (kph)

1 kph = 0.6214 mph

1 foot = 0.3048 meter

1 meter = 3.2808 feet

INTRODUCTION

Left turns at signalized intersections have a significant impact on capacity and safety. The introduction or use of a separate left turn phase can be used to increase safety and to satisfy large left turn demands. Vehicular delays to all entering vehicles and capacity are also affected by the use of left turn phasing or the lack of such phasing.

At the present time, there is no uniform method of application of left turn phasing in Arizona. Different jurisdictions use different approaches to determine which type of left turn phasing should be used. The Arizona Department of Transportation (ADOT) and other jurisdictions need a tool that can be uniformly applied to evaluate the need for separate left turn phasing at intersections. ADOT has a left turn signal warrant policy that has been in use for several years but it has not been used by other jurisdictions. The ADOT policy has been useful but it is not a part of this project for evaluation or analysis. ADOT operating policy #11 - Guidelines for Considering Left-Turn Signals is in Appendix C. Suitable warrant for all jurisdictions would enhance uniformity throughout the state and provide all jurisdictions with a rational basis for the installation of the proper type of left turn phasing as well as determining priorities for the expenditure of available funds. Application of suitable warrants should lead to improved intersection safety and capacity and reduction of delay.

There are four types of left turn phasing in general use. They are:

Permissive left turn - Vehicles are allowed to make a turn on a circular green indication but must yield to opposing traffic. (Sometimes called a "permitted" left turn).

Exclusive left turn - Vehicles are allowed to make a turn only on a green arrow indication and have the right of way while the green arrow is displayed. (Sometimes called a "protected" left turn).

Exclusive/permissive - Vehicles are allowed to make a turn either on a green arrow indication or on the circular green after the green arrow has been terminated but must then yield to oncoming traffic.

Split phasing - This is a specialized form of exclusive left turn phasing. With split phasing one approach is directed to proceed, including left turning vehicles on an exclusive left turn arrow. When this approach is stopped the opposing approach is directed to proceed, including left turns on an exclusive arrow indication.

RESEARCH APPROACH

Study Objectives

The basic objective of this study was to determine suitable warrants for left turn signal phasing so that decision makers can decide, on a rational basis, when and where to commit resources to install left turn phases at signalized intersections.

The specific objectives were as follows:

(a) A thorough examination of current warrants, practices, and guidelines used in the U.S. and other countries for possible adaptability to Arizona's needs.

(b) Examination of the use of permissive, exclusive, and exclusive-permissive phasing.

(c) Determination of the most appropriate parameters or warrants for use in left turn phasing.

(d) Determine and document the most economical and practical methodology for acquiring the field data necessary to evaluate the parameters or warrants identified so that a rational evaluation procedure is available for use by Arizona jurisdictions.

Study Tasks

To fulfill the above objectives the tasks noted below were accomplished during the study. Additional detailed descriptions of each task appear later in this report.

I. Evaluation of Other State's Criteria - Other state's criteria for selecting left-turn signal phasing were evaluated.

II. Select Variables and Criteria and Determine Data Needs - Variables which could be used to determine the appropriate type of left turn signal phasing were selected. Criteria for optimizing intersection operation were selected and the data required to establish optimum intersection operation were determined.

III. Select Intersection Locations - Locations for data collection (time-lapse filming) were selected.

IV. Intersection Inventory and Data Collection - An inventory of each intersection location was compiled.

V. Data Reduction - Time-lapse films were viewed to determine traffic volumes and vehicle delay.

VI. Data Analysis - Volume, delay and other data were analyzed to evaluate the different types of left turn phasing.

VII. Develop Warrants - Warrants for left turn signal phasing were developed.

WARRANTS, GUIDELINES, AND CRITERIA USED BY OTHERS

Other states' warrants, guidelines, criteria, techniques, policies and procedures for selecting left-turn signal phasing were evaluated. The primary purpose of the evaluation was to seek guidance in selecting those characteristics to be incorporated and tested for use in Arizona's warrants.

A review of the warrants or guidelines used by other states and jurisdictions showed two main points. First, there is great variety in the warrants or guidelines used in various jurisdictions - there is no universally accepted standard. Second, in many cases current warrants or guidelines are based mostly on habit and individual engineering judgment and preference rather than on strong, objectively based research.

An excellent summary of other states' warrants or guidelines was prepared in a 1978 study by K.R. Agent (source 2). He surveyed 45 states to determine their procedures for determining the need for left turn phasing. Only six of the 45 states had numerical warrants for left turn phasing. These numerical criteria included the following.

1. the product of left-turn volume and opposing traffic volume
2. $\geq$ five left-turn accidents in 12 month period
3. cross product of left turn and conflicting through peak hour volumes $\geq$ 100,000
4. delay to left-turn vehicles of > 2 per cycle (maximum delay 73 seconds, average delay 35 seconds)
5. one left-turn vehicle delayed $\geq$ one cycle in a one hour period
6. at pretimed signals, peak hour left-turn volume > two vehicles per approach per cycle
7. average speed of through traffic > 45 m.p.h. and left-turn volume $\geq$ 50 per hour on approach during the peak hour

8. left-turn volume > 100 vehicles per peak hour

9. > 90 vehicles/any hour making left turn

The 1978 study also documented the qualitative considerations which were used by various states. They included: accident experience, capacity analysis, conflicts, congestion, delay, volume counts, turning movements, speed, geometrics, queue lengths, gaps, and sight distance.

Review of two dozen additional sources* describing warrants or guidelines in use shows that the above numerical criteria and qualitative considerations are still representative of those factors considered by traffic engineering agencies. Review of these more recent publications and discussions with traffic engineers around the United Stated demonstrates that there is still great variety in guidelines being used and that decisions are often simply based on judgment. Recent discussions with traffic engineers from Washington State, Colorado, and Los Angeles (source 13), for example, revealed that these geographic areas have no definite quantitative criteria for deciding when to use left turn phasing.

Some states have been quite active in developing strong definitive guidelines. They include Kentucky (sources 1-4), Florida (source 9), Maryland (source 26), and Kansas (sources 29-32). The most comprehensive set of guidelines for selecting type of left turn phasing has been developed by Florida (source 9). The Florida report presents the following guidelines for selecting type of left turn phasing once the need for left turn phasing has been firmly established.

1. Exclusive/permissive left turn phasing (green arrow preceding green ball) should be used at all intersection approaches where a

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*These sources are listed in the list of references left turn phase is required unless there is a strong reason for a different type of left turn phasing.

2. Exclusive left turn phasing should be used for an intersection approach if any of the following conditions exist:

   a. Double left-turn only lanes;

   b. Geometric restrictions;

   c. Sight distance to opposing traffic <250 feet at $\leq$ 35 mph or <400 feet at $\geq$ 40 mph

      (this represents the sight distance required to detect an acceptable gap for making a left turn);

   d. Approach is lead portion of lead/lag intersection phasing sequence.

3. Possibly call for exclusive phasing when permissive left turn phasing would be hazardous and:

   a. there is poor sight distance to opposing traffic due to geometry or opposing left-turn vehicles; or

   b. the speed limit of opposing traffic > 45 m.p.h.; or

   c. left turn traffic must cross three or more lanes of opposing thru traffic; or

   d. use of exclusive/permissive phasing has resulted in more than six left turn angle accidents per year; or

   e. there are unusual geometrics that confuse or endanger permissive left-turn vehicles.

4. Permissive/exclusive phasing (green arrow following the green ball) should be limited and used only in the following situations:

   a. An approach to a Tee intersection where opposing U turns are prohibited;

   b. approach to four-way intersection where the opposing approach has prohibited left turns or exclusive left turn phasing;
   c. Opposing approaches to a four-way intersection where the left turn volumes from the opposing approaches do not substantially differ from each other throughout the day.
5. Split phasing is effective if:
   a. the geometric offset of opposing approaches makes simultaneous left turns hazardous or impossible; or
   b. left-turn volumes of opposing approaches are heavy and nearly equal to adjacent through movement critical lane volume; or
   c. the left-turn volume is heavy on an approach without a left-turn lane; or
   d. there are more than one left-turn lanes, but one of the lanes permits both left turn and through movements.

To summarize, the criteria used most frequently by other states and, therefore, the criteria felt to be most important by the traffic engineering community are delay (along with associated congestion), volume of traffic accommodated (capacity), and accident experience or observed vehicle conflicts.

CRITERIA FOR OPTIMIZING INTERSECTION OPERATION

Based upon review of previous research and warrants and guidelines being used by other jurisdictions, three basic objectives, or criteria, were selected for optimizing intersection operation. The intent in developing warrants or guidelines for left turn signal phasing is to prepare a method for selecting left turn phasing type which will result in optimum intersection operation. The basic objectives, or criteria, which were selected for optimizing intersection operation were as follows:

1. Provide some minimum level of service or maximum delay time for left turning vehicles.
2. Minimize delay on the intersection approach (left, through, and right turn movements combined) consistent with objective number 1).
3. Minimize left turn related accidents to the extent practical and be consistent with objectives 1 and 2.

For practical application of warrants or guidelines it is important that choice of left turn phasing type be a function of easily and quickly measured intersection characteristics or variables. Based upon the literature review the most promising potential candidate variables appeared to be:

1. left turn volume;
2. adjacent through volume;
3. opposing volume;
4. number of lanes; and
5. number of left turn related accidents.

Other characteristics or variables which were found to have been used by other agencies included: conflicts, vehicle speed, geometric characteristics, and sight distance. In addition, delay had occasionally been used. It is not as quickly and easily measured as volume, for example, and thus is not as promising for practical application.

SELECTION OF INTERSECTIONS

The previous paragraphs described the criteria for optimizing intersection operation and the intersection variables which were of interest. The variables included volume and delay. The data collection method used to obtain data on volume and delay at field study locations was time-lapse photography.

Six intersection locations were selected to represent the three types of left turn phasing and a variety of other intersection characteristics. The intersections selected for study were chosen to provide a range of values for the following variables:

- Type of left turn phasing
- Number of opposing lanes
- Left turn volume
- Volume of opposing traffic

All six intersections had separate left turn lanes. Initially, the study team considered collecting data at intersections where the left turning vehicles would have one lane of opposing traffic. A review of signalized intersection locations in Tempe, Mesa, Scottsdale and Phoenix showed that signalized intersections with this characteristic are rare. For this reason it was decided to concentrate data collection efforts where the results would have greatest application - namely, locations with two or three opposing lanes. Therefore, six intersections were selected: two with permissive phasing; two with exclusive/permissive phasing; and two with exclusive phasing. For each type of phasing one intersection was selected with two opposing lanes and the other intersection was selected with three opposing lanes.

It was found that signalized intersections with exclusive/permissive phasing and three opposing lanes are also rare in the Phoenix urban area.

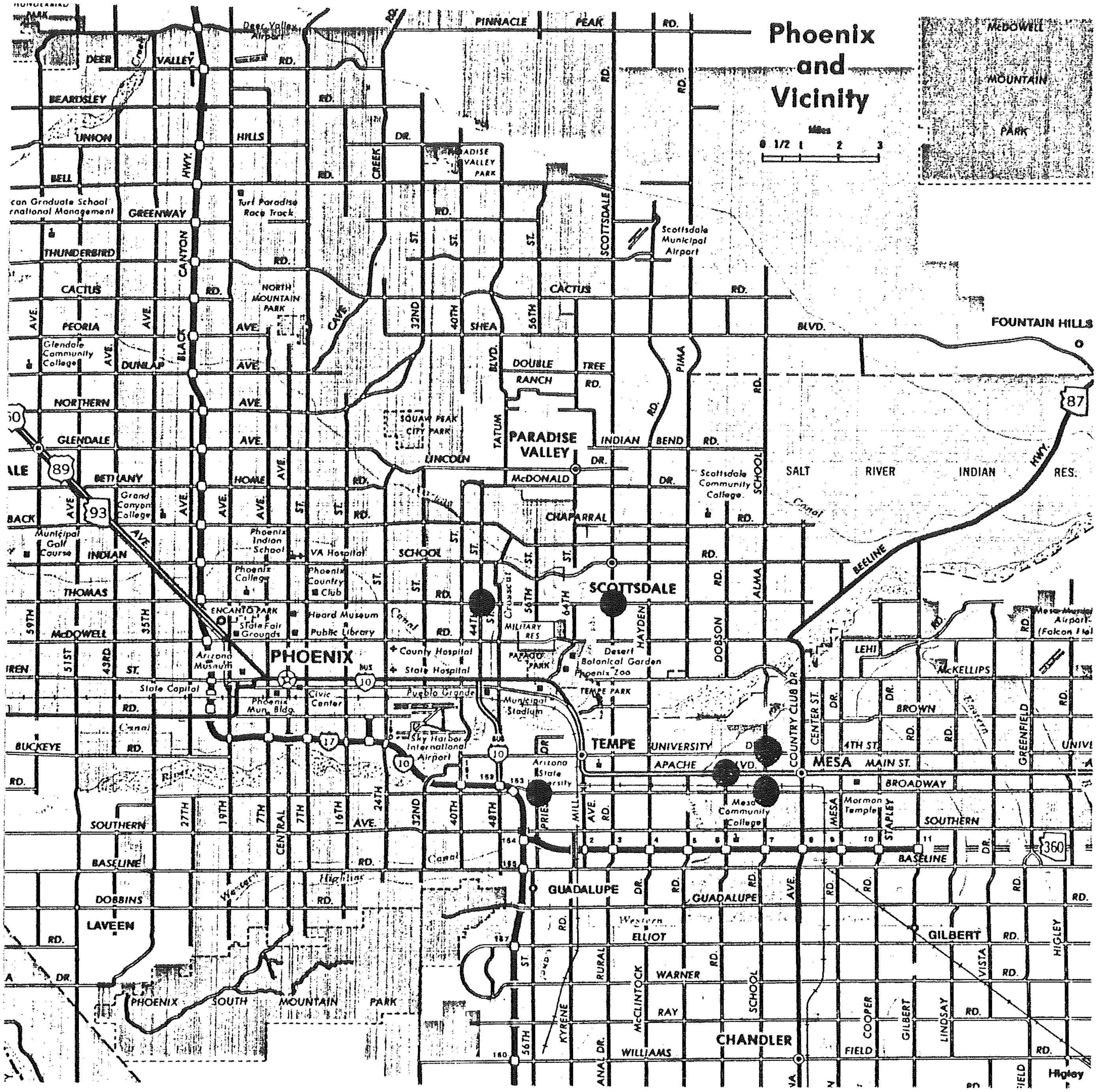
Tempe has only one intersection approach with exclusive/permissive phasing and Mesa's policy is to not use exclusive/permissive phasing when there are three opposing lanes. This policy is based on studies which show this situation has an accident problem since left turn motorists have greater difficulty in identifying acceptable gaps when there are three lanes of opposing traffic. An exclusive/permissive location with three opposing lanes was found in Scottsdale and it was chosen as a study site.

Intersections were matched so that they were similar in terms of the number of lanes of opposing traffic, signal display and signing, speed, traffic composition, and geometry. Pedestrian interference was not a factor at any intersection studied as pedestrian (and pedacycle) volumes were very small. A wide range of left turn volumes and opposing volumes was desired for the study and was a factor in intersection selection.

A further constraint was the need for a suitable site to locate the time-lapse camera. A space was needed, off the street and sidewalk, where a lift truck could be parked and from which the intersection could be clearly seen from the lift truck platform (30 feet high). Trees, buildings, and power lines were the most common obstacles. Quite often, intersections were identified which satisfied all of the study needs but which did not have a suitable camera location. Some compromises were made in selecting intersection locations in order to have a suitable camera location. Parking lots such as those found in shopping centers were found to be ideal locations.

Traffic Engineering Officials from the cities of Mesa, Phoenix, Scottsdale, and Tempe were very helpful in assisting the study team in identifying suitable intersections and in supplying volume, turning movement count, geometric, and signal timing data. Accident data were supplied by ADOT.

Figure 1 shows the locations of the intersections selected for study.



Indicates Study Site

Intersection	City	Type of Left Turn Phasing	Number of Opposing Lanes
Alma School and University	Mesa	Permissive	2
Alma School and Broadway	Mesa	Exclusive/Permissive	2
Broadway and Priest	Tempe	Exclusive	2
Thomas and 44th Street	Phoenix	Permissive	3
Scottsdale and Thomas	Scottsdale	Exclusive/Permissive	3
Dobson and Main	Mesa	Exclusive	3

Figure 1

STUDY SITE LOCATIONS

INTERSECTION INVENTORY AND DATA COLLECTION

An inventory of each intersection was compiled to obtain information on the following characteristics:

Physical Inventory

- Geometry
- Number of lanes

Traffic Control Device Inventory

- Signal Display
- Signing

Traffic Inventory

- Speed
- ADT
- Peak Hour Volumes - two-way and directional
- Left turn Counts

Accident Inventory

- Severity - Fatal/injury/property damage only
- Type - Left turn involvement?
- Vehicle involvement
- Time of day - Peak, non-peak, day, night

ADOT and local agencies provided existing information on traffic volumes, turning movement counts, and accident records. Accident records for the three previous years were provided by ADOT. Concurrent with review of the accident reports it was determined if there had been any changes made in the signal phasing, particularly left turn phasing, during the three previous years and provide an opportunity of comparing before and after accident data.

Additional data were collected using time lapse photography at each site. Time-lapse photography was used because it was the only practical data collection method for accurately obtaining information on volume and associated vehicle delay.

The time-lapse camera was located on a lift truck adjacent to the right hand lane of an approach and approximately 300 feet in advance of the intersection. From this location the through and left turn movements on two opposite approaches were observed and recorded on film. For example, at Broadway and Priest the camera was mounted adjacent to the eastbound approach and both eastbound and westbound through, right, and left turn movements were recorded.

The films were used to determine left turn volumes, opposing volumes, delay (both to left turn and through vehicles), and conflicts. Approximately seven hours of film were taken at each intersection at a rate of one frame a second. The camera used was a Super 8mm Time Lapse model 1260 system. This is a battery operated system. The camera was mounted on a lift truck provided by ADOT. The height of the camera above the roadway was approximately 30 feet. The lift platform was raised to the maximum height for every filming sequence, except where there were obstacles to line of sight. Filming was conducted from about 8:00 a.m. to 5:00 p.m. on week days in March and April, 1984. The hours filmed included portions or all of the AM and/or PM peak periods.

Filming was continuous in order to be able to calculate delays at one second intervals; a speed of one frame per second was used for all filming. Each roll of film had 3600 frames (50 foot roll) and ran for one hour.

There were occasional, short breaks in filming for changing film, changing batteries, and other operational problems.

The ADOT lift truck was normally located so that the signal heads and all lanes were visible through the camera lens. For a normal 84 foot wide arterial street, 300-400 feet from the intersection was adequate.

No significant problems were encountered using the lift truck for filming. Due to the distance from the intersection, it was normally impossible to clearly see the green arrow indication. There was, however, no difficulty in seeing the yellow, or red ball indication. At some locations the green ball was very difficult to see on the film, particularly if the sun was behind the camera.

There was no evidence that the presence of the lift truck or study team affected driver behavior in any way.

INTERSECTION DATA

This section describes the intersection inventory information collected.

Alma School and University (Figure 2)

This intersection of two major arterials is located in the City of Mesa. Filming was done on the eastbound approach of University approximately 300 feet west of the intersection. Both eastbound and westbound approaches have two through lanes and a left turn lane. The signal is a two phase system, left turns are permitted only on a green ball indication. Cycle lengths vary from 50 to 55 seconds. No significant pedestrian interference was observed.

Traffic volume counts were supplied by the Mesa traffic engineering department.

University ADT = 26,860 vehicles per day

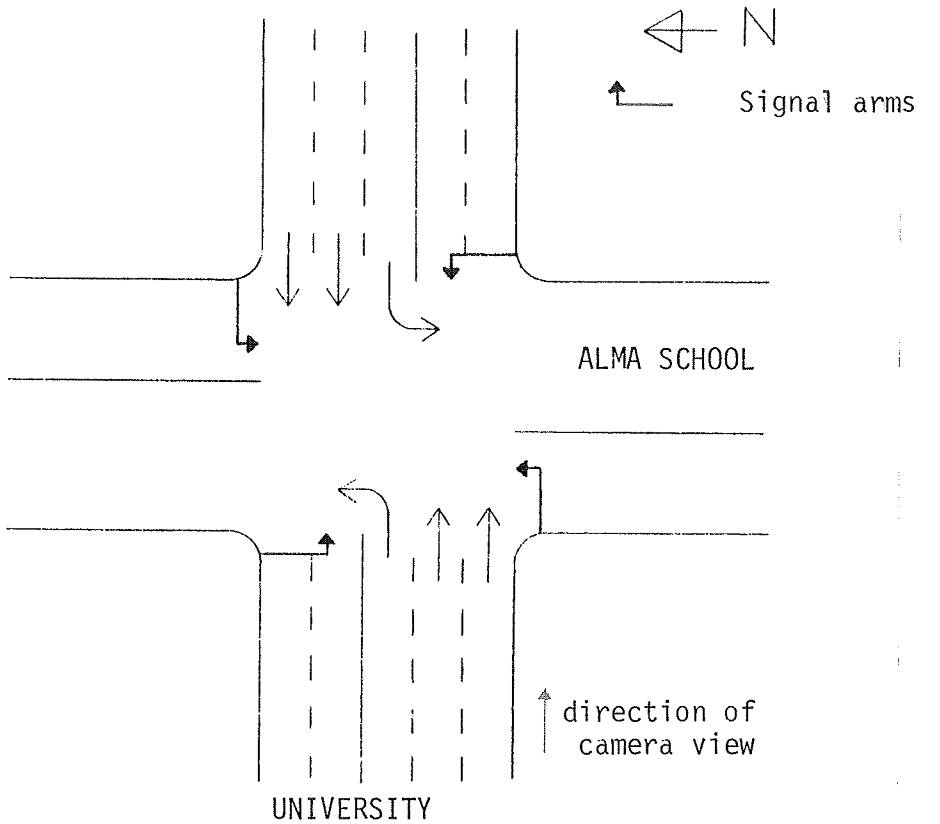
AM peak: 6:00 - 8:00 AM

PM peak: 2:00 - 5:00 PM

The estimated number of vehicles entering the intersection on an average weekday is 54,500; observed values were slightly higher.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on University Approaches	Total Intersection	
1.06	.905	1981
6.37	1.51	1982
6.37	1.51	1983



CYCLE LENGTH: Min 50 sec Max 55 sec

			Min	Max
A	E/W	Green	21 sec	24.2 sec
		Yellow	4 sec	3.85 sec
		All Red	2 sec	1.65 sec
B	N/S	Green	17 sec	19.8 sec
		Yellow	4 sec	3.85 sec
		All Red	2 sec	1.65 sec

Fig 2 ALMA SCHOOL & UNIVERSITY (PERMISSIVE)

Alma School and Broadway (Figure 3)

This intersection is in the City of Mesa. Both streets are major arterials. Each street has two through lanes and a left turn lane. The signal system has an eight phase controller, with an exclusive left turn phase with permissive left turns allowed on the green ball indication. The traffic signal is fully actuated. Filming was done on the northbound approach on Alma School.

Pedestrian traffic was not a factor, however there was a great deal of interference caused by traffic using the many driveways close to the intersection.

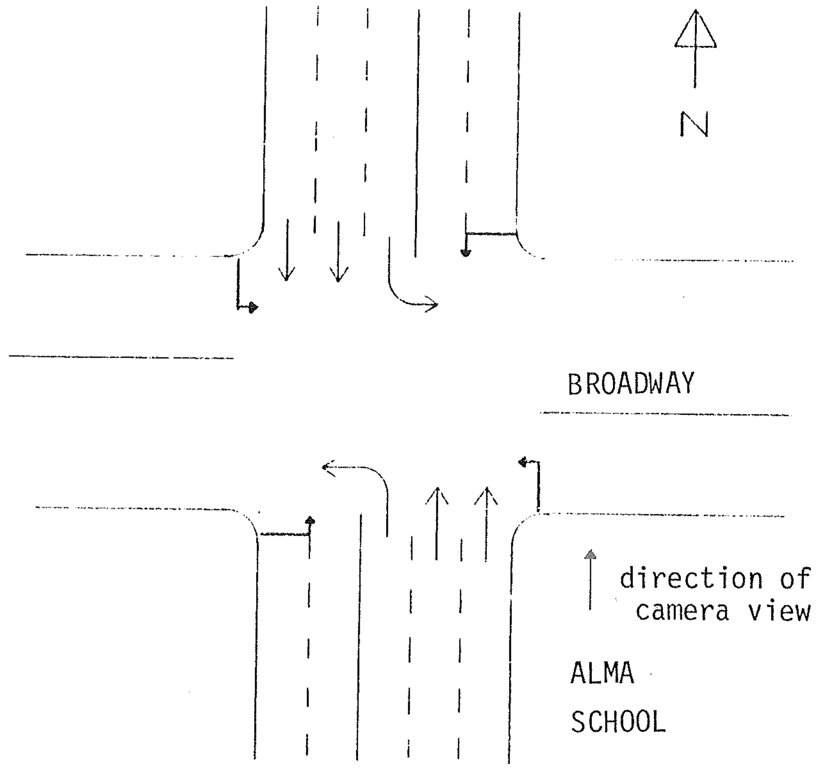
Directional split was essentially balanced but northbound left turn volume was slightly larger than the southbound left turns. Based on the traffic volumes during the eight hours of filming, the estimated ADT on Alma School is 27,210 vehicles per day.

Estimated volume on Broadway was 27,000 vehicles per day

The estimated number of vehicles entering the intersection on a weekday is 54,210.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on Alma School Approaches	Total Intersection	Year
2.75	2.12	1981
2.06	1.42	1982
4.12	1.82	1983



CYCLE LENGTH: Max 143.5 sec

3	NBLT	Green = 12 sec	Same as 1 EBLT
7	SBLT	Yellow = 3 sec	and 5 WBLT
		All Red = .5 sec	
4	SBTHRU	Green = 50 sec	Same as 2 WBTHRU
8	NBTHRU	Yellow = 4 sec	and 6 EBTHRU, Except
		All Red = 2 sec	Yellow = 4.5 sec

All intervals given are maximums

Fig 3 ALMA SCHOOL & BROADWAY (EXCLUSIVE/PERMISSIVE)

Broadway and Priest (Figure 4)

This intersection is in the City of Tempe. Both streets are major arterials. Broadway is a major access route to Interstate 10 and the Phoenix metropolitan area. The eastbound approach on Broadway was used as the filming site. The eastbound approach consists of two through lanes, a left turn lane and a right turn lane. The signal has an eight phase controller, all left turns are leading exclusive. The intersection is fully actuated.

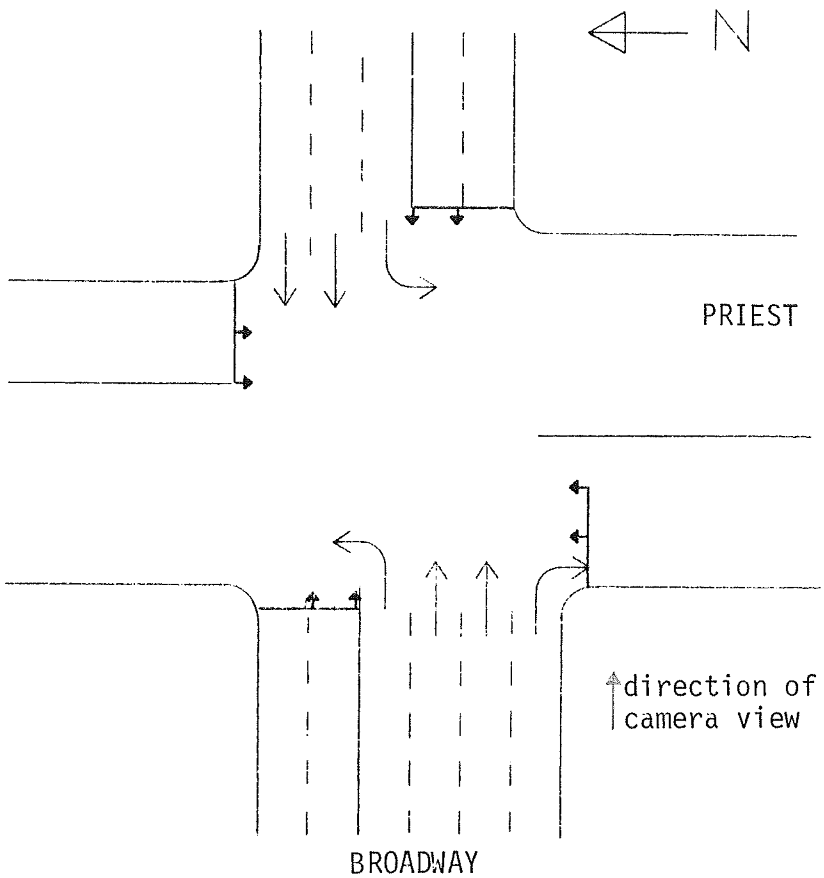
There was no significant pedestrian activity, however, the percentage of large trucks in the traffic stream was approximately double that seen at the other intersections studied.

The City of Tempe traffic engineering office supplied current traffic counts.

> The estimated number of vehicles entering the intersection on a weekday is 58,300 vehicles per day
>
> The eastbound approach volume is 19,400 vehicles per day with an opposing volume of 16,000 vehicles per day.
>
> The AM peak begins at 11:00 AM and the PM peak at 4:45 PM.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on Broadway Approaches	Total Intersection	Year
0.60	3.57	1981
1.27	1.60	1982
0.60	1.60	1983



CYCLE LENGTH: MAX CYCLE LENGTH = 123 sec.

		min	max	(sec)
A_1, EBTHRU	Green	10.0	40.0	
A_2, WBTHRU	Yellow	4.5	4.5	vehicle extension = 2 sec
	All Red	1.5	1.5	
B_1, W.B.L.T.	Green	3.0	12.0	
	Yellow	3.0	3.0	
	All Red	1.0	1.0	
B_2, E.B.L.T.	Green	3.0	15.0	vehicle extension = 1 sec
	Yellow	3.0	3.0	
	All Red	1.0	1.0	

Fig 4 BROADWAY AND PRIEST (EXCLUSIVE)

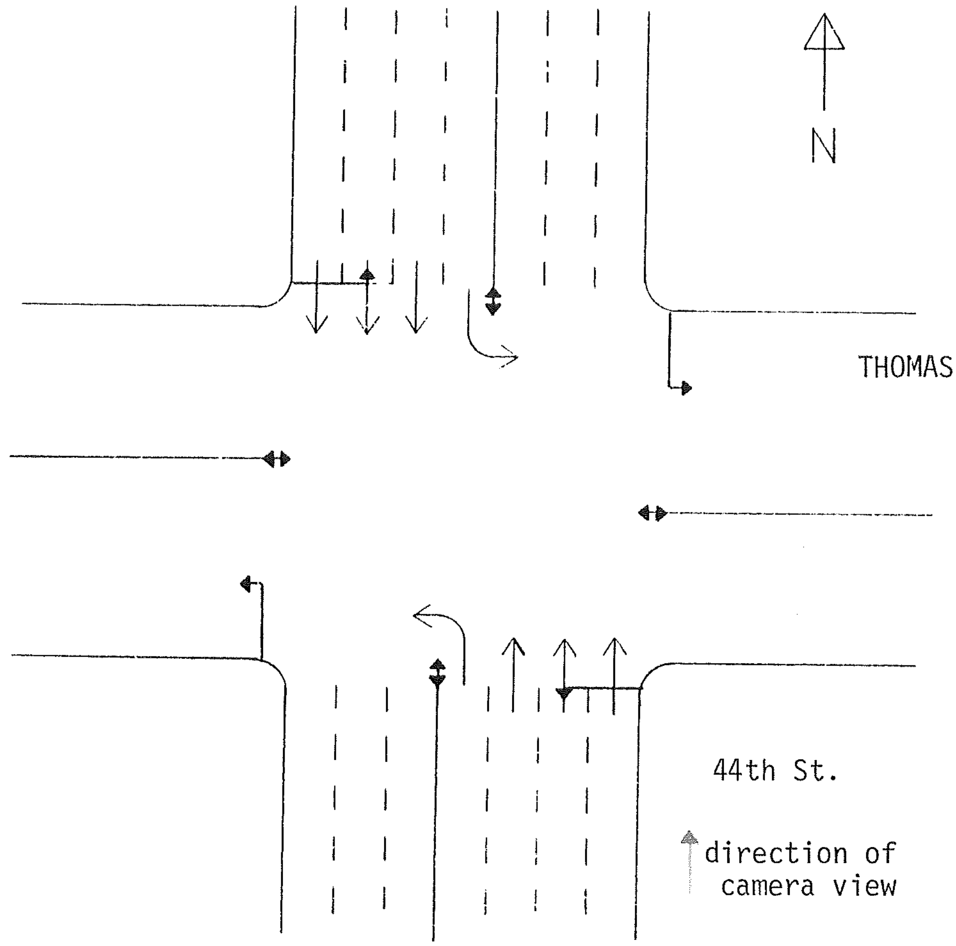
Thomas and 44th Street (Figure 5)

This intersection is in the city of Phoenix. Both streets are major arterials. Filming was done on the northbound approach on 44th. The left turn signal phasing was permissive. There are three through lanes and one left turn lane on both the north and south approaches on 44th street. The AM peak ends at approximately 9:00 AM. There is a noontime peak from 11:30 to 1:00 and a PM peak starting at approximately 2:30 PM.

City traffic engineering data show that the estimated number of vehicles entering the intersection on a weekday is 92,700. The volume on Thomas Road is 49,200 vehicles per day. 44th Street volume is 43,500 vehicles per day.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on 44th Street Approaches	Total Intersection	Year
not available	not available	1981
2.76	2.07	1982
1.84	1.77	1983



	TIME OF OPERATION 7:00-8:30 AM AM	8:30-4:00 AM PM	4:00-6:30 PM PM
CYCLE LENGTH	55 sec	50 sec	55 sec
N/S GREEN	25.3	20.5	20.9
N/S CLEARANCE	4.4	4.5	4.4

Fig. 5 THOMAS & 44th St. (PERMISSIVE)

Scottsdale and Thomas (Figure 6)

This intersection is in the city of Scottsdale. Both streets are major arterials. Filming was done on the westbound approach on Thomas. There are two westbound through lanes and a left turn lane on the westbound approach. On the eastbound approach there are three eastbound through lanes with a left turn lane. The signal has an eight phase fully actuated controller. Left turn phasing is exclusive/permissive.

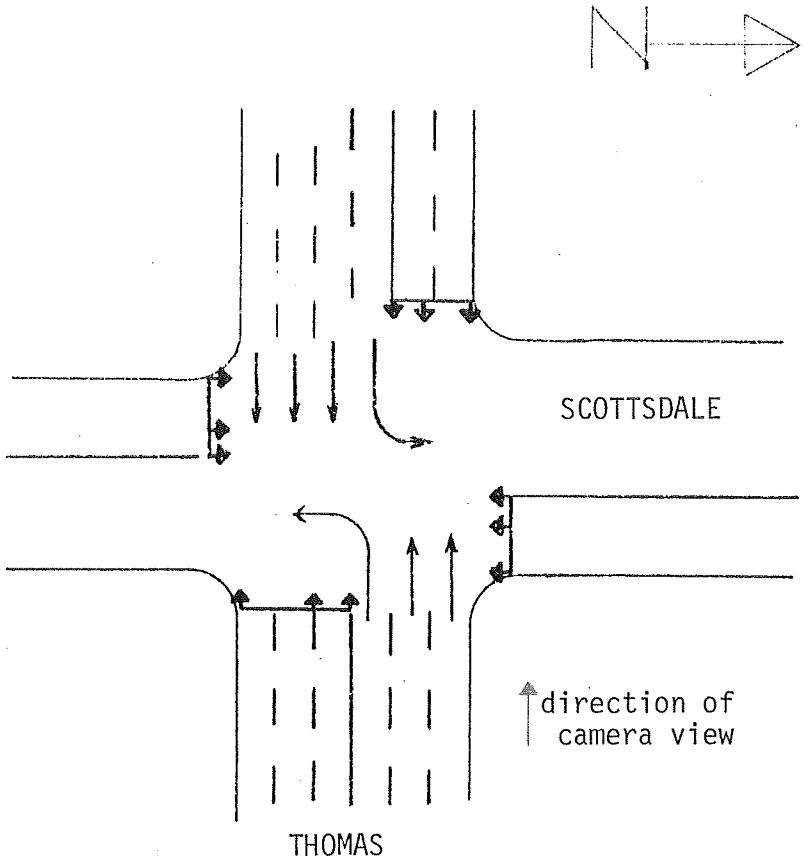
Some pedestrian activity was observed but did not appear to affect left turn movements. Driveway interference occurred but it was not a consistent problem. No distinguishable AM peak was observed. The PM peak began at 4:00 PM for west bound traffic.

The estimated number of vehicles entering the intersection on a weekday is 63,000

Estimated volume on Thomas Rd. is 27860 vehicles per day.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on Thomas Road Approaches	Total Intersection	Year
not available	not available	1981
0.59	0.70	1982
1.78	1.48	1983



		7:30-8:30 AM AM	8:30-10:30 AM AM	10:30-4:00 AM PM	4:00-6:00 PM PM
		TIME OF OPERATION			
CYCLE LENGTH		106 sec	94 sec	94 sec	109 sec
1 EBLT	Green	12 sec	10 sec	10 sec	15 sec
5 WBLT	Yellow	3	3	3	3
	All Red	0	0	0	0
2 WBTHRU	Green	40.5	29.5	23.5	26.5
6 EBTHRU	Yellow	4.0	4.0	4.0	4.0
	All Red	.5	.5	.5	.5

Fig 6 SCOTTSDALE & THOMAS (EXCLUSIVE/PERMISSIVE)

Dobson and Main (Figure 7)

This intersection is in the City of Mesa. Filming was done on the westbound approach on Main. Both streets are major arterials, the west bound approach has two through lanes and left and right turn lanes. The eastbound approach has three through lanes and a left turn lane. Left turn phasing is leading exclusive. The signal has an eight phase controller and is fully actuated. No significant pedestrian activity was observed.

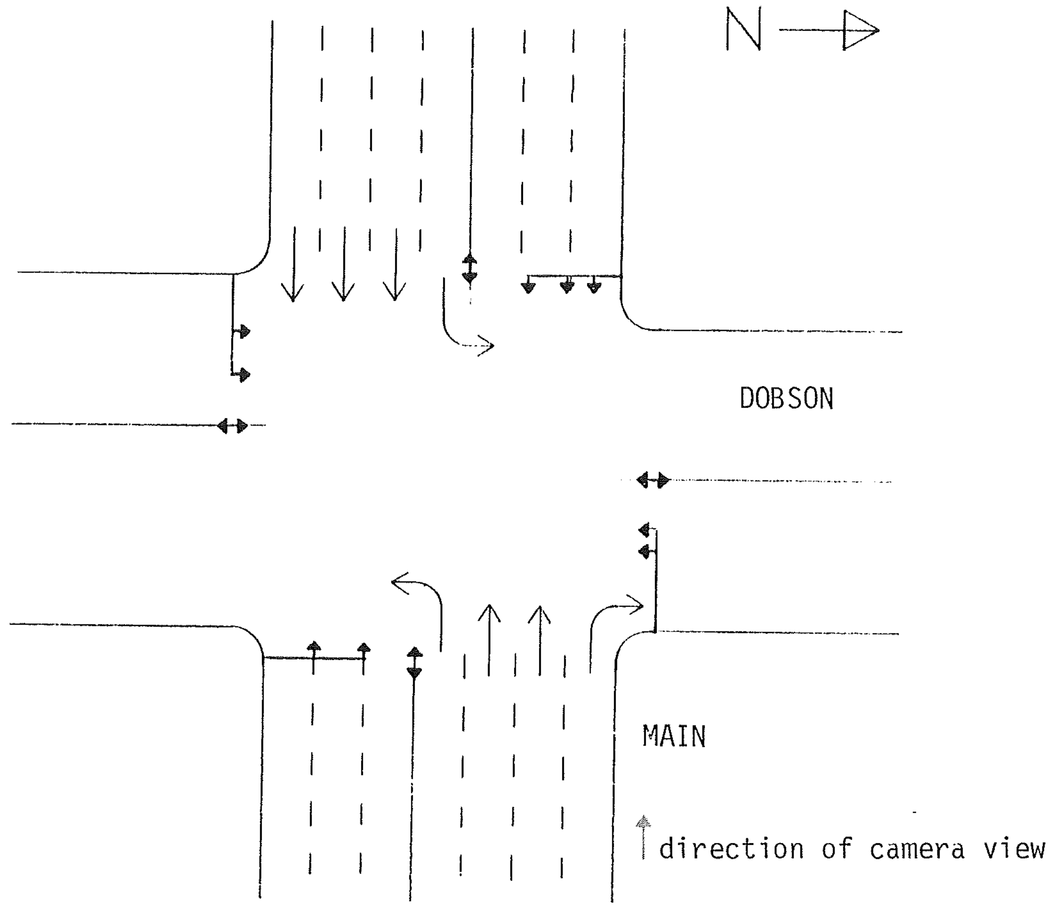
No traffic counts were available from the city so volume data are based on the expansion of film data using volume percentages calculated from the Alma School and University counts. There was no observed AM peak for eastbound traffic, volumes for through traffic increased steadily throughout the morning. The eastbound PM peak began at 3:30 PM. Westbound traffic experienced a slight noon peak between 11:45 and 12:45, but the westbound PM peak was not observed during the filming period. Westbound volumes also increased during the day but showed more fluctuation than the eastbound traffic which was heavier than the westbound volumes.

Estimated ADT on Dobson = 27,000 vehicles per day.

Estimated ADT on Main = 23,100 vehicles per day.

Accident Rates/per one million entering vehicles

Left Turn Related Accidents on Main St. Approaches	Total Intersection	Year
0.48	1.31	1981
1.45	0.87	1982
1.45	1.86	1983



CYCLE LENGTH: MAX 115 sec

1 EBLT	Green = 15 sec	Yellow = 3 sec	All Red = .5 sec	5 WBLT	Green = 20 sec	Yellow = 3; All Red = .5
also 3 NBLT						
and 7 SBLT						
2 WBTHRU	Green = 30 sec	Yellow = 4.5	All Red = 2.0	4 SBTHRU		
6 EBTHRU				8 NBTHRU		

Fig. 7 DOBSON & MAIN (EXCLUSIVE)

DATA REDUCTION

Time-lapse film

The forty-five hours (real time) of time-lapse film exposed at the six field sites were projected using a Time-lapse model 1260 system projector at a slow rate of speed. Viewing of the films, observation of vehicle movements and tabulation of data resulted in the collection of data on volume, the number of vehicles stopping, the number of vehicles not stopping, total delay, average delay per stopped vehicle, average delay for all vehicles, and the percent of vehicles which stopped. These data were collected separately for left turn and through movements and for the near side and far side approaches to the intersection. These data were tabulated for five-minute intervals as shown in Figure 9. Viewing of the films was extremely time consuming; each real-time hour of intersection operation required several hours of film viewing.

Although the time-lapse film was exposed at a rate of one frame per second, five-second intervals were used for recording volume and delay data. This interval facilitated data reduction and analysis. A five-second interval of film was projected and the number of vehicles that: 1) were stopped; 2) had previously stopped or would later stop; and 3) would not stop at all while traversing the intersection were observed and tallied. A stopped vehicle was defined as one which was stopped and waiting for the signal to turn to green or for a suitable gap (in the case of left-turn vehicles). Figure 8 shows an example of a tally sheet.

The technique used for calculating delay was the stopped time delay method. It measures the time a vehicle is stopped and does not include time losses caused by deceleration or acceleration. In this study, stopped vehicles were counted in five second intervals. Every five seconds, the number of vehicles stopped (in through or left turn lanes) were recorded (see Figure 8). The total delay was calculated as the total number of vehicles observed multiplied by the observation interval (5 seconds).

From the tally sheets (Figure 8) volume and delay data were summed for 5-minute periods for entry on the calculation sheets (Figure 9). Five-minute periods were used so that relationships between volume and delay could be developed over short time intervals. Average delay per stopped vehicle, average delay per approach vehicle, and the percent of vehicles that stopped were calculated from the volume and delay data and entered on the calculation sheets.

Two minor problems were encountered in viewing the films. First, where long queues developed on the opposing approach, stopped vehicles (for delay calculation) were sometimes difficult to detect. Second, large trucks in the vehicle stream sometimes obscured other vehicles, making it difficult to count number of vehicles for volume or delay purposes. This was a particular problem at the Broadway and Priest intersection. Since viewing of the film sequence could be repeated, the required data could usually be obtained.

While signal timing of cycle and phase length was not a part of this research, observation of the films and on-site observations were made with regard to phase and cycle length adequacy. It was observed that no green phases were significantly under utilized; there were no long periods of unused green. It was concluded that signal cycle and phase timing did not appreciably affect delay values obtained in this study.

Conflicts were difficult to observe on film; it was frequently not possible to accurately determine whether or not a vehicle was braking normally or was under conflict. This was due to the distance of the filming

LEFT TURN STUDY

LOCATION: 44th STREET & THOMAS

DIRECTION OF CAMERA VIEW: NORTH BOUND ON 44th

DATE: 4-12-84

TIME: 8:00 AM   REEL #:

TYPE OF L.T. PHASING: PERMISSIVE

CYCLE LENGTH:

TIME	LEFT TURN			THRU			RIGHT TURN			LEFT TURN			THRU			RIGHT TURN			
	DELAY	VOLUME		DELAY	VOLUME		DELAY	VOLUME		DELAY	VOLUME		DELAY	VOLUME		DELAY	VOLUME		
SEC.	STPD	STPPG	NSTP	STPD	STPPG	NSTP	STPD	STPPG	NSTPD	STPD	STPPG	NSTP	STPD	STPPG	NSTP	STPD	STPPG	NSTP	
0										—	—	—	—	—	—	—	—	—	0
5														2					5
10													2	6					10
15													8	6					15
20													14	4					20
25													17						25
30													10						30
35																			35
40																			40
45												1			3				45
50															5				50
55														1	3				55
60													1						60
5														4					5
10											1		4	2					10
15										1			6	2					15
20										1	1		8	4					20
25										2			10						25
30										2	1								30
35										3									35
40										3	1				7				40
45										4					3				45
50										3									50
55										2					1				55
60										2				1					60
5										2			1	2					5
10										2			3	3					10
15										2			6	3					15
20										2			9	7					20
25										2			16	2					25
30										2			6						30
35										2									35
40										2					1				40
45										2									45
50															1				50
55															1				55
60														1					60
COLUMN TOTALS																			

Figure 8

SAMPLE TALLY SHEET

LEFT TURN WARRANT STUDY

FILM DATA REDUCTION

LOCATION: THOMAS : 44th
DIRECTION OF CAMERA VIEW: NORTH BOUND ON 44th

DATE: 4-12-84
TIME: 11:40 AM

TYPE OF L.T. PHASING: PERMISSIVE

CYCLE LENGTH:

5 MINUTE INTERVALS	TOTAL DELAY (VEHICLE-SECONDS)			# STOPPING			# NOT STOPPING			AVERAGE DELAY (sec) STOPPED VEHICLE			AVERAGE DELAY (sec) APPROACH VEHICLE			% STOPPED		
	L.T.	THRU	R.T.	L.T.	THRU	R.T.	L.T.	THRU	R.T.	L.T.	THRU	R.T.	L.T.	THRU	R.T.	L.T.	THRU	R.T.
1	2935	620		13	30		0	75		225.8	20.7		225.8	5.9		100.0	28.6	
2	1390	320		18	16		0	80		77.2	20.0		77.2	3.3		100.0	16.7	
* 3	1870	340		17	27		0	68		110.0	12.6		110.0	3.6		100.0	28.4	
4	1765	370		17	40		0	78		103.8	9.3		103.8	3.1		100.0	33.9	
5	2860	460		18	33		0	75		158.9	13.9		158.9	4.3		100.0	30.6	
6	2230	615		17	42		0	82		131.2	14.6		131.2	5.0		100.0	33.9	
7	2945	475		19	41		0	85		155.0	11.6		155.0	3.8		100.0	32.5	
8	2605	405		14	24		0	66		186.1	16.9		186.1	4.5		100.0	26.7	
9	2295	155		20	23		0	75		114.7	6.7		114.7	1.6		100.0	23.5	
10	2225	140		13	30		0	80		171.2	4.7		171.2	1.3		100.0	27.3	
11	1785	445		25	33		0	77		71.4	13.5		71.4	4.0		100.0	30.0	
12	3270	730		16	44		0	73		204.4	16.6		204.4	6.2		100.0	37.6	
TOTAL	28,175	5075		207	383		0	914										
OPPOSING TRAFFIC:				BOUND														
1	810	565		14	44		0	69		57.9	12.8		57.9	4.9		100.0	38.3	
2	1045	680		15	53		0	53		69.7	12.8		69.7	6.4		100.0	50.0	
* 3	655	220		12	30		0	74		54.6	7.3		54.6	2.1		100.0	28.8	
4	500	375		10	22		0	74		50.0	17.0		50.0	3.9		100.0	22.9	
5	485	240		14	25		1	86		34.6	9.6		32.3	2.2		93.3	22.5	
6	925	375		12	29		0	74		77.1	12.9		77.1	3.6		100.0	28.2	
7	1110	615		12	37		0	71		92.5	16.6		92.5	5.7		100.0	34.3	
8	1055	595		16	40		0	66		65.9	14.9		65.9	5.6		100.0	37.7	
9	1255	320		13	29		0	64		96.5	11.0		96.5	3.4		100.0	31.2	
10	535	340		12	27		0	65		44.6	12.6		44.6	3.7		100.0	29.3	
11	550	280		13	26		0	67		42.3	10.7		42.3	3.0		100.0	28.0	
12	1850	430		14	28		0	63		132.1	15.4		132.1	4.7		100.0	30.8	
TOTAL	10,775	5035		157	390		1	836										

* 35 sec short on 11th min

Figure 9
SAMPLE CALCULATION SHEET

site from the intersection. Based on a further review of the literature on conflict analysis and discussions with other researchers who had conducted conflict analysis, the study team decided that the observing of conflicts on film was inadequate for a proper investigation of conflicts. For this reason, no conflict data extracted from the film were recorded or used. Conflicts were not used as a basis for evaluating different types of left turn phasing or for developing warrants.

Accident Data

Accident rates were calculated based on accidents per one million entering vehicles. Collision diagrams supplied by ADOT were used as the source of accident information. Left turn accident rates (defined as left turn related accidents per one million entering left turn vehicles) were calculated for each left turn movement. Average Daily Traffic (ADT) counts and turning movement counts were either obtained from the appropriate jurisdiction, if available, or were estimated based on film volumes expanded to a 24-hour volume. Accident rates are included in the intersection data section of this report.

ANALYSIS OF DATA

The thrust of the effort in data analysis was to compare and distinguish between the three different types of left turn phasing based upon their effects on intersection operation. This section will describe the important observations made in analyzing data.

The previous section described the data reduction process. The five items of data generated by the data reduction process, appearing on the Sample Calculation Sheet (Figure 9) were the principal items evaluated in the data analysis phase. This phase attempted to identify meaningful relationships between type of left turn phasing, number of opposing lanes, left turn delay, through delay, total intersection delay, left turn volume, and opposing volume.

Several combinations of the above variables were analyzed to determine if there were meaningful relationships or correlations. The combinations included:

Left turn delay vs. Opposing volume
Left turn delay vs. Left turn volume
Thru delay vs. Left turn volume
Left turn delay vs. Volume Cross Product

(Volume cross product is the left turn volume multiplied by the opposing through volume). For each of these combinations data were separately plotted for each of the six intersections. The data plotted corresponded to the five-minute intervals shown on the Sample Calculation Sheet. Thus, each plot had approximately 180 data points (7 1/2 hours of filming x 12 five-minute intervals per hour x 2 approaches). Plots for permissive phasing, exclusive/permissive phasing, and exclusive phasing were then compared with one another to determine if the type of left turn phasing had different impacts.

Most of the combinations analyzed displayed no meaningful relationships of interest in this study. Two important exceptions were: 1) the relationship between left turn delay and volume cross product; and 2) the relationship between thru delay and volume cross product. Volume cross product was used as a variable because it presents the opportunity to consider the effect of both left turn volume and opposing volume at the same time. The combination of both left turn volume and opposing volume has greater significance than either one used alone.

Figures 10 and 11 illustrate the relationship between the average left turn approach delay (the average delay for all left turning vehicles) versus the volume cross product (left turn volume multiplied by the opposing through volume).

These figures represent a simplification of the original plots in that all of the original 180 data points for each type of left turn phasing are not plotted. Each point shown on Figures 10 and 11 represents the mean of the left turn approach delay values for a range of volume cross product values. For example, the lowermost exclusive/permissive point (a triangle) on Figure 10 shows that for cases when the volume cross product was between 0 and 200 the mean value of average left turn approach delay was 16. The scale on these figures shows the volume cross product in terms of five minute intervals used in data reduction (vehicles^2/5 minutes) as well as the equivalent hourly values (vehicles^2/hour).

Figures 10 and 11 present some very interesting observations. Figure 10, which illustrates the case of two opposing lanes, shows the following.

1. A change from permissive phasing to exclusive phasing would increase left turn delay. With exclusive phasing left turning vehicles must wait until that small portion of the cycle with an exclusive left

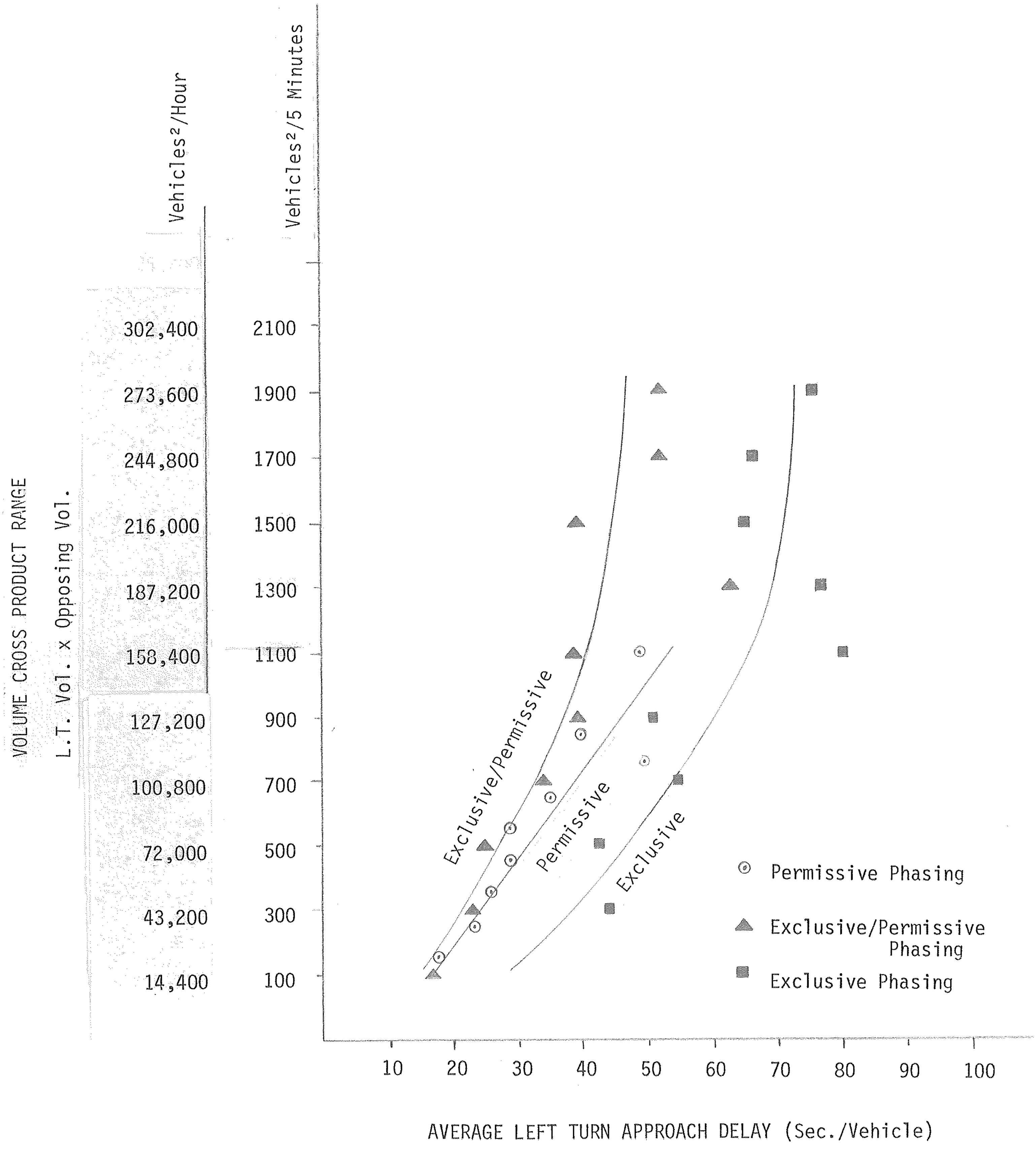


Figure 10

PLOT OF AVERAGE LEFT TURN DELAY VS. VOLUME CROSS PRODUCT (2 opposing lanes)

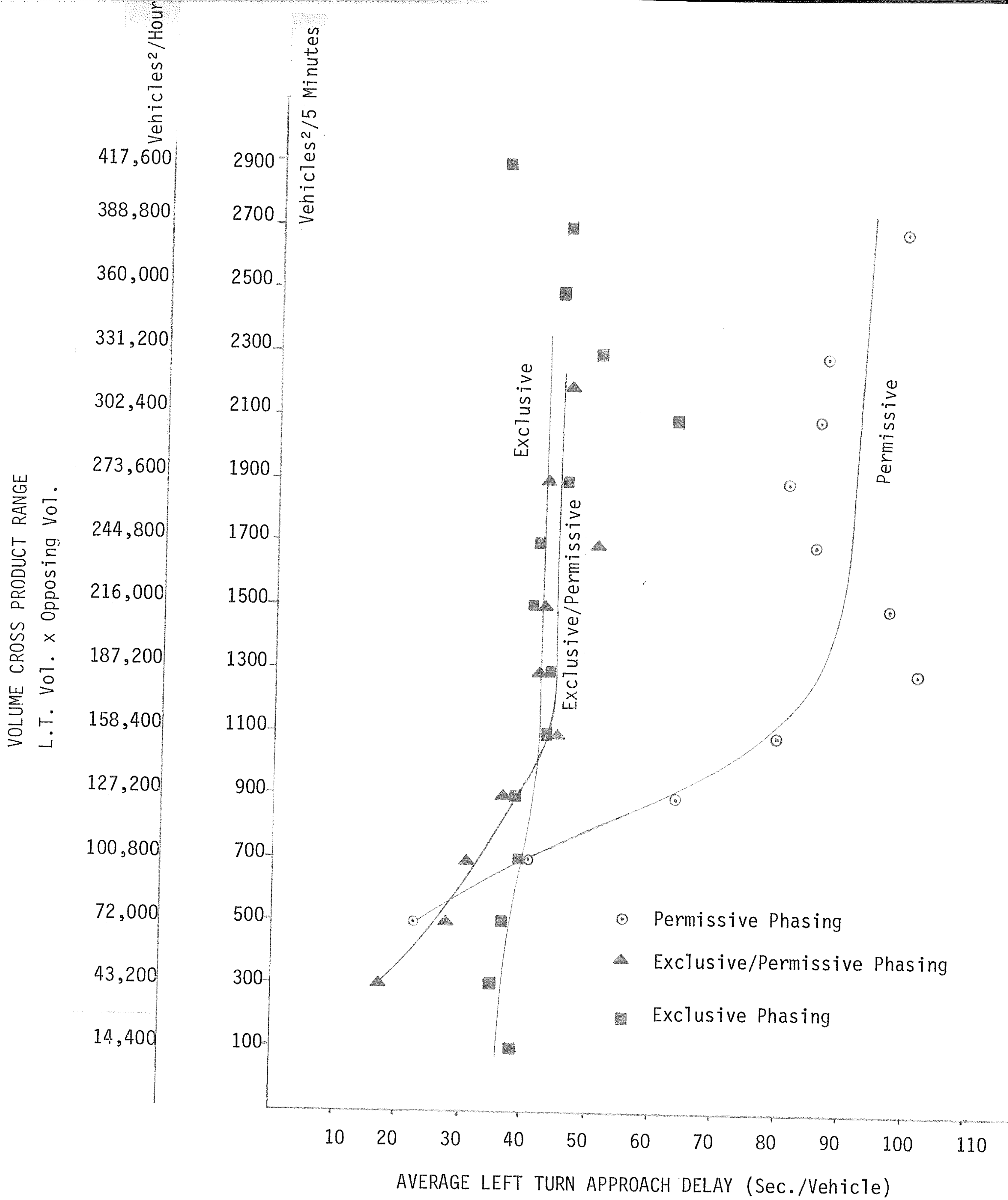


Figure 11

PLOT OF AVERAGE LEFT TURN DELAY VS. VOLUME CROSS PRODUCT
(3 opposing lanes)

turn movement; with permissive phasing they may turn during nearly one-half of the cycle.

2. At low volume levels (less than about 1000 vehicles^2/5 minutes), exclusive/permissive phasing results in very little reduction in left turn delay as compared to permissive phasing. In these cases left turn demand is so low that most left turners are turning on the green ball anyway and the exclusive portion of the phase offers very little reduction in average left turn delay.

3. At higher volume levels (greater than 1000 vehicles^2/5 minutes), exclusive/permissive phasing does result in a significant reduction in left turn delay. In these cases left turn demand and/or opposing volume is so high that the exclusive portion of the phase is used much more.

4. Exclusive/permissive phasing results in much less left turn delay than exclusive phasing at all volume levels. With exclusive/permissive phasing left turning vehicles have opportunities to make left turns during the permissive portion of the cycle as well as the exclusive portion thus reducing delay.

Figure 11 illustrates the case of three opposing lanes and shows the following relationships.

1. At low volumes (less than about 700 vehicles^2/5 minutes) permissive phasing works very effectively.

2. At higher volume levels left turn delay increases rapidly when permissive phasing is used.

3. At low volumes (less than about 700 to 900 vehicles^2/5 minutes) exclusive/permissive phasing results in lesser left turn delay than exclusive phasing. As volume decreases, exclusive/permissive

performs better and better than exclusive because more and more left turning vehicles can make their maneuver on the green ball.

4. At high volumes (greater than 1000 vehicles^2/5 minutes) there is no significant difference in left turn delay between exclusive phasing and exclusive/permissive phasing. At these volume levels opposing volumes are so high that there are inadequate gaps for vehicles to execute left turns on the green ball. Therefore, the exclusive/permissive phasing functions as if it were exclusive phasing. It was noted earlier in this report that many jurisdictions, by policy, do not install exclusive/permissive phasing when there are three opposing lanes. This observation suggests that those jurisdictions are not sacrificing great reductions in left turn delay by using only exclusive phasing.

5. The curves representing left turn delay for permissive phasing and exclusive phasing intersect at a volume cross product of 700 vehicles^2/5 minutes which is equivalent to 100,800 vehicles^2/hour. This value is remarkably close to the volume cross product criteria of 100,000 used by many jurisdictions to install exclusive left turn phasing (see previous section of report on "Warrants, Guidelines, and Criteria Used by Others").

A comparison of Figures 10 (two opposing lanes) and 11 (three opposing lanes) shows that there are substantial differences in the relationships between types of left turn phasing. For two opposing lanes (Figure 10) exclusive/permissive phasing performs substantially better than exclusive. For three opposing lanes there is virtually no difference in performance. This suggests that when there are three opposing lanes of traffic that left turners are much more reluctant to make a turn on a green ball indication.

With three opposing lanes it is more difficult for the driver to see and judge suitable gaps. The driver must check three lanes rather than two and there is a greater chance that one vehicle will mask out another. A further factor is that with three opposing lanes longer gaps are necessary since vehicles must cross three lanes instead of two.

Figures 12 and 13 illustrate the relationship between the average thru approach delay (the average delay for all thru vehicles) versus the volume cross product (left turn volume multiplied by the opposing through volume). Like Figures 10 and 11, these figures represent a simplification of the original plots in that all of the original 180 data points for each type of left turn phasing are not plotted. Each point shown on Figures 12 and 13 represents the mean of the through approach delay values for a range of volume cross product values. The reader should note that the horizontal scale is different on Figures 12 and 13 than on Figures 10 and 11.

Figure 12 illustrates the case of two opposing lanes. It shows the following.

1. Average thru approach delay is very small for permissive phasing. It is 2 to 3 seconds per vehicle, regardless of the size of the volume cross product.
2. Average thru approach delay is much smaller for permissive phasing than for either exclusive/permissive or exclusive phasing. A change from permissive phasing to either exclusive/permissive or exclusive phasing would increase thru delay.
3. Exclusive/permissive phasing results in about 4 to 5 seconds less delay to thru vehicles than does exclusive phasing.

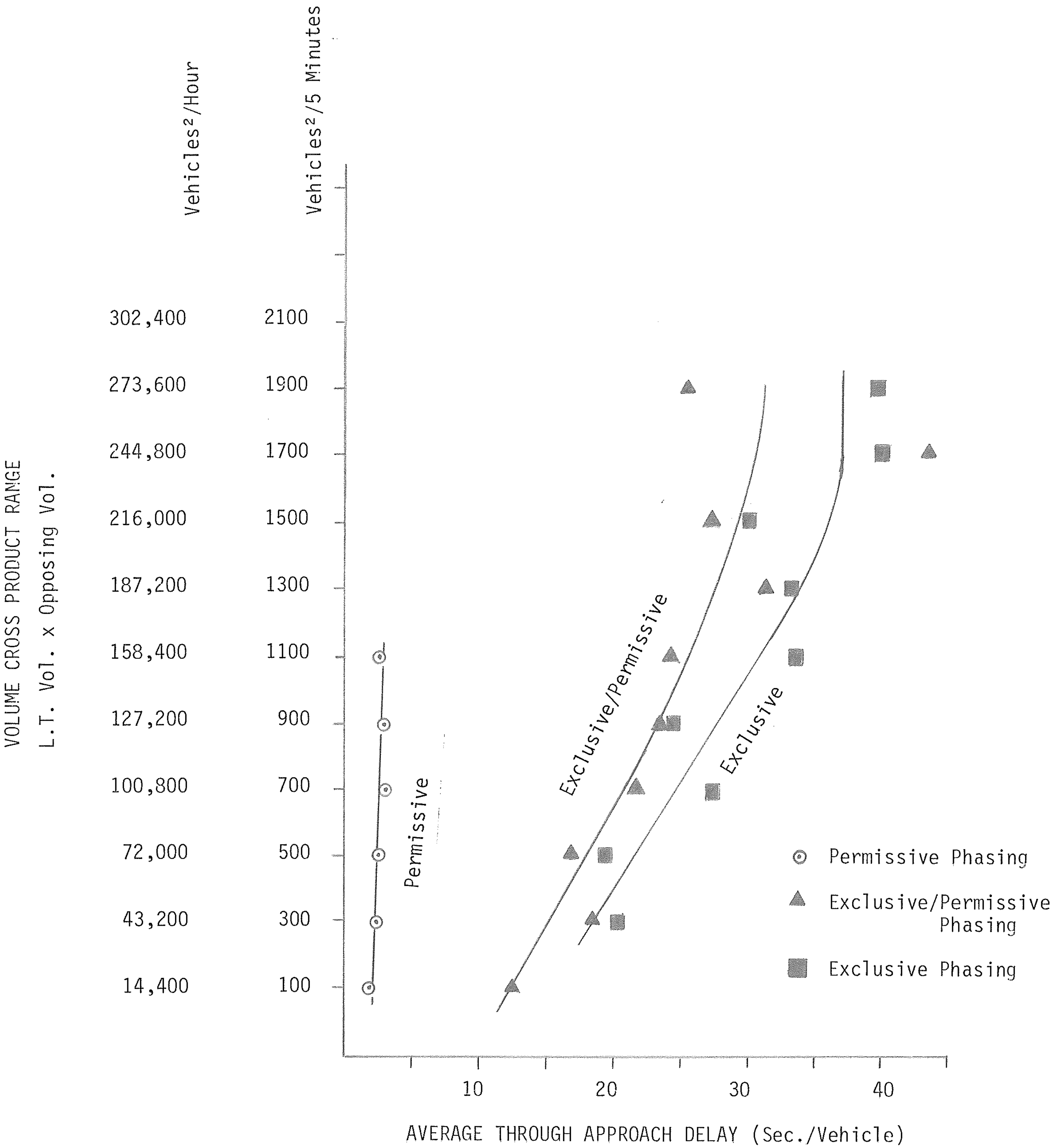


Figure 12

PLOT OF AVERAGE THROUGH DELAY VS. VOLUME CROSS PRODUCT (2 opposing lanes)

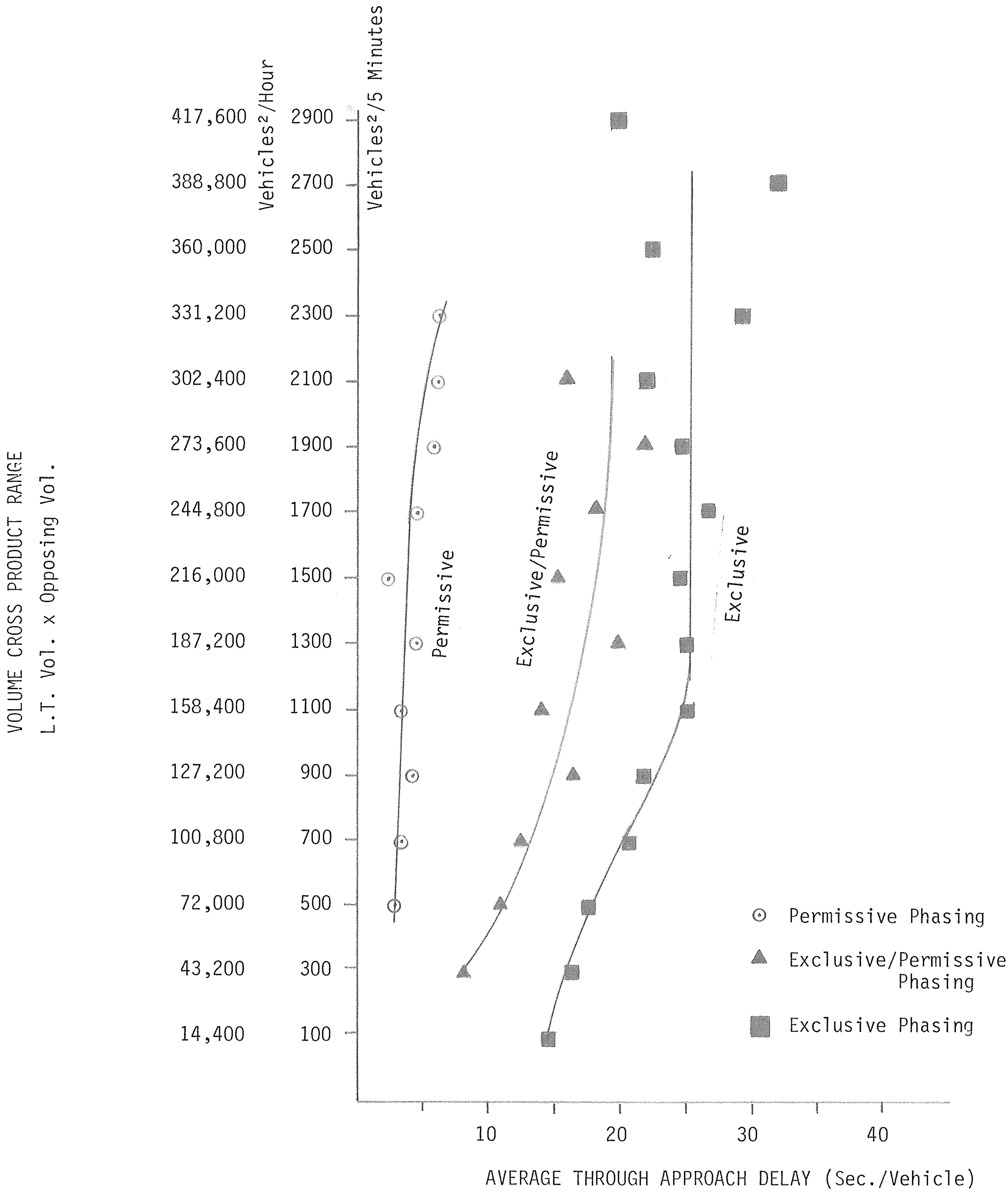


Figure 13

PLOT OF AVERAGE THROUGH DELAY VS. VOLUME CROSS PRODUCT
(3 opposing lanes)

4. The magnitude of the delay to thru vehicles increases with increasing volume cross product.

Observation of both Figures 10 and 12 shows that exclusive phasing results in the greatest delay for both left-turn and thru vehicles

Figure 13 illustrates average thru approach delay for the case of three opposing lanes. It shows the following.

1. Average thru approach delay is 3 to 6 seconds per vehicle.
2. Average thru approach delay is much smaller for permissive phasing than for either exclusive/permissive or exclusive phasing. A change from permissive phasing to either exclusive/permissive or exclusive phasing would increase thru delay.
3. Exclusive/permissive phasing results in about 6 to 8 seconds less delay to thru vehicles than does exclusive phasing.
4. The magnitude of the delay to thru vehicles increases with increasing volume cross product.

Comparison of Figures 12 (two opposing lanes) and 13 (three opposing lanes) shows that the effect of the three types of left turn phasing on thru delay is basically the same regardless of the number of opposing lanes.

Analysis of the data on accident rates at the limited number of intersections studied suggests that left turn phasing has a significant effect on left turn accidents at signalized intersections.

Table 1 shows the accident rates based on one million entering vehicles. The left turn accident rate was calculated using left turn volumes. The accident rate for the entire intersection was also calculated.

Table 1 ACCIDENT RATES AT SIX STUDY SITES

	Type of Left Turn Phasing: Permissive		Exclusive/Permissive		Exclusive		Year
	Alma School & University	44th Street & Thomas	Alma School & Broadway	Scottsdale & Thomas	Broadway & Priest	Dobson & Main	
LEFT TURN ACCIDENT RATE ON OBSERVED APPROACHES (left turn related accidents per one million entering left turn vehicles)	1.06	*	2.75	*	0.60	0.48	81
	6.37	2.76	2.06	0.59	1.21	1.45	82
	6.37	1.84	4.12	1.78	.60	1.45	83
ACCIDENT RATE (ALL APPROACHES) (total accidents per one million entering vehicles)	0.91	*	2.12	*	3.57	1.31	81
	1.51	2.07	1.42	0.70	1.60	0.87	82
	1.51	1.77	1.82	1.48	1.60	1.86	83

*Data not available

As shown in Table 2, the type of left turn phasing appears to have an effect on the left turn accident rate.

Table 2

LEFT TURN ACCIDENT RATE BY TYPE OF LEFT TURN PHASING

Type of Left Turn Phasing	Left Turn Accident Rate*
Permissive	3.68
Exclusive/Permissive	2.24
Exclusive	0.97

*Left turn related accidents per one million entering left turn vehicles on observed approaches.

Note: Each value in this table represents an average of the annual accident rate at two intersections in 1981, 1982, and 1983.

Exclusive phasing has the lowest left turn accident rate. This is because left turns are permitted only on the green arrow. Left turn vehicles do not enter the intersection at the end of the through green and attempt left turns during the clearance interval. The potential for conflicts and accidents with opposing through or cross traffic is relatively low.

Exclusive/permissive phasing also shows a reduction in left turn accident rates as compared to permissive phasing. Most left turns are made on the left turn arrow (exclusive condition) and few are required to make left turns on the green ball (permissive condition) or the clearance interval following the green ball. The opportunity for conflicts and collisions is reduced because during most cycles, the left turn demand is satisfied by the exclusive portion of the cycle.

It appears that the accident reduction potential of exclusive and exclusive/permissive phasing can be an important consideration in the selection of signal phasing.

CONCLUSIONS

This section describes the major findings of the research project.

1. For intersections with two opposing lanes exclusive phasing results in larger left turn delays than permissive phasing.
2. For intersections with two opposing lanes exclusive/permissive phasing results in very little reduction in left turn delay as compared to permissive phasing at low volume levels. At higher volume levels use of exclusive/permissive phasing does result in significant reductions in left turn delay.
3. For intersections with two opposing lanes exclusive/permissive phasing results in much less left turn delay than exclusive phasing.
4. For intersections with three opposing lanes permissive phasing works very well at low volume levels; left turn delay increases rapidly as volumes increase.
5. For intersections with three opposing lanes exclusive/permissive phasing results in lesser left turn delay than exclusive phasing at low volumes. At high volumes there is no difference in left turn delay between exclusive phasing and exclusive/permissive phasing.
6. For intersections with three opposing lanes permissive phasing will work well up to a volume cross product level of about 100,000 vehicles^2/hour. Above this level exclusive phasing results in less left turn delay.

7. The relative performance of permissive, exclusive/permissive, and exclusive phasing are substantially different for two opposing lanes as compared to three opposing lanes.
8. Thru delay is very small for permissive phasing compared to both exclusive/permissive phasing and exclusive phasing.
9. Exclusive/permissive phasing results in about 4 to 8 seconds less delay to thru vehicles than does exclusive phasing.
10. Based on a limited sample, the left turn accident rate decreases in going from permissive phasing to exclusive/permissive phasing to exclusive phasing.

RECOMMENDED WARRANT FOR LEFT TURN SIGNAL PHASING

The basic objective of this study was to determine a suitable warrant for left turn signal phasing. This section describes how the left turn warrant was developed, lists the intersection data required to use the warrant, presents the warrant itself, and describes how the warrant is applied. Adoption of the warrant by jurisdictions in Arizona would lead to better uniformity in use of left turn signalization in the state.

Development of the warrant considered a variety of information from two sources: that obtained from the review of the warrants, guidelines and criteria used by others; and that produced in this study. Listed below are the important points of information which directly influenced the warrant that was developed.

1. It is generally accepted in the traffic engineering community that with permissive phasing two left turning vehicles can clear the intersection at the end of the green ball. If left turn demand in the peak hour is greater than two vehicles per cycle, on the average, then either exclusive or exclusive/permissive phasing is required to accommodate left turns.
2. This study showed that, for intersections with two opposing lanes:
   a. permissive phasing works well when the volume cross product is less than 1000 vehicles^2/5 minutes (144,000 vehicles^2/hour);
   b. exclusive/permissive phasing significantly reduced left turn delay (as compared to permissive phasing)

when the volume cross product exceeded 1000 $vehicles^2/5$ minutes (144,000 $vehicles^2/hour$);

c. exclusive/permissive phasing resulted in significantly less left turn delay than exclusive phasing at all volume levels.

3. This study showed that, for intersections with three opposing lanes:

   a. permissive left turn phasing works well when the volume cross product is less than 700 $vehicles^2/5$ minutes (100,000 $vehicles^2/hour$);

   b. above 100,000 $vehicles^2/hour$ use of exclusive phasing results in the lowest left turn delay.

4. In several instances guidelines, warrants, and criteria used by other agencies recommend that exclusive phasing, rather than exclusive/permissive phasing, be used when left turning traffic must cross three or more lanes of opposing through traffic. (One such study is the Florida report - reference 9).

5. Similarly, it is suggested that exclusive phasing, rather than exclusive/permissive phasing, be considered when the speed limit of opposing traffic is greater than 45 mph. At high speeds it is more difficult for left turning motorists to judge acceptable gaps.

6. Restricted sight distance to opposing traffic creates potential accident situations. Sight distance may be restricted due to roadway geometry or opposing left turning vehicles. The Florida report (reference 9) recommends use of

exclusive left turn phasing when sight distance fails to meet the following criteria:

250 feet for speeds of 35 mph or less

400 feet for speeds greater than 35 mph.

7. Separate left turn phasing can reduce left turn accidents. This study presented accident rates for a limited number of intersections (six).

A final factor which guided development of a warrant was a philosophical factor. Although a warrant must be somewhat sophisticated so that it will accurately select the appropriate type of left turn phasing, it must also be of a form that is easily used. It should establish a quick and easy means of evaluating an individual intersection to determine what type of left turn signal phasing is best for its particular characteristics.

The data required to use the left turn warrant developed in this study are:

Left turn volume (hourly) during the peak hour. (Use the hour of highest left turn demand if it is not the peak hour. This does not imply that the warrant is just for the peak hour; however, the peak hour usually determines the need for left turn phasing.)

Cycle length

Opposing volume during the peak hour (or hour of highest left turn demand)

Number of opposing lanes

Speed of opposing traffic

The available sight distance

Accident history, including left turn accidents.

All of these items are usually easily acquired and readily available.

The warrant developed in this study is based upon the factors described above. The warrant itself is presented in the form of a flowchart (shown in Figure 14). The following steps describe application of the warrant. (Note that the warrant applies only to locations that have a separate left turn lane).

I. Determine the left turn volume in the hour of highest left turn demand and divide by the number of cycles per hour. Determine if the answer is greater than 2.0.

II. Determine the number of lanes of traffic opposing the left turn movement. These lanes would be all lanes on the opposite approach with through and/or right turning vehicles.

III. Multiply the left turn hourly volume times the hourly volume for opposing through traffic. Use the same hour as in I. Compare the answer to either 100,000 or 144,000, as appropriate.

IV. Determine if the speed on the opposing approach is greater than 45 mph.

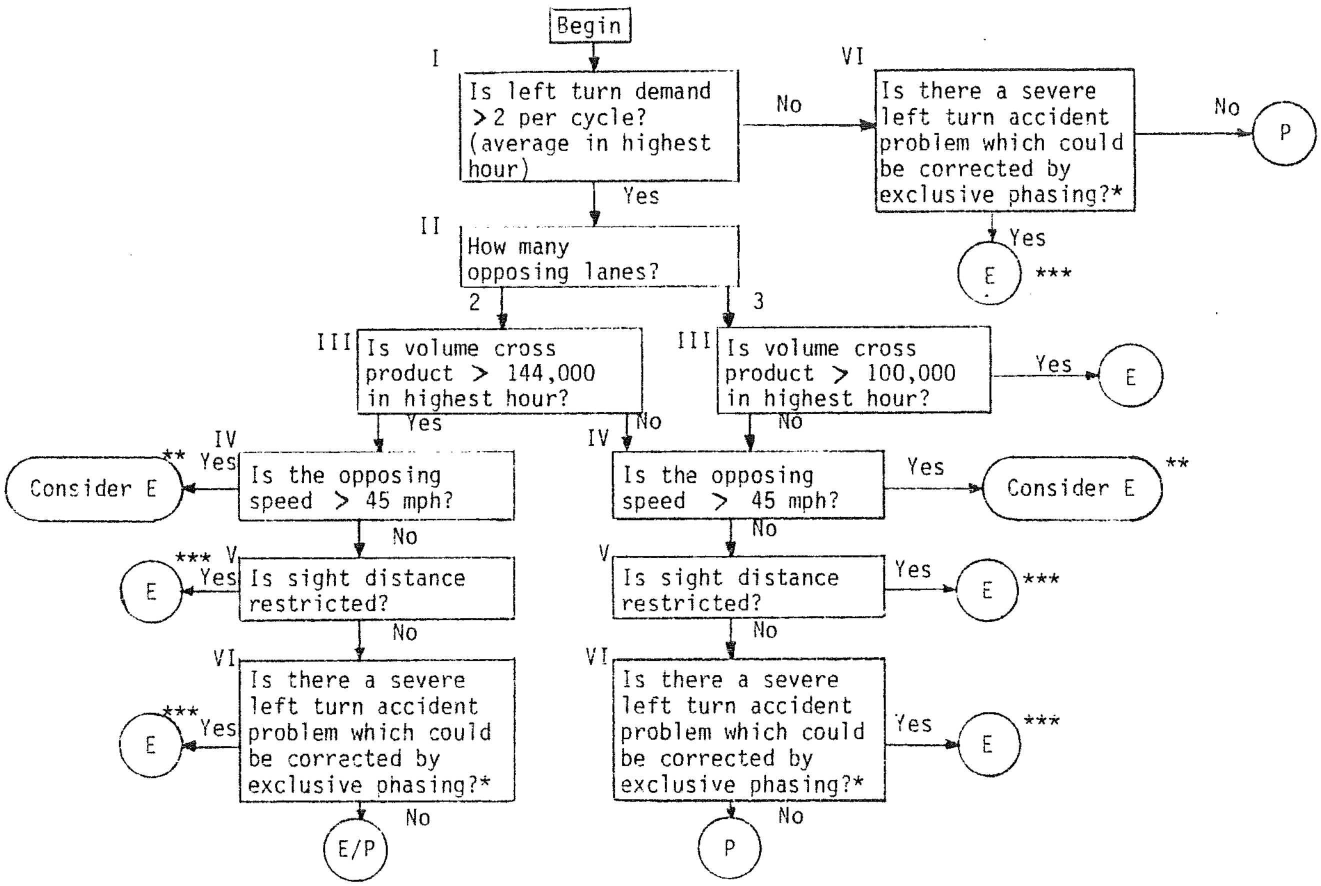
V. Determine if sight distance is restricted.

Restricted sight distance is:

<250 feet when speeds are 35 mph or less;

<400 feet when speeds are 40 mph or more.

VI. Determine if there is a severe left turn accident problem which could be corrected by exclusive phasing. There are no clear-cut criteria for a severe left turn accident problem which can apply to all jurisdictions. Each jurisdiction should develop its own accident rate criteria. The following data may be useful in



(P) - Permissive

(E/P) - Exclusive/Permissive

(E) - Exclusive

Note: This procedure applies to locations that have a separate left turn lane

Restrictive Sight Distance is:

< 250 feet when speeds are 35 mph or less;

< 400 feet when speeds are 40 mph or more

* See text for definition of severe left turn accident problem

** An opposing speed > 45 mph indicates a potential left turn accident problem. Consider exclusive phasing, realizing that non-left turn accidents may increase.

*** Use exclusive phasing with the understanding that non-left turn accidents may increase.

Figure 14

Procedure for Determining Type of Left Turn Phasing determining whether the number of left turn accidents is unusually high.

A. This study calculated the following accident rates at six intersections (two for each type of phasing).

Type of left turn phasing	Left Turn Related Accidents per one million entering left turn vehicles
Permissive	3.68
Exclusive/Permissive	2.24
Exclusive	0.97

B. A second study (reference 9) found the following annual average number of left turn angle accidents at a sample of 28 intersections.

Type of left turn phasing	Average Annual number of left turn angle accidents per approach
Exclusive/Permissive	3.38
Exclusive	0.48

It must be recognized that while changing the type of left turn phasing will reduce left turn accidents, other types of accidents may increase.

It is recommended that when exclusive or exclusive/permissive phasing is installed that it be traffic actuated with left turn phase lengths varied according to actual demand on any cycle.

Use of this warrant is intended to be an aid to traffic engineers. As such, the warrant is a guide to be used as an evaluation tool and is not, of itself, a decision making process.

RECOMMENDATIONS FOR FURTHER STUDY

The basic approach used in this study was to compare delay and other operational descriptors at intersections where the type of left turn phasing was different but where all other intersection characteristics were the same (as nearly as possible). Intersections were matched in terms of number of opposing lanes, left turn volume, opposing volume, signal display and signing, speed, traffic composition, pedestrian interference, geometry, and other factors. This approach was valid and the study results are meaningful, useful, and valid.

It was not possible, in this study, to obtain perfect matches among intersections. There were some differences in percentages of left turns, total traffic volume, cycle length, and split between intersections. In addition, two intersections were parts of signal systems and vehicle arrivals tended to be more platooned than random at those locations.

Although these differences could not be normalized in this study, it would be of interest to compare different types of left turn phasing at a single intersection. Through a before and after type study volumes, turning movement percentages, and the pattern of vehicle arrivals would be fairly consistent while the type of left turn phasing is varied. With the cooperation of a traffic engineering agency it would be possible to have control over cycle length, split, G/C ratio, and signal timing.

The City of Phoenix is currently conducting an experimental program with left turn signal phasing. Preliminary discussions indicate that the City of Phoenix would have an interest in cooperating in a before and after type study. Thus, a unique opportunity exists to conduct the before and after type of study described above. The results of such a study would complement the just completed research project and further add to the body of knowledge about left turn signal phasing.

The effect of introducing left turn phasing in progressive signal networks was not evaluated. Only one of the data collection sites was part of a signal system; the other five sites were isolated intersections. The effect of left turn phasing on a progressive system, as well as on system-wide operations, should be a part of a follow-on study.

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APPENDIX A

GLOSSARY

Definition of Types of Left Turn Signal Phasing

Permissive Left Turn - Vehicles are allowed to make a left turn on a circular green indication after they yield to oncoming traffic (sometimes called a permitted left turn)

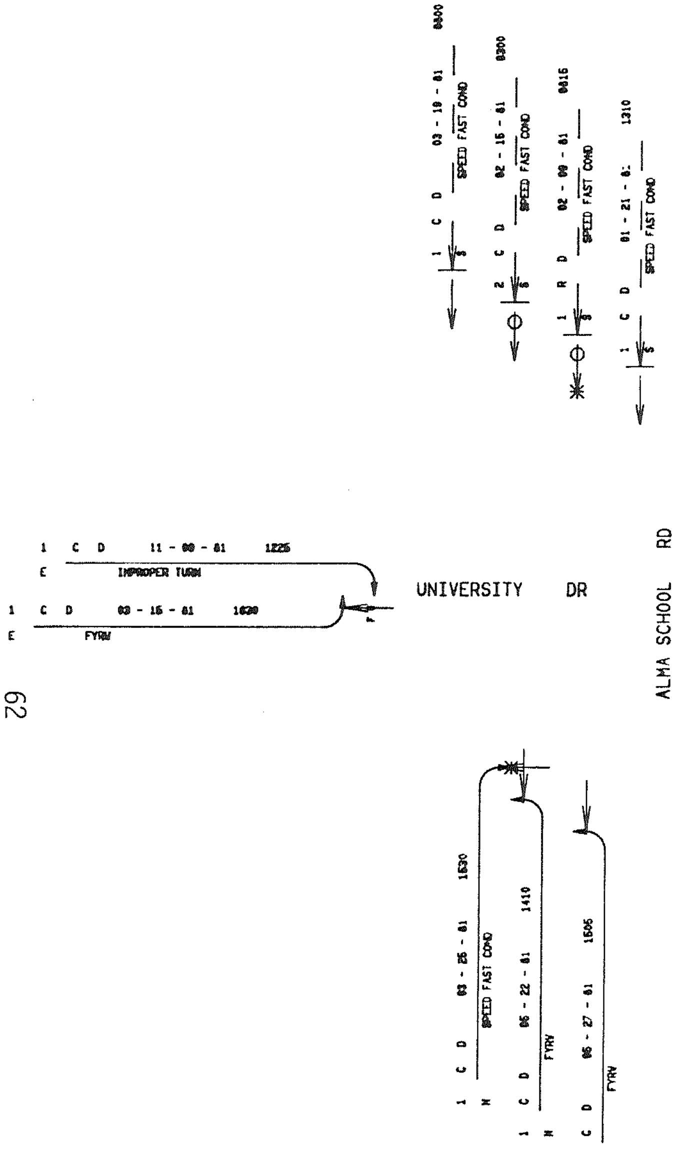
Exclusive Left Turn - Vehicles are allowed to make a left turn only on a green arrow indication (sometimes called a protected left turn)

Exclusive/Permissive Left Turn - Vehicles are allowed to make a left turn either on a green arrow indication <u>or</u> on a circular green indication after yielding to oncoming traffic (sometimes called protected/permitted left turn). The exclusive portion of the signal cycle (the green arrow) may either precede (lead) or follow (lag) the permissive (circular green) portion of the cycle.

Split phasing - This is a specialized form of exclusive left turn phasing. With split phasing one approach of an intersection is directed to proceed, including left turn drivers on an exclusive left turn. When this approach is stopped the opposing approach is directed to proceed, including left turn drivers on an exclusive left turn.

APPENDIX B

SAMPLE COLLISION DIAGRAMS FOR STUDY SITES



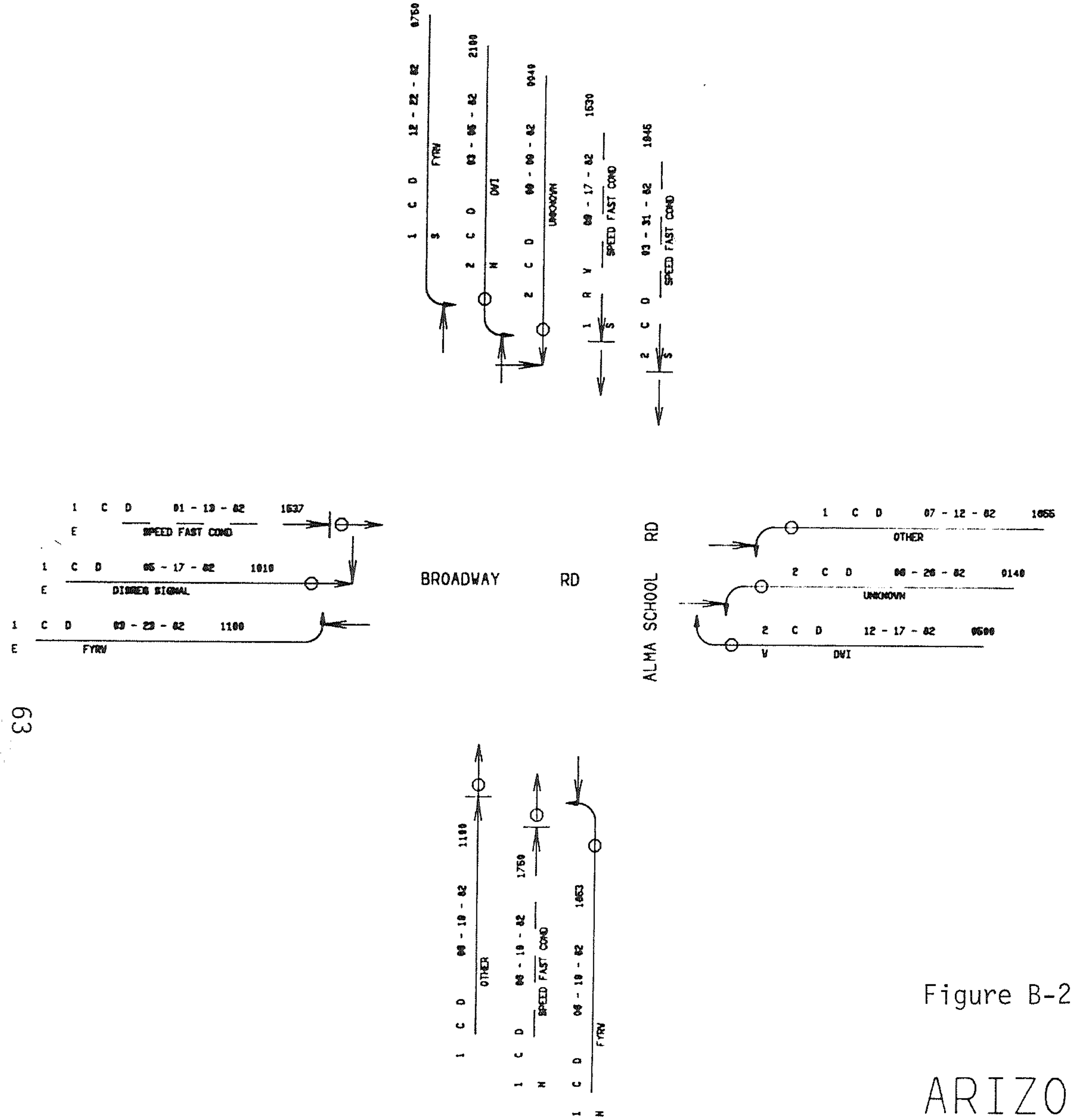
	DAY	NIGHT	TOTAL
ANGLE	0	0	0
LEFT TURN	3	0	3
REAR END	3	1	4
SINGLE VEH	1	0	1
OTHER	1	0	1
TOTAL	8	1	9

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	1	1	2
PROPERTY DAMAGE	7	0	7
PED. FATAL	0	0	0
PED. INJURY	0	0	0
PEDALCYCLIST	0	0	0

Figure B-1

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION ALMA SCHOOL RD.UNIVERSITY DR
PERIOD COVERED 01-01-81 TO 12-31-81
DATE COMPILED 05-10-84



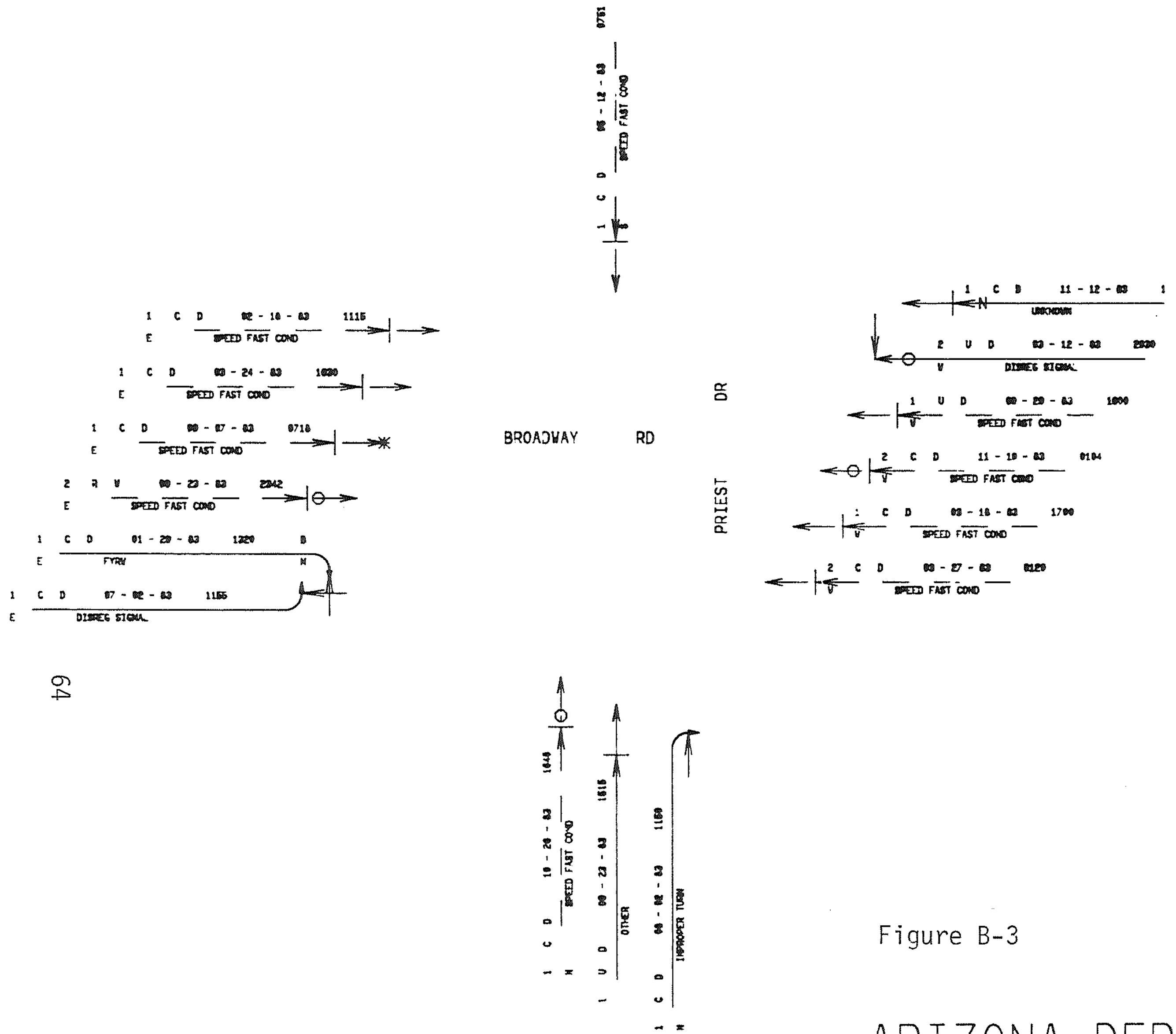
	DAY	NIGHT	TOTAL
ANGLE	1	1	2
LEFT TURN	4	2	6
REAR END	4	1	5
SINGLE VEH	0	1	1
OTHER	0	0	0
TOTAL	9	5	14

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	6	4	10
PROPERTY DAMAGE	3	1	4
PED. FATAL	0	0	0
PED. INJURY	0	0	0
PEDALCYCLIST	0	0	0

Figure B-2

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION ALMA SCHOOL RD.BROADWAY RD
PERIOD COVERED 01-01-82 TO 12-31-82
DATE COMPILED 05-10-84



	DAY	NIGHT	TOTAL
ANGLE	0	1	1
LEFT TURN	1	0	1
REAR END	9	3	12
SINGLE VEH	0	0	0
OTHER	3	0	3
TOTAL	13	4	17
UNABLE TO PLOT		1	

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	2	3	5
PROPERTY DAMAGE	11	1	12
PED. FATAL	0	0	0
PED. INJURY	0	0	0
PEDALCYCLIST	1	0	1

Figure B-3

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION PRIEST DR.BROADWAY RD
PERIOD COVERED 01-01-83 TO 12-31-83
DATE COMPILED 05-10-84

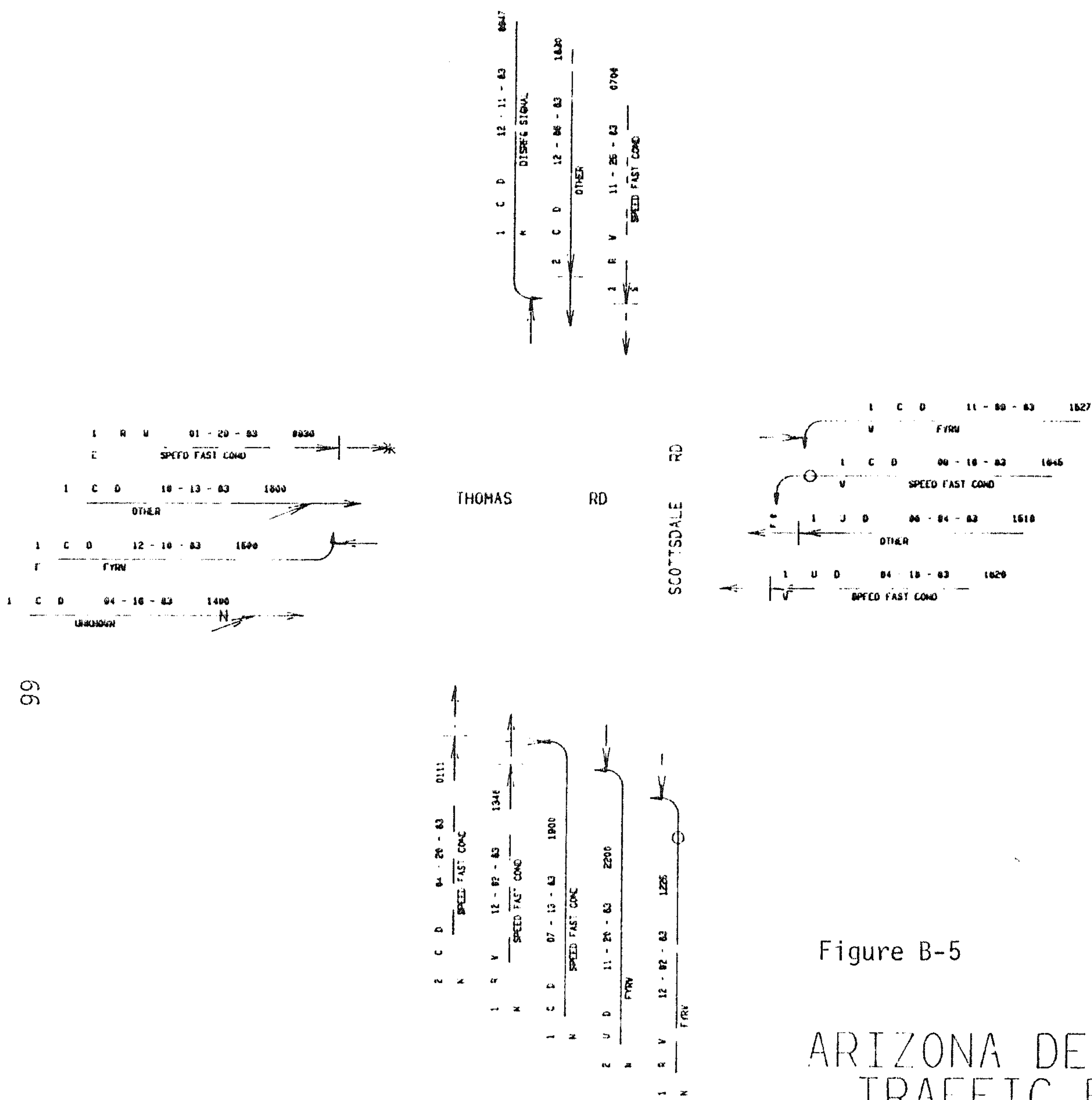
	DAY	NIGHT	TOTAL
ANGLE	1	4	5
LEFT TURN	12	8	20
REAR END	3	3	6
SINGLE VEH	0	2	2
OTHER	1	1	2
TOTAL	17	18	35

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	5	10	15
PROPERTY DAMAGE	12	8	20
PED. FATAL	0	0	0
PED. INJURY	0	1	1
PEDALCYCLIST	0	0	0

Figure B-4

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION 44TH ST. THOMAS RD
PERIOD COVERED 01-01-82 TO 12-31-82
DATE COMPILED 05-10-84



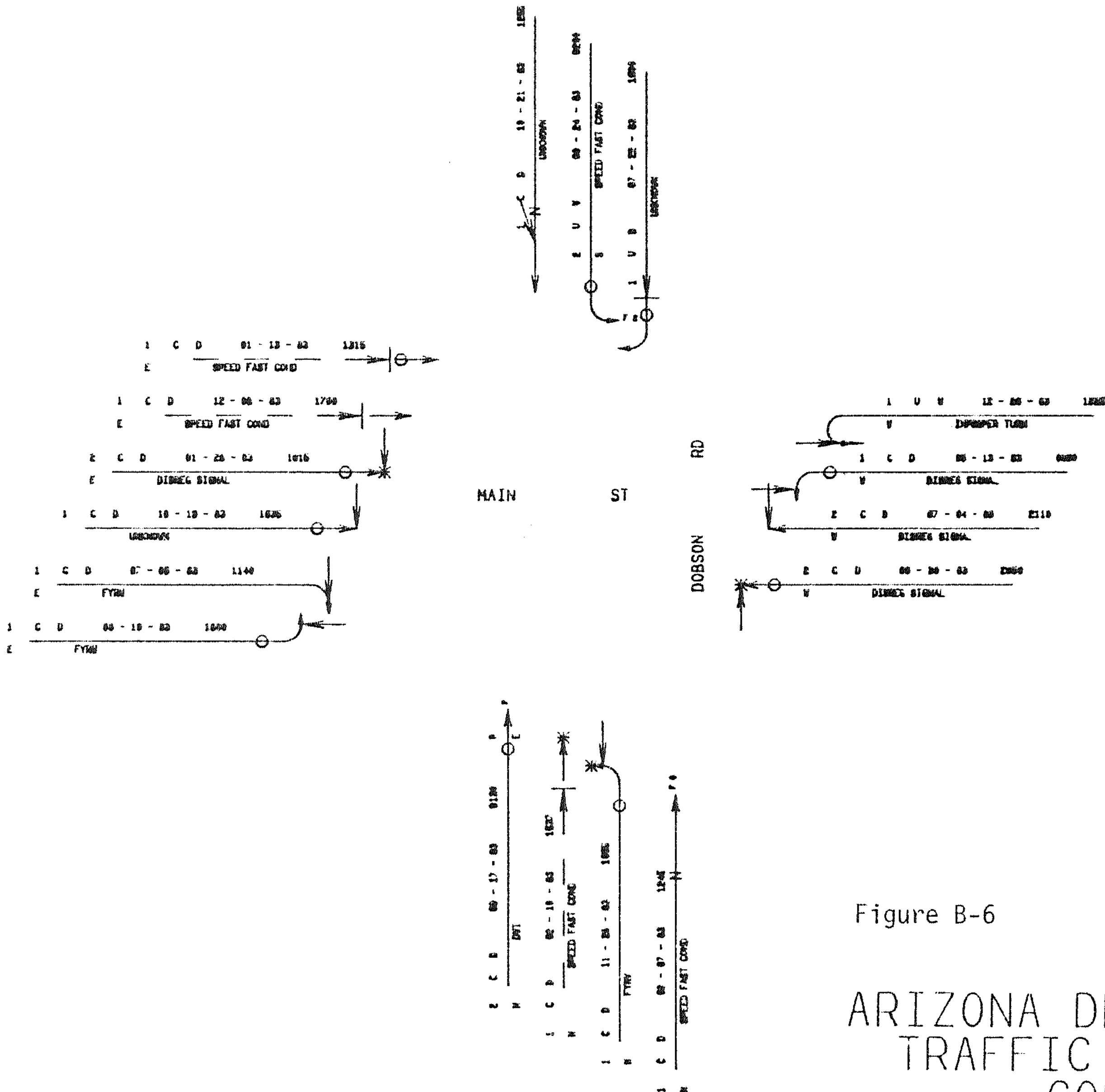
	DAY	NIGHT	TOTAL
ANGLE	0	0	0
LEFT TURN	5	1	6
REAR END	5	2	7
SINGLE VEH	1	0	1
OTHER	3	0	3
TOTAL	14	3	17
UNABLE TO PLOT		1	

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	3	0	3
PROPERTY DAMAGE	11	3	14
PED. FATAL	0	0	0
PED. INJURY	1	0	1
PEDALCYCLIST	1	0	1

Figure B-5

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION SCOTTSDALE RD. THOMAS RD
PERIOD COVERED 01-01-83 TO 12-31-83
DATE COMPILED 05-10-84



	DAY	NIGHT	TOTAL
ANGLE	1	3	4
LEFT TURN	3	0	3
REAR END	4	0	4
SINGLE VEH	1	2	3
OTHER	3	0	3
TOTAL	12	5	17

	DAY	NIGHT	TOTAL
FATAL	0	0	0
INJURY	6	4	10
PROPERTY DAMAGE	6	1	7
PED. FATAL	0	0	0
PED. INJURY	0	1	1
PEDALCYCLIST	0	0	0

Figure B-6

ARIZONA DEPT. OF TRANSPORTATION
TRAFFIC ENGINEERING SECTION
COLLISION DIAGRAM

LOCATION DOBSON RD. MAIN ST
PERIOD COVERED 01-01-83 TO 12-31-83
DATE COMPILED 05-10-84

APPENDIX C

ADOT OPERATING POLICY #11

A... ONA DEPARTMENT OF TRANSPORTAT...

OFFICE MEMO

HIGHWAYS DIVISION

February 10, 1981

ATTACHMENT #4

Issued 20 September 1976
Revised 10 February 1977
Revised 10 February 1981

TO: AREA 1 & AREA 2 ENGINEERS

FROM: BENJAMIN E. BURRITT
Assistant Traffic Engineer
Operations Studies Branch

RE: Operating Policy #11 - Guidelines for Considering Left-Turn Signals

In future studies evaluating the need for left-turn signal phases at intersections having left-turn channelization, all of the following guidelines must be considered:

1. Accident Experience -- Consider left-turn phasing if the following criteria are met:

   a. One approach -- four left-turn accidents in one year or six in two years.

   b. Both approaches -- six left-turn accidents in one year or ten in two years.

2. Delay -- Consider left-turn phasing if a left-turn delay of 2.0 vehicle-hours or more occurs in a peak hour on an approach. Also, there must be a minimum left-turn volume of 50 during the peak hour, and the average delay per left-turning vehicle must be at least 35 seconds.

3. Volumes -- Consider left-turn phasing when the product of left-turning and opposing volumes during peak hours exceeds 100,000 on a four-lane street or 50,000 on a two-lane street. Also, the left-turn volume must be at least 50 during the peak-hour period. Volumes meeting these levels indicate that further study of the intersection is required.

4. Traffic Conflicts -- Consider left-turn phasing when a consistent average of 14 or more total left-turn conflicts or 10 or more primary left-turn conflicts occur in a peak hour.

STUDY PROCEDURE

A. Left-turn Delay

Left-turn delay is defined as the time from when a vehicle arrives in a queue or at the stop bar until it departs from the stop bar.

B. Traffic Conflicts

Primary left-turn conflicts occur when a left-turning vehicle crosses in front of or blocks the lane of an opposing through vehicle. This conflict is counted when the through vehicle brakes or weaves. Another type of conflict is a continuation of the primary type. If a second through vehicle following the first one also has to brake, this act is counted as a secondary conflict. The last type of conflict occurs when vehicles turn left on red. This signal violation conflict is counted when a vehicle enters an intersection after the signal has turned red. Vehicles which enter the intersection legally and complete their movement after the signal changes are not counted. As a general rule, a maximum of two vehicles can enter an intersection legally and complete their turns after the signal changes.

C. Special Considerations

When a left-turn signal is recommended based on factors other than accident experience, consideration may be given to permitting left turns after the protected portion of the phase. If such an approach is initially used, the operation of the intersection shall be monitored to determine if motorists are capable of safely negotiating left turns during the permissive portion of the phase. If it is determined that motorists can not be relied upon to choose adequate gaps, the operation of the left-turn signal shall be modified by eliminating the permissive phase and, if necessary, extending the protected phase.

An exclusive left-turn phase increases intersection delay. Use of a leading left-turn arrow can make protected left-turn movements less of an economic hardship to the motorists. Consideration should be given to recommending leading left-turn arrows, as opposed to exclusive left-turn phases, when traffic imbalances favor such treatment.

STUDY PROCEDURE - CONT.

C. Special Considerations - Cont.

Arrow assemblies are gaining acceptance and their use is encouraged. For permissive phasing, the five-head assembly (three ball - two arrow) is appropriate. For exclusive phasing, the three-head assembly (three arrow) can be used in conjunction with a "LEFT ON GREEN ARROW ONLY" sign.

BEB:mm

cc: Adrian R. Pollock
Thomas M. Newton

APPENDIX C

ADOT OPERATING POLICY #11

ARIZONA DEPARTMENT OF TRANSPORTATION

OFFICE MEMO

HIGHWAYS DIVISION

November 14, 1983

Issued 20 September 1976
Revised 10 February 1977
Revised 10 February 1981
Revised 14 November 1983

TO: STUDIES UNIT I ENGINEER AND
STUDIES UNIT II ENGINEER

FROM: RONALD D. MIDKIFF
Assistant Traffic Engineer
Operations Studies Branch

RE: Operating Policy #11 - Guidelines for Considering Left-Turn Signals

In future studies evaluating the need for left-turn signal phases at intersection having left-turn channelization, all of the following guidelines must be considered:

1. Accident Experience -- Consider left-turn phasing if the following criteria are met:

   a. One approach -- four left-turn accidents during a 12-month period or six during a 24-month period.

   b. Both approaches -- six left-turn accidents during a 12-month period or ten during a 24-month period.

2. Delay -- Consider left-turn phasing if a left-turn delay of 2.0 vehicle-hours or more occurs in a peak hour on an approach. Also, there must be a minimum left-turn volume of 50 during the peak hour, and the average delay per left-turning vehicle must be at least 35 seconds.

3. Volumes -- Consider left-turn phasing when the product of left-turning and opposing volumes during peak hours exceeds 150,000 on a four-lane street or 75,000 on a two-lane street. The left-turn peak hour volume must be at least 120 under existing two-phase operation, 90 under existing three-phase operation, and 60 under existing four or more phase operation. Volumes meeting these levels indicate that further study of the intersection is required.

4. Traffic Conflicts -- Consider left-turn phasing when a consistent average of 14 or more total left-turn conflicts, or 10 or more primary left-turn conflicts occur in a peak hour.

STUDY PROCEDURE

A. Left-Turn Delay

Left-turn delay is defined as the time from when a vehicle arrives in a queue or at the stop bar until it departs from the stop bar.

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Ronald D Midkiff

RDM:ks

cc: Thomas Newton