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16. Abstract

The report documents the development of guidelines and recommendations for the selection of the left-turn phasing, indication sequences and auxiliary signs. The guidelines developed are based on field studies of over 100 intersections in nine Texas counties and utilize easy to obtain data for the selection process.

A three-level decision process regarding the suitability of left-turn phasing treatment to be used is established. The process favors the least restrictive permissive left-turn phase unless traffic and geometric conditions warrant the more restrictive protected/permissive or protected only phasings. The guidelines developed are based on threshold values designed to determine what constitute an "excessive" value for any particular decision variable beyond which more restrictive left-turn phasing treatments may be justified.

Recommendations concerning signal indications and auxiliary signs are made based on delay, safety and degree of motorists' understanding. The study results show that selection of any particular phasing is a multi-objective process involving a number of factors, and in many cases more than one condition must be met to justify the selection of a particular phase to ensure an optimum solution.

17. Key Words

Protected only, protected/permissive, permissive only, phasing, lead, lag, left-turn, accidents, conflicts, delay,sequence, indications, auxiliary signs

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by

Seth A. Asante
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and
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and
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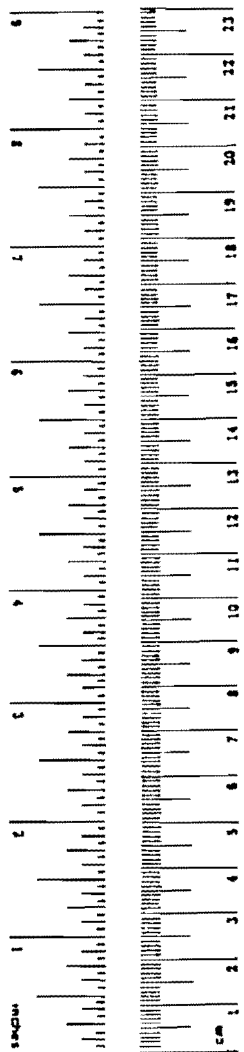
METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	centimetres	cm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	centimetres squared	cm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
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
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

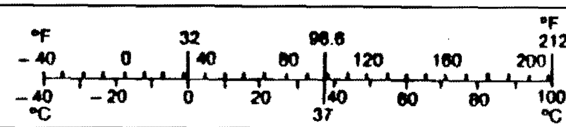
NOTE: Volumes greater than 1000 L shall be shown in m^3.

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



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			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectares (10 000 m^2)	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
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3
	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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

* SI is the symbol for the International System of Measurements

ABSTRACT

This report documents the development of guidelines and recommendations for the selection of the left-turn phasing, indication sequences and auxiliary signs. The guidelines developed are based on field studies of over 100 intersections in nine Texas counties and utilize easy to obtain data for the selection process.

A three-level decision process regarding the suitability of left-turn phasing treatment to be used is established. The process favors the least restrictive permissive left-turn phase unless traffic and geometric conditions warrant the more restrictive protected/permissive or protected only phasings. The guidelines developed are based on threshold values which statistically determine what constitutes an "excessive" value for any particular decision variable, beyond which more restrictive left-turn phasing treatments may be justified.

Recommendations concerning signal indications and auxiliary signs are made based on delay, safety and degree of motorists' understanding. The study results show that selection of any particular phasing is a multi-objective process involving a number of factors, and in many cases more than one condition must be met to justify the selection of a particular phase to ensure an optimum solution.

KEYWORDS:
Protected only, protected/permissive, permissive only, phasing, lead, lag, left-turn, accidents, conflicts, indications, sequences, auxiliary signs, traffic signals.

SUMMARY

Numerous combinations of left-turn signal phase patterns and indication sequences exist for left-turn treatment and operation. A variety of standard and non-standard auxiliary left-turn signs are also in use with these signal indications. Substantial gains in efficiency and safety of left-turn operations, as well as energy savings and reductions in emissions, can be realized through the implementation of appropriate left-turn signal treatments.

Field studies at over 100 sites in nine Texas counties, and accident and conflict studies at many of those intersections, provided information on the operational efficiency and relative safety of various left-turn treatments. A mail survey of 6000 drivers was conducted to assess motorists' degree of understanding of left-turn signal indications and accompanying auxiliary signs in use in Texas.

Statistical analyses were conducted to address the following decisions regarding the suitability of left-turn phasings to be used:

- Is a permissive only left-turn phase adequate or should some form of protection (green arrow) be provided?
- If protection is called for, is a more restrictive, protected only phase justified or would protected/permissive operation suffice?
- If protected/permissive operation is to be used, would leading lefts be sufficient, or should a lead/lag or Dallas phase sequence be provided? Also, if a protected only phase is prescribed, could a lead sequence be used or should a lag option be considered?

Threshold values are designed to statistically assess what constitutes an "excessive" value of any particular decision variable, beyond which a specific left-turn phasing treatment can be justified. The study results show that the selection of any particular phasing is a multi-objective process involving a number of factors, and, in many cases, more than one condition must be met to justify the selection of a particular phase to ensure an optimal solution. Recommendations concerning signal indications and auxiliary signs are made based on delay, safety, and motorists' understanding of such indications.

IMPLEMENTATION STATEMENT

This document presents guidelines and recommendations for the selection of left-turn phasing, indication sequences, and auxiliary signs. The study shows that phase pattern selection is a multi-objective process involving many factors, and in many cases more than one condition must be met to justify a particular phase to ensure an optimum solution.

Specific signal indications and auxiliary signs were found to be misunderstood by many drivers and should not be used. A circular red and green arrow, for example, should not be shown simultaneously on a five-section head as it is confusing to many drivers. Findings and recommendations have been summarized and in some cases presented in a graphical form to facilitate usage. The guidelines developed are based on easy-to-obtain field data and may be converted into and distributed as an interactive PC-based computer routine.

In addition to benefits such as reductions in delays and in user and environmental costs over time, immediate benefits in increased safety as a direct result of increased motorist understanding could also be realized. As drivers become more accustomed to systematic and standard applications of left-turn phase sequences and signal indications, vehicular flows should also increase, thereby resulting in higher capacities and more efficient intersection operations.

The findings and recommendations of this study may be disseminated within the Texas Department of Transportation by its incorporation into departmental design and operations manuals, and possibly as an appendix to the Texas MUTCD. It is expected that the findings and recommendations will be permissible under the current Texas MUTCD, potential revisions to the national MUTCD could be submitted to the National Committee on Uniform Traffic Control Devices.

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A special thanks is also extended to a number of traffic engineers statewide who assisted in the selection of intersections and provided accident and other data. These individuals are: Mr. Van Cook and Mr. Albert Ruiz, City of Lubbock; Mr. Gerry de Camp, City of Las Vegas, Nevada, formerly with the City of Austin; Mr. Rick Denney, City of San Antonio; Mr. Andy Mao, Harris County; Mr. Ali Mozdbar, City of Arlington; Mr. Enoch Needham, TxDOT, Austin District; Mr. Walter Ragsdale and Mr. John Black, City of Richardson; Ms. Beth Ramirez, City of Dallas; Mr. Bill Stebbins, TxDOT, Odessa District; Mr. Jim Taylor, D-18, TxDOT; and Mr. Russ Wiles, City of Fort Worth.

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DISCLAIMER

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CHAPTER 1

INTRODUCTION

PROBLEM DEFINITION

Several combinations of left-turn signal phase patterns and indication sequences exist for left-turn treatment and operation. A variety of standard and non-standard auxiliary left-turn signs are also in use with these signal indications. Substantial gains in efficiency and safety of left-turn operations, as well as energy savings and reductions in emissions, can be achieved through the implementation of appropriate left-turn signal treatments.

Selection of the appropriate left-turn signal treatment from the various phase patterns, indication sequences, and auxiliary signs is a difficult task. Meanwhile, there have been no comprehensive guidelines to assist traffic engineers. Existing guidelines are inadequate and often the engineer must rely on experience or try different treatments until a suitable one is found. This often leads to reductions in efficiency and safety as well as increases in user cost.

Comprehensive guidelines are needed for the selection of the appropriate combination of signal phase pattern, indication sequence, and auxiliary left-turn sign at a given intersection. Pivotal in the development of such guidelines is an understanding of how motorists interpret the various signal indications, signs, and phase patterns. Moreover, the relative operational safety of each left-turn signal treatment combination must be assessed through analyses of conflicts and accidents.

The developed guidelines must incorporate both the commonly used criteria (e.g., volumes, number of lanes, speed, and sight distance) as well as operational safety (accidents and conflicts) without sacrificing efficiency (delays and stops). Also to be considered is the degree of motorists' understanding of these indication sequences and auxiliary signs.

Aside from benefits such as reduction in delays and user and environmental costs over time, immediate benefits in increased safety as a direct result of increased motorist understanding could also be realized. As drivers become more accustomed to systematic and standard applications of left-turn phase sequences and signal indications, vehicular flows should also increase, thereby resulting in higher capacities and more efficient intersection operations.

Left turns at signalized intersections can be accommodated by several different phase sequences, depending on the degree of protection desired and whether the left turn precedes or follows its associated through movement. The left turn phasing treatments considered in this study are listed below:

- permissive only (figure 1.1),
- leading, protected only (figure 1.2),
- lagging, protected only (figure 1.3),
- leading, protected/permissive (figure 1.4),
- lagging, protected/permissive (figure 1.5),
- lead/lag, protected only (figure 1.6), and
- lead/lag, protected/permissive (figure 1.7).

This is not an exhaustive list of phase sequences, since overlaps are not considered for the leading and lagging sequences (figures 1.2 through 1.5) and the lead/lag sequences are only considered with an overlap.

An overlap phase occurs when one of the protected lefts is terminated before the other (in the leading left case), allowing its opposing through green to start. The resulting interval consists of a protected left and its accompanying through movement. In the lagging case, one of the through movements is terminated before the other, resulting in a similar overlap phase. While the capability of providing overlaps allows unbalanced flows to be treated more efficiently, this distinction was not considered to be important for the purposes of this study, as explained below. The overlap phase in the lead/lag sequence is the dual through movement; without the overlap, split phasing results.

The lead/lag, protected/permissive phase sequence, as shown in figure 1.7, results in a yellow trap for southbound traffic (if north is taken to be towards the top of the sheet). A yellow trap occurs whenever dual through greens are not terminated simultaneously. In the case of the lead/lag, protected/permissive phase sequence, circular greens

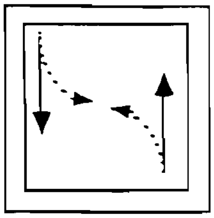
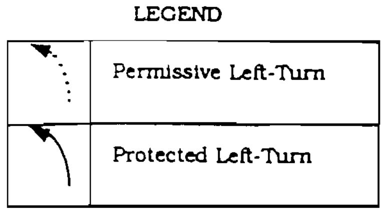


Figure 1.1 Permissive Only Phasing



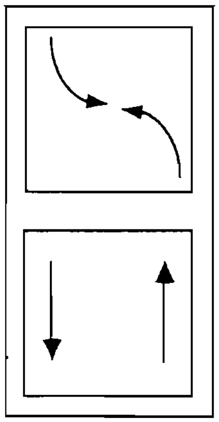


Figure 1.2 Leading Protected Only Phasing

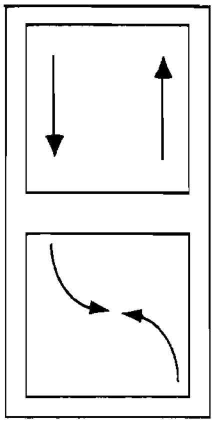


Figure 1.3 Lagging Protected Only Phasing

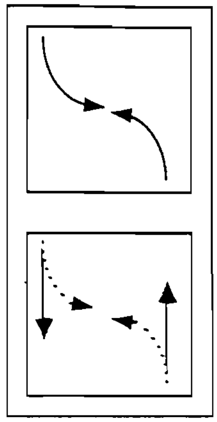


Figure 1.4 Leading Protected /Permissive Phasing

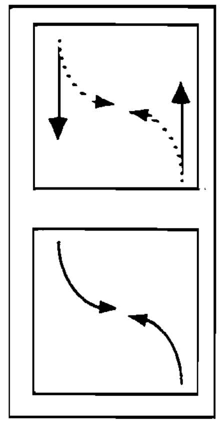


Figure 1.5 Lagging Protected /Permissive Phasing

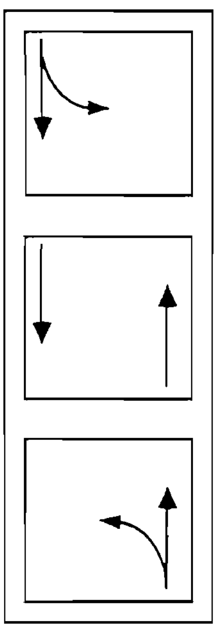


Figure 1.6 Lead/Lag Protected Only Phasing

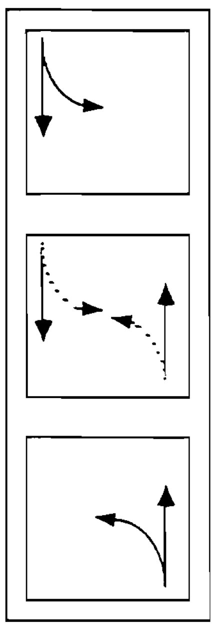


Figure 1.7 Lead/Lag Protected /Permissive Phasing

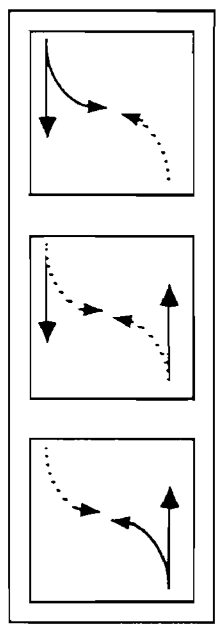


Figure 1.8 Dallas Phasing

are shown for the throughs and lefts in both directions during the dual through movement. Before displaying a green arrow for the northbound left, the southbound throughs and lefts are shown a circular yellow. Any southbound left-turning traffic which had been unable to find a gap in the northbound (opposing) traffic would likely try to turn during the yellow. Unfortunately, the circular green is still shown to the northbound traffic, and the yellow trap is created.

The yellow trap can be eliminated in any of the following ways:

- Convert the leading left turns (southbound in figure 1.7) to protected only. The northbound lefts retain the advantages of protected/permissive operation, however, since the display and signal head requirements for protected only and protected/permissive are different, the lead/lag operation could not be reversed, i.e., northbound leading and southbound lagging, thus reducing its flexibility in accommodating other traffic patterns.
- Use protected-only operation, as shown in figure 1.6. The flexibility to switch to other sequences is retained, but neither approach receives the advantages of protected/permissive operation.
- At several locations in Ector County, Texas, strict protected/permissive operation was retained, as shown in figure 1.7, but an auxiliary sign was added for the approach with the leading protected left (southbound in the figure). The sign message was "NO LEFT TURN ON (symbolic yellow ball)." This sequence/sign combination was only used on low volume approaches, and none were included in this study. This particular solution for the yellow trap is not recommended.
- A special sequence, developed in Dallas (figure 1.8), solves the yellow trap problem, retains protected/permissive operation in both directions, and has the flexibility needed to accommodate different phase sequences. In this sequence, a circular green (indicating permissive lefts) is shown only to left-turning traffic when the opposing throughs have green and the opposing lefts have a green arrow. Thus, the permissive left-turn indication (circular green) will remain when the adjoining through traffic is shown a circular yellow, and will stay

green after the adjoining through is shown red and the opposing lefts have a green arrow. It will go to yellow only when the opposing through traffic gets its yellow, thus eliminating the yellow trap. This sequence is called the Dallas phasing in this study, and the first and last phases (as shown in figure 1.8) are called the Dallas display. It should be noted that implementation of Dallas phasing requires five-section signal heads for the left-turn approaches. The Dallas phasing is described in detail by de Camp and Denney (1992).

Since the yellow trap is created whenever the throughs do not end simultaneously (if they are shown together at any point in the cycle), it will also arise if overlaps are used with the lagging protected/permissive operation (figure 1.5). The yellow trap can be eliminated in this case by any of these four techniques.

While the differences between, say, leading lefts and lead/lag are important in terms of overall intersection or system performance, a driver approaching an intersection sees only the indication shown to that approach. Thus, the driver is unlikely to be able to differentiate between, for example, leading lefts and the leading approach of lead/lag operation. With this in mind, the phase pattern options investigated in this study were strictly approach-based, i.e., the indications and sequences as seen by a left-turning driver approaching the intersection. Thus, the options available to the engineer in selecting phase sequences are:

- permissive only (figure 1.1),
- leading, protected only (figure 1.2 and southbound in figure 1.6),
- lagging, protected only (figure 1.3 and northbound in figure 1.6),
- leading, protected/permissive (figure 1.4 and southbound in figure 1.7),
- lagging, protected/permissive (figure 1.5 and northbound in figure 1.7),
- leading, protected/permissive with Dallas display (southbound in figure 1.8), and
- lagging, protected/permissive with Dallas display (northbound in figure 1.8).

It is unnecessary to consider the effect of overlaps, since they are not detectable by the average driver who sees only one approach.

The overall goal of this study has been to develop guidelines for selection of left-turn phase sequences and auxiliary signs which are least misunderstood and will minimize measures of effectiveness such as delay, accidents, and conflicts.

The objectives of this study have been three-fold:

1. To develop guidelines for the selection of an appropriate left-turn phase pattern for an intersection from among those listed immediately above.
2. To develop recommendations for signal indication sequences under each of the above phasing conditions.
3. To develop guidelines for the use of auxiliary signs with left-turn phasing and signal indications, including possible recommendations on improvements in the design of signs.

The guidelines and recommendations developed have the following attributes:

- maintain continuity and build on previous research studies in this area,
- are based on statistical and traffic engineering analyses of actual field data,
- provide easy to use quantitative measures,
- incorporate motorists' understanding of left-turn signal indications and auxiliary signs, and
- identify the most suitable left-turn phase patterns and signal sequence change for a given set of intersection conditions.

STUDY APPROACH

Data was collected from a number of sites from across Texas incorporating a variety of population characteristics. This has been of particular interest to the study, as the age distribution of the driver population varies from region to region. Other site selection parameters have included intersection geometrics and signal phasing and indications. Such diversification has also led to a reduction in coverage error and has provided a representative sample size of drivers. The five factors considered in site selection were:

1. Geographic Distribution: Nine Texas counties were selected to represent major population centers as well as to provide a wide geographical distribution with varying population characteristics across the state. Also considered in the site selection process were the local left-turn signalization policies and

practices. The selected counties (with their principal cities in parentheses) are: Bexar (San Antonio), Cameron (Brownsville and Harlingen), Dallas (Dallas), Ector (Odessa), Harris (Houston), Lubbock (Lubbock), Nueces (Corpus Christi), Tarrant (Fort Worth), and Travis (Austin) (see figure 1.9).

2. Speed of Opposing Traffic: Six different opposing speed limits commonly found in urban networks, from 30 to 55 mph in 5 mph increments, have been considered in the selection of study sites.
3. Number of Left-turn Lanes: Two conditions were examined: single and double left-turn lanes. One case with three left-turn lanes is also included.
4. Number of Opposing Lanes: Four conditions were addressed, namely, one, two, three, and four opposing lanes. The latter condition was difficult to find and is represented at only a few intersections.
5. Phase Pattern: Seven phase sequences were studied. These were permissive only; leading, protected only; lagging, protected only; leading, protected/permissive; lagging, protected/permissive; leading, protected/permissive with Dallas display; and lagging, protected/permissive with Dallas display.

Intersections representing as many of the combinations of these five factors as possible were selected for study. Unfortunately, a number of the factor combinations did not exist in some counties, in particular, those with populations below 300,000 (Cameron, Ector, Lubbock, and Nueces).

Left-turn operations at each of the selected sites were video-taped for one hour during peak periods. The information on the videotapes was reviewed and reduced to obtain the following for each site:

- left-turn volume,
- opposing volume,
- number of conflicts involving left-turn vehicles,
- vehicle mix for left-turning traffic,
- average left-turn delay, and
- average overall intersection delay.

Other site-specific data, such as signal indication sequence and available sight distance for both opposing and left-turning traffic, were also determined for each

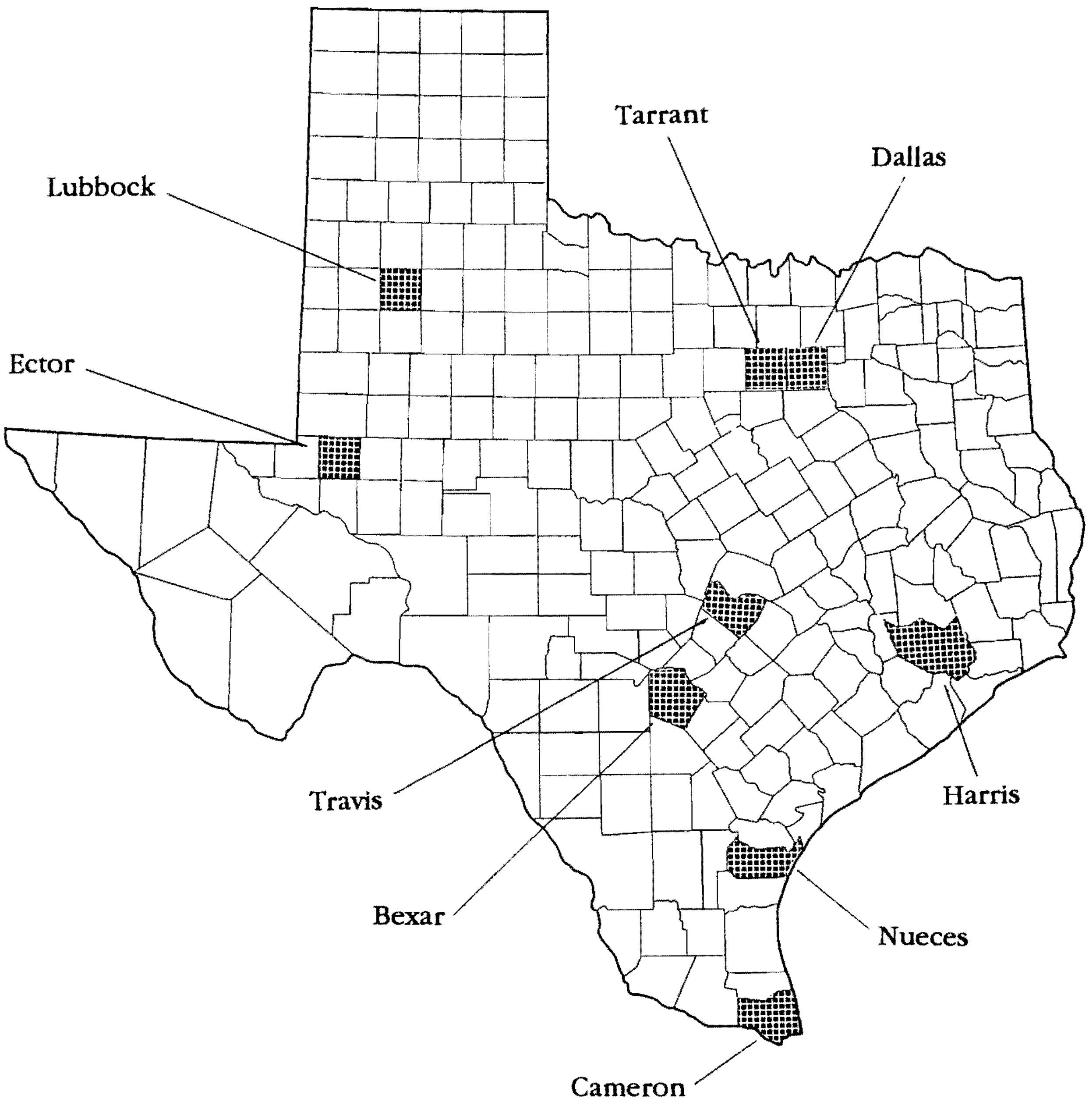


Figure 1.9. Counties Selected for Data Collection.

intersection. The fraction of drivers over age 65 was obtained from the 1990 census data for each of the nine counties.

The collected data were grouped into three sets of variables:

- design variables,
- measures of effectiveness, and
- decision variables.

Design variables are those design aspects of left-turn treatments for which guidelines and recommendations are to be developed. The three design variables are:

- type of left-turn phasing,
- sequence of signal indications, and
- auxiliary left-turn sign.

Measures of effectiveness (MOEs) are those variables through which the performance of the intersection is to be assessed. They are various types of delays, total accident or accident rates, and conflict rates. Thus, the objective is to select a set of design variables for which these MOEs are minimized.

The design variables are selected by determining threshold values for a set of easy-to-measure surrogate variables referred to as decision variables. The decision variables for this particular problem may, for example, include opposing and left-turn volumes, number of opposing and left-turn lanes, sight distance, speed limit, vehicle mix, progression in a coordinated system, and intersection geometry.

Following this approach, selection criteria based on a systematic procedure using easy-to-obtain data are developed. This report is a description of field studies and data collection procedures and analyses which have led to the development of these guidelines. The report consists of eight main chapters and two appendices. This chapter has included a brief description of the problem, project objectives, and an outline of the approach taken to accomplish the objectives. Chapter 2 reviews previous research studies in this area conducted in several states including Texas. A detailed description of the findings and shortcomings of those studies is also presented. Chapter 3 describes the survey on motorist understanding of left-turn signal indications and auxiliary signs. The survey design, results, and recommendations are discussed. Chapter 4 contains the observational design and reduction aspects of the field studies. Data analysis of the field observations are presented in Chapter 5. Phase pattern selection criteria based on decision variables, excluding the safety considerations, are also included in Chapter 5. Chapter 6 comprises of accident and conflict studies; phase pattern selection based on operational safety is also presented. The recommended guidelines incorporating motorist understanding, operational safety, intersection performance, and geometrics are contained in Chapter 7. Conclusions, recommendations, and future directions are discussed in Chapter 8. This report contains two appendices; the first contains a complete set of questionnaire sheets used in the motorist survey, and a complete list of intersections used in the data collection effort are in the second appendix.

CHAPTER 2

LITERATURE REVIEW

A detailed review of previous research on guidelines for the selection of left-turn phasing, indication sequences, and auxiliary signs was undertaken. The focus of previous research in this area has been on the development of guidelines for left-turn phasing and not on selection of indication sequences and auxiliary signs. Most of these studies have used accidents and delays as criteria. In most cases, either a subset of the factors involved were studied and/or sample sizes were very small, making the conclusions limited in scope. Left-turn studies undertaken in various states include those in Kentucky (Agent & Deen 1979 and Agent 1985), Texas (Machemehl & Lin 1982 and Machemehl & Mechler 1983), Arizona (Upchurch 1985), Florida (Florida ITE 1982), and Virginia (Cottrell 1986). Through these studies, a number of guidelines have been formulated for selecting among three types of left-turn phasing, namely,

- permissive,
- protected/permissive, and
- protected only.

Agent and Deen (1979) surveyed 45 states to assess the procedure used in each state to determine left-turn treatment. They concluded that only six of the 45 states had numerical warrants for left-turn phasing. Upchurch (1986) also reported considerable variation in the procedure for selection of left-turn phasing, not only among states, but also across jurisdictions within a state. Machemehl & Lin (1982) developed an elaborate set of measures of performance to aid in the selection of left-turn phasing. A series of nomographs was developed, based on TEXAS model simulations (Lee, Rioux, & Copeland 1977), as guidelines on whether or not protected left-turns were justified. The suggested measures of performance included:

- average left-turn queueing delay,
- 90% left-turn queueing delay,
- percent of left-turns delayed more than two cycles in one hour, and
- number of left-turns delayed more than two cycles in one hour.

A computer routine, LTAP (1989), was developed to provide quick application of these guidelines.

Additionally, Upchurch (1985), through an analysis of 45 hours of time-lapse film at six intersections, developed decision guidelines for selecting left-turn phasing based on the following criteria:

- cycle length,
- product of left-turn and opposing volumes (a volume cross product),
- speed of opposing traffic,
- number of opposing lanes, and
- left-turn accidents.

According to Upchurch, left-turn phasing with some protection should be provided when left-turn volume during the peak hour is more than two vehicles per cycle, and the volume cross product is greater than 144,000 $(vph)^2$ and 100,000 $(vph)^2$ for two and three opposing lanes, respectively. Upchurch's study recommended protected/permissive phasing unless

- the opposing speed is greater than 45 mph, or
- there are three or more opposing lanes, or
- sight distance is restricted, or
- a severe accident problem exists.

However, Upchurch did not consider G/C ratios, double left-turn lanes, overall intersection delay, and sneakers in protected/permissive treatment versus permissive only or protected only phasing patterns.

Cottrell (1986) also developed guidelines for the use of protected/permissive left-turn phasing. Data were collected at 45 sites in Virginia, including 20 with protected/permissive lefts, 15 with protected only lefts, and 10 with permissive only lefts. Based on these field observations, specific guidelines were developed using the following criteria:

- left-turning and opposing volumes,
- left-turn accidents,
- traffic conflicts,
- site geometric conditions, and
- delay-accident trade-offs.

Protected/permissive phasing was recommended by Cottrell for consideration when all of the following conditions are met:

- peak hour volume cross product is between 50,000 $(vph)^2$ and 200,000 $(vph)^2$, and the left-turn volume exceeds two vehicles per cycle,
- average peak hour delay for left-turns exceeds 35 sec/veh and the total peak hour left-turn delay exceeds two vehicle-hours (with permissive lefts only),
- adequate sight distance,
- no more than two opposing lanes,
- good intersection geometrics and good access management, and
- annual protected/permissive delay less than that of protected only phasing.

Cottrell's recommendations are considerably more elaborate than the guidelines by Upchurch, but include all the variables used in Upchurch's study. In addition, Cottrell leaves room for engineering judgement. However, Cottrell studied only leading lefts, and did not include double left-turn lanes among the 45 sites considered.

Another significant study in this field was undertaken by the Florida Section of ITE (1982). Accident analyses were conducted at 17 approaches that were converted from protected only to protected/permissive operation. The average annual left-turn accident totals per approach increased from 0.5 to 2.5 while the average annual accident totals for non-left-turn accidents increased from 12 to 14.5. At 11 other sites, where the phasing was changed from protected/permissive to protected only, the average annual left-turn accident totals per approach dropped from 5 to 2.5, and the average annual accident totals for non-left-turn accidents increased from 19 to 31.5. The authors concluded that the large decrease in left-turn accidents at the latter 11 intersections suggested that protected/permissive phasing was inappropriate for those intersections. It should be noted that these differences were not tested for statistical significance.

The guidelines developed by the Florida Section of ITE are presented below. The report stated that protected/permissive phasing should be provided for all intersection approaches for which protected lefts are provided unless there is a compelling reason for using protected only phasing. Conditions where protected only phasing was recommended include the following:

- a double left-turn lane,
- restrictive intersection geometry requiring protected only,

- restricted sight distance,
- the leading left of a lead/lag phasing sequence,
- speed limit of opposing traffic greater than 45 mph,
- three or more opposing lanes, and
- more than six left-turn accidents in one year on the approach with protected/permissive phasing.

The Florida Section of ITE recommendations are comprehensive and consider intersection geometry, neglected in many of the previous studies. Their recommendations also leave room for engineering judgement. Even though delay was mentioned as one of the advantages of the use of protected/permissive phase patterns, the final recommendations do not mention delay and how it can be incorporated into the procedure for left-turn phasing selection. The study also does not consider vehicle mix and its impact on left-turn operations.

Hummer, Montgomery, & Kumares (1990 & 1991) developed guidelines for the use of leading and lagging left-turn signal phasing through a survey of licensed drivers in Indiana, an examination of traffic conflicts and accidents, and traffic simulation. Their recommendations generally are in agreement with already documented findings on the use of leading and lagging left-turns. However, this study also fails to consider double left-turn lanes, which are being increasingly used.

Collins (1988) compared delay to left-turning vehicles under two different lead/lag phasing arrangements, specifically, the conventional lead/lag protected/permissive (figure 1.7) and a special lead/lag operation known as the Dallas phasing (figure 1.8). The Dallas phasing differs from conventional protected/permissive lead/lag in that permissive left turns are allowed when the opposing left turn is protected, thus avoiding the yellow trap. Using the TEXAS simulation model for six different cases (which are unique combinations of cycle lengths and phase length arrangements), several traffic volumes were tested for each case. Two cycle lengths, 60 and 90 seconds, a left-turn volume of 300 vph, and opposing volumes ranging from 200 vph to 1500 vph were used in the simulation. The following observations were made regarding the two different lead/lag arrangements:

- the Dallas phasing produces less left-turn delay,

- a significant reduction in left-turn delay is observed for the Dallas phasing for opposing volumes less than 1000 vph (above this volume reduction in delay is small, as there are not enough gaps for left-turners to filter through),
- reduced delay for vehicles in the direction with the leading protected turn of the Dallas phasing is more significant than for those with the lagging protection, and
- benefits which can be realized from the leading and lagging phases of the Dallas phasing are dependent on the magnitude of the opposing volume and the G/C for the through traffic.

Collins' study was limited in that it relied solely on simulation data and also did not consider double left-turn lanes, vehicle mix, and other than two opposing lanes. His study concentrated on delay, hence further research on the safety aspects of these two phasing arrangements is needed for a better assessment of their performance.

Fambro (1991) also studied the Dallas phasing and developed modeling parameters for use with this type of phasing. Field data were collected at four sites in Dallas during peak and off-peak periods. Four hours of observations were made during both peak and off-peak periods for each intersection using video, electronic, and manual data collection systems. PASSER II was used to evaluate the 360 different combinations of two left-turn phase sequences (Dallas and conventional protected/permissive, lead/lag lefts), two cycle lengths (90 and 120 seconds), three G/C ratios (0.4, 0.5, and 0.6), five left-turn volumes (100-300 vph in 50 vph increments), and six opposing volumes (300-800 vph per lane in 100 vph increments). Fambro's findings were generally in agreement with the conclusions in Collins' study.

Brookes, Collins, & Haenel (1991) examined the safety aspect of Dallas phasing. A two-year before and after accident study at 27 intersections which were converted to Dallas phasing from conventional protected or protected/permissive phase patterns showed a 23% reduction in total accidents for all the intersections involved.

The studies reviewed herein have largely concentrated on whether a protected left-turn phase is to be used, and, if so, the type of phasing to use (protected only or protected/permissive). The above studies, however, do not offer guidelines for decisions on

- left-turn phase sequence (i.e., leading, lagging, or lead/lag),
- signal indications (e.g., green arrow-circular red, followed by yellow arrow-circular red, followed by circular green), and
- auxiliary left-turn signs (e.g., LEFT TURN YIELD ON GREEN [symbolic green ball] (MUTCD sign R10-12), LEFT TURN ON ARROW ONLY (MUTCD R10-5), etc.).

In general, these studies are either based on a small number of intersections or on simulation only. Furthermore, no discussions are offered on safety implications and motorist understanding of each of the above options. Drivers' understanding of the left-turn signal indications and auxiliary signs are particularly crucial in light of the increased aging of the U.S. driver population (TRB Special Report 218, 1988).

This study has involved detailed data collection at over 100 signalized intersections in Texas representing the seven left-turn phasing sequences, namely:

- permissive only,
- leading, protected only,
- lagging, protected only,
- leading, protected/permissive,
- lagging, protected/permissive,
- leading, protected/permissive with Dallas display, and
- lagging, protected/permissive with Dallas display.

The data collection and analysis concentrate on documenting the responses of drivers to the above phasing patterns as well as different signal indication sequences. In addition, accident data are analyzed for the intersection sites under study. The objective has been to correlate MOEs such as total accidents, conflict rates, the drivers' level of understanding, operational efficiency under the various left-turn phase patterns, and signal indications to the following decision variables:

- speed,
- number of left-turn lanes,
- number of opposing lanes,
- sight distance available to both left-turn and opposing traffic,
- driver age distribution,

- left-turn volume,
- opposing volume, and
- G/C values.

In the experimental design, special effort has been made to address the major shortcomings of the previous studies. A large number of drivers were surveyed and a sufficiently large sample of intersections with a variety of geometric conditions and left-turn treatments were selected. The experimental design was formulated to specifically include those situations which have not been addressed in prior studies, i.e., those with more than two opposing lanes, more than 45 mph opposing speeds, and more than one left-turn lane. A number of sites with Dallas phasing are also included in the study.

CHAPTER 3

DRIVER SURVEY

A left-turn at a signalized intersection is the most difficult maneuver for drivers and the most challenging aspect of signal design. Once the decision whether to provide protection is made, the traffic engineer must decide how to effectively communicate this message to the motorist. Rules for the use of specific signal indications and auxiliary left-turn signs, intended to supplement the appropriate signal head, are provided in the Manual on Uniform Traffic Control Devices (MUTCD 1988). State MUTCDs (e.g., Texas MUTCD 1980) may also provide additional guidance and/or options. The traffic engineer can then use a combination of signal indications and auxiliary signs used in that particular city or region, under the assumption that, since it is already in use, the motorists understand it.

As a result, a myriad of signal indications and auxiliary left-turn signs are in use for similar situations in different cities. Often significant differences exist even among cities within a metropolitan area. It is, therefore, imperative that, as part of this study, the motorists' understanding of signal indications and auxiliary signs be examined. To this end, a survey was mailed to randomly-selected Texas motorists. The next two sections of this chapter describe the survey design and the selection of sample sizes. Results are detailed in the following sections, first with respect to the demographic information requested in the questionnaire, then with responses to individual indication/sign combinations. Finally the results are summarized and specific recommendations are made concerning the use of signal indications and auxiliary signs.

SURVEY DESIGN

When motorists intend to turn left at a signalized intersection, they must first decide whether the left turn is prohibited during the current signal interval, and, if not, whether the left-turn is protected or permitted. The survey questionnaire assumed the driver was in a left-turn bay approaching a signalized intersection. Details of the intersection geometrics, and position and size (3- or 5-section) of the signal heads were shown in a sketch at the top of each page of the questionnaire. There were four combinations of geometrics and size (number of lenses) and position of signal heads:

Type 1. No median; five-section head at the end of the mast arm over the left-turn bay, three-section head over the through lanes and a pole mounted three-section head.
Type 2. No median; same as Type 1, with a three-section head at the end of the mast arm.
Type 3. Same as Type 2, except no pole-mounted signal head.
Type 4. Raised median; three-section, pole-mounted head facing the left-turn bay.

A sketch of each respective geometry is shown in tables 3.1A through 3.1D.

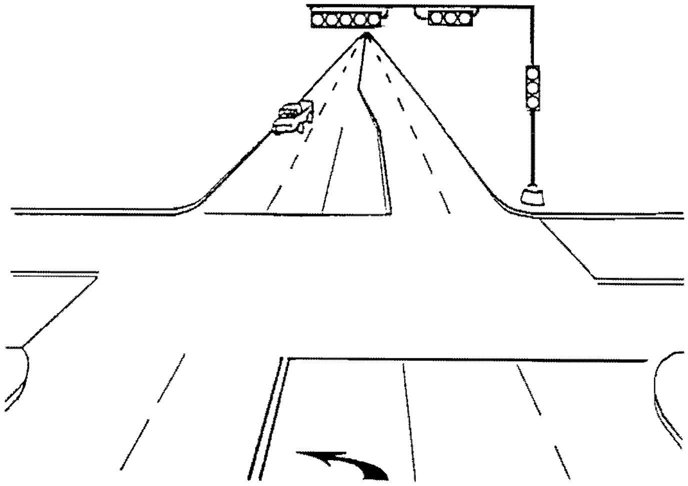
The eighteen signal indications chosen for use in the questionnaire are shown in figure 3.1. Eleven left-turn auxiliary signs were selected for inclusion in the survey and are numbered as shown in figure 3.2. Each sign can be found in the 1988 MUTCD, the Texas 1980 MUTCD, and/or on the street in at least one Texas city.

Each questionnaire page consisted of the following:

- intersection sketch, selected from tables 3.1A through 3.1D,
- signal indications, selected from figure 3.1, including, in some cases, a left-turn auxiliary sign, selected from figure 3.2,
- questions asking the motorist if left-turns were allowed during the particular conditions shown, and, if so, whether the left-turns were protected or permitted,
- a second set of signal indications and, in some cases, a left-turn auxiliary sign, and
- the same set of questions as those under the first set of signal indications.

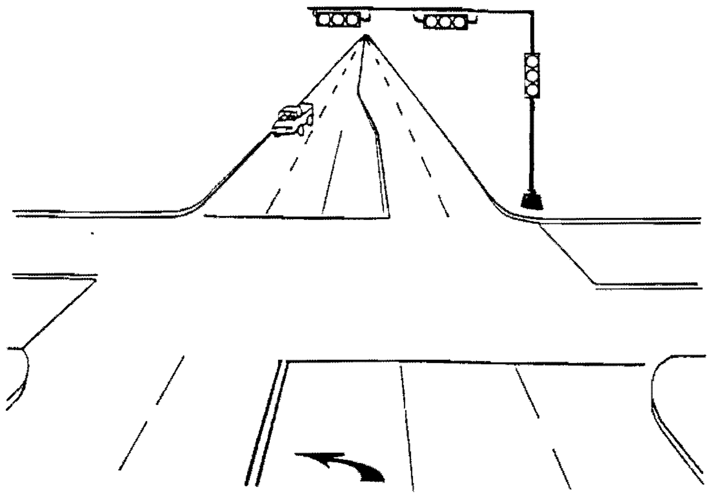
An example questionnaire form is shown in figure 3.3. Note that both sets of signal indications correspond to the signal heads in the sketch at the top of the page. Also, if a sign is used with a particular signal indication, one is shown in the sketch next to the appropriate signal head.

At a first glance, there would appear to be 864 potential combinations (4 intersection geometric cases x 18 signal indication cases x 12 auxiliary sign cases, including the no sign case). However, since each sign corresponds to only certain indications, and specific indications correspond to specific sketches, many of these potential combinations can be eliminated.



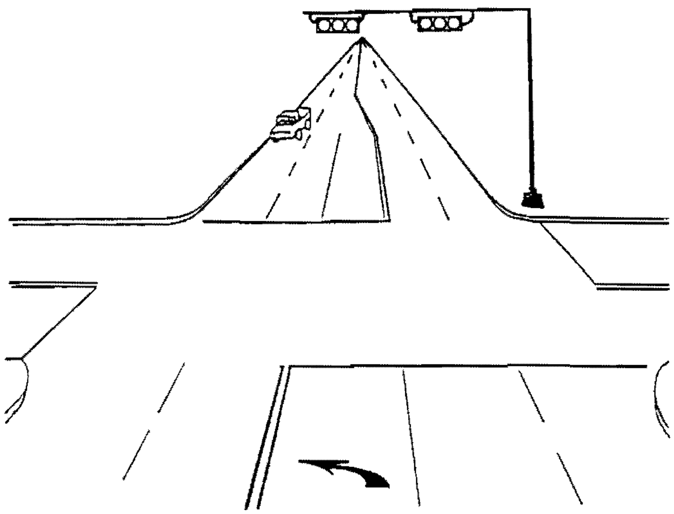
Signal Display	Sign	Scenario	No. of Responses	% Inconsistent	% Wrong	% Incorrect
Ⓖ Ⓖ Ⓖ	None	1	79	10	15	25
Ⓖ Ⓡ Ⓡ	None	2	93	5	29	34
Ⓖ Ⓡ Ⓡ	Left Turn Yield on Green ● (6)	3	92	3	11	14
Ⓖ Ⓖ Ⓖ	Left Turn Protected on Arrow Only (8)	4	86	11	13	24
Ⓡ G← Ⓡ Ⓡ	None	11	79	2	21	23
G← Ⓖ Ⓖ	None	12	93	5	8	13
G← Ⓖ Ⓖ Ⓖ	None	13	80	6	13	19
G← Ⓡ Ⓡ	None	14	80	6	14	20
G← Ⓖ Ⓖ Ⓖ	Protected Left on Green Arrow (2)	15	91	2	6	8
Ⓡ G← Ⓡ Ⓡ	Left Turn Signal (7)	16	93	1	33	34
G← Ⓖ Ⓖ	Protected Left Turn on Arrow Only (9)	17	93	1	17	18
G← Ⓡ Ⓡ	Protected Left Turn on Green Arrow Only (11)	18	86	1	4	5

Table 3.1A. Description and Responses for Type 1 Geometry.



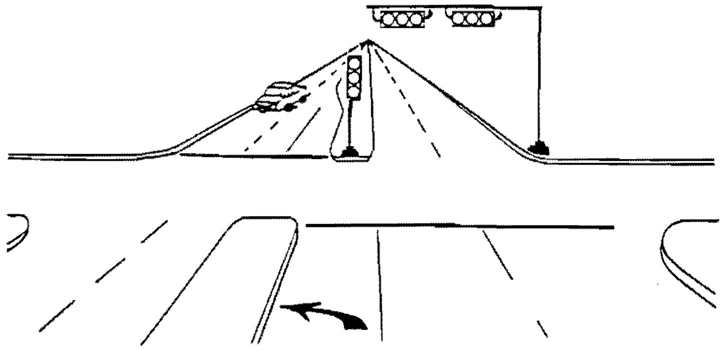
Signal Display	Sign	Scenario	No. of Responses	% Incon-sistent	% Wrong	% Incorrect
Ⓖ Ⓖ Ⓖ	None	5	102	3	29	32
Ⓖ Ⓡ Ⓡ	None	6	83	4	27	31
G← Ⓡ Ⓡ	None	19	83	4	13	17
G← Ⓖ Ⓖ	None	20	109	5	11	16
G← Ⓡ Ⓡ	Left Turn Signal (7)	21	81	6	11	17
G← Ⓖ Ⓖ	Left Turn on Arrow Only (1)	22	82	6	14	20
Ⓖ Ⓡ Ⓡ	Left Turn Signal (4)	23	73	3	39	42
Ⓖ Ⓖ Ⓖ	Left Turn Signal (4)	24	96	6	59	65
Ⓡ Ⓖ Ⓖ	None	33	103	16	8	24
R← Ⓖ Ⓖ	None	34	110	17	16	33
R← Ⓖ Ⓖ	Left Turn Signal (7)	35	75	20	32	52
Ⓡ Ⓖ Ⓖ	Left Turn on Arrow Only (1)	36	95	19	2	21

Table 3.1B. Description and Responses for Type 2 Geometry



Signal Display	Sign	Scenario	No. of Responses	% Incon-sistent	% Wrong	% Incorrect
Ⓖ Ⓖ	None	7	88	9	13	22
Ⓖ Ⓖ	Left Turn Yield on Green ● (6)	8	80	4	9	13
Ⓖ Ⓖ	Left Turn on Green After Yield (10)	9	80	4	14	18
Ⓖ Ⓖ	Protected Left on Green (3)	25	89	7	36	43

Table 3.1C. Description and Responses for Type 3 Geometry.



Signal Display	Sign	Scenario	No. of Responses	% Inconsistent	% Wrong	% Incorrect
Ⓖ Ⓖ Ⓖ	None	10	84	2	48	50
Ⓖ Ⓡ Ⓡ	None	26	107	2	45	47
G← Ⓡ Ⓡ	None	27	96	5	4	9
G← Ⓖ Ⓖ	None	28	95	5	22	27
G← Ⓡ Ⓡ	Left Turn Signal (4)	29	103	10	7	17
G← Ⓖ Ⓖ	No Turn on Red (5)	30	103	6	25	31
G← Ⓡ Ⓡ	Left Turn Signal (7)	31	92	4	10	14
G← Ⓖ Ⓖ	Left Turn Signal (7)	32	69	9	14	23
R← Ⓖ Ⓖ	None	37	107	15	14	29
Ⓡ Ⓖ Ⓖ	None	38	87	7	6	13
R← Ⓖ Ⓖ	Left Turn Signal (4)	39	91	19	12	31
Ⓡ Ⓖ Ⓖ	No Turn on Red (5)	40	68	15	13	28

Table 3.1D. Description and Responses for Type 4 Geometry.

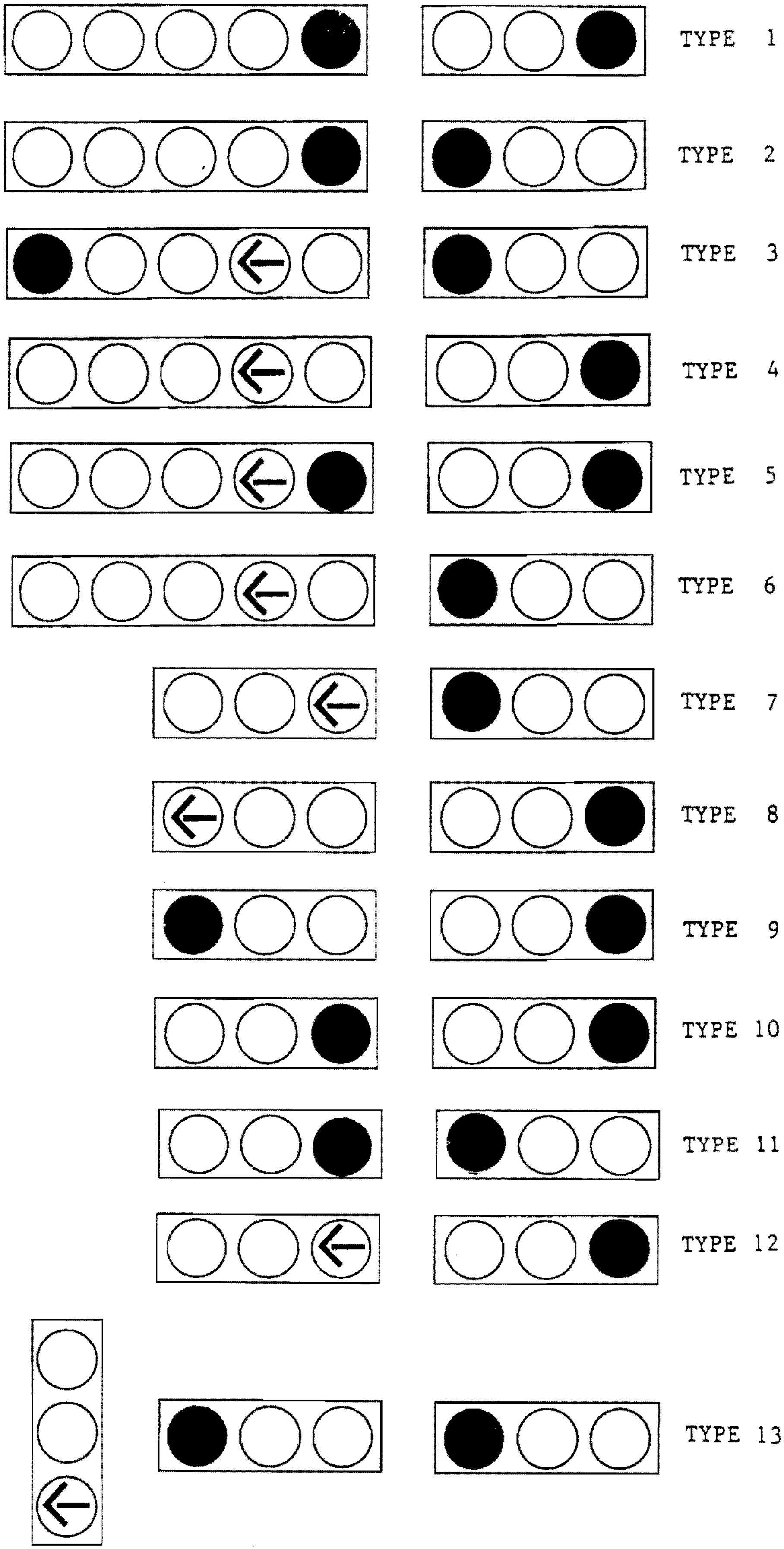


Figure 3.1 Signal Indications

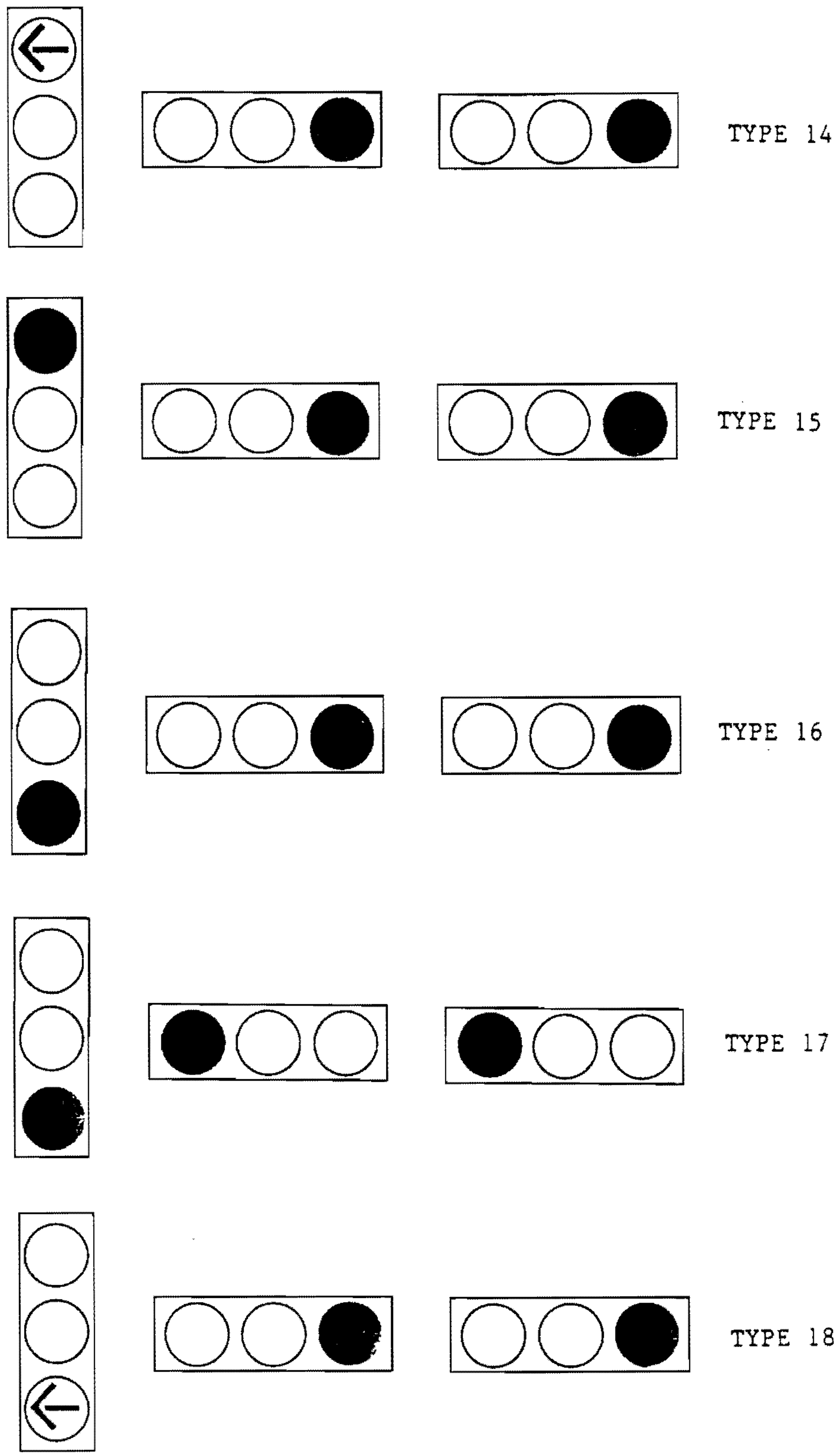


Figure 3.1 (continued)

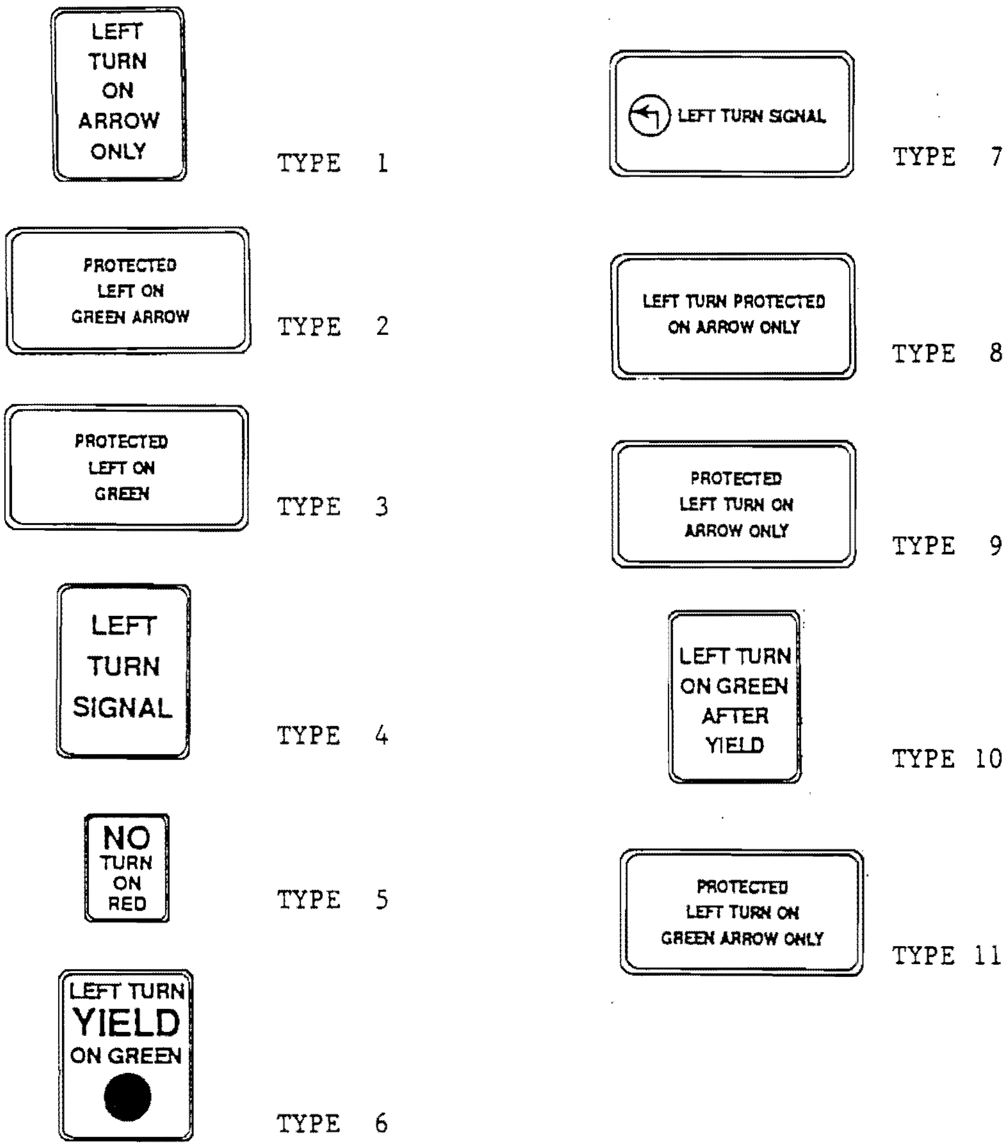
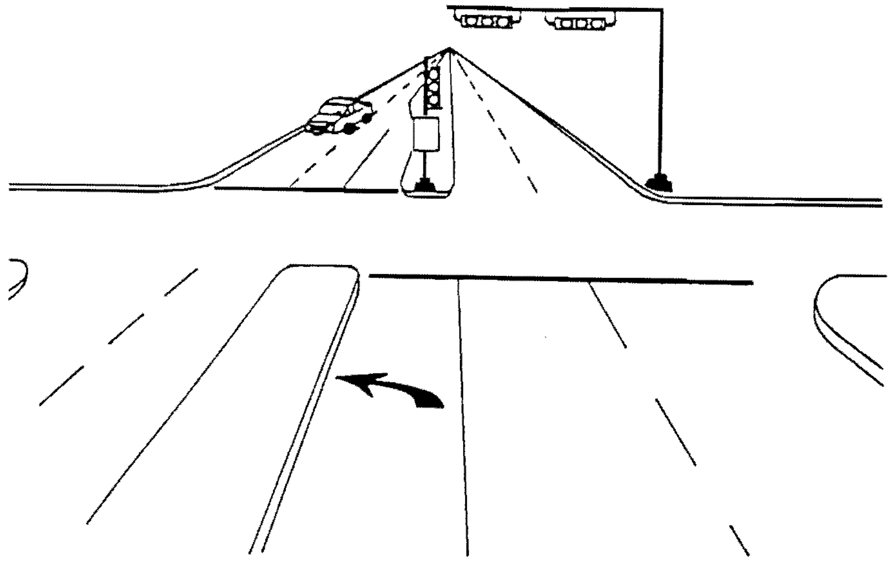
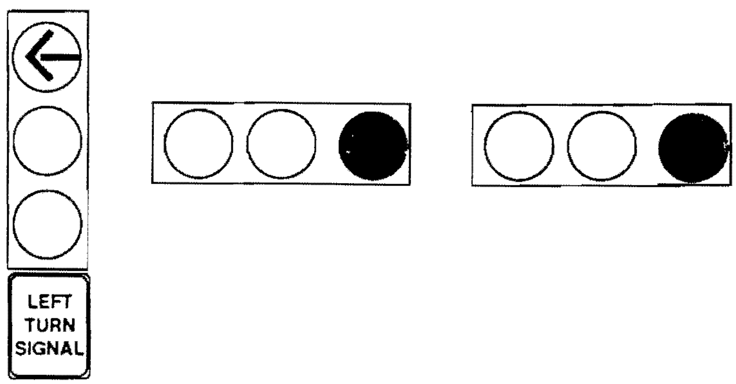


Figure 3.2 Left-turn auxiliary signs.

8-14-4
8-17-7





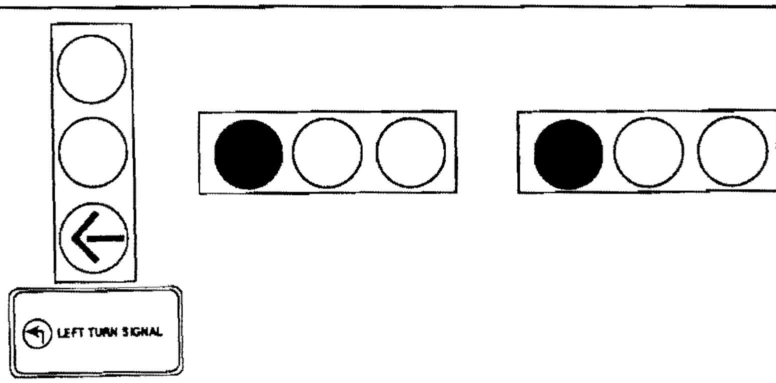
If you are waiting to turn left and see the above signal indication:

1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

   ☐ You must wait for a large enough opening in the oncoming traffic.

   ☐ You may turn if the intersection is clear, since the oncoming traffic must stop.



If you are waiting to turn left and see the above signal indication:

1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

   ☐ You must wait for a large enough opening in the oncoming traffic.

   ☐ You may turn if the intersection is clear, since the oncoming traffi

Figure 3.3 Questionnaire Sheet.

A total of forty combinations were selected after eliminating impracticable combinations and those that are not used in Texas. All the forty combinations are in use in at least one Texas city. The selections were made to include the common combinations in use in many counties as well as those that are uncommon or used only in one or two counties. These scenarios were found to provide both a wide coverage and a representative sample of all the indications and auxiliary sign combinations observed in the field. A complete set of the forty combinations is included in Appendix A. The combinations are also shown in tables 3.1A through 3.1D. Since two scenarios appeared on each sheet (figure 3.3), a total of twenty sheets were required for the forty scenarios.

One portion of the survey contained several demographic questions and is shown in figure 3.4. The following information was sought from each respondent: sex, age, driving experience, level of education, and language spoken at home. In total, the following was mailed to each survey recipient:

- cover letter describing and providing instructions for the survey,
- two non-identical questionnaire sheets, an example of which is shown in figure 3.3; thus, each recipient was requested to respond to four scenarios,
- demographic sheet (figure 3.4), and
- post-paid return envelope.

Also, the first questionnaire page was stamped with the name of the county in which the recipient resided. Approximately the same number of each questionnaire sheet were sent to each county, and the number of responses (shown in tables 3.1A through 3.1D) indicate the number of each scenario returned. While two scenarios were included on each questionnaire sheet (i.e., four to each recipient), occasionally one or more scenarios were left unanswered.

SAMPLE SIZE SELECTION

Initially, a pilot survey was sent to 150 addresses in the Dallas-Fort Worth metropolitan area in order to fine tune the questionnaire and to estimate the response rate. The 150 addresses were randomly selected from zip codes within the metroplex. The selection was made to provide a wide coverage and also a fairly representative sample

Finally, we need some general information about you to help us classify your responses. Remember, do not sign this form.

Sex

- ☐ Female
- ☐ Male

Age

- ☐ 25 or under
- ☐ 26 to 35
- ☐ 36 to 45
- ☐ 46 to 55
- ☐ 56 to 65
- ☐ 66 to 75
- ☐ 76 or over

How many years have you been driving?

- ☐ 5 or less
- ☐ 6 to 10
- ☐ 11 to 20
- ☐ 21 to 30
- ☐ 31 to 40
- ☐ 41 to 50
- ☐ 51 or more

How many years of school have you attended?

- ☐ Less than 12 years
- ☐ High school degree
- ☐ Some college work
- ☐ Associates degree
- ☐ Bachelors degree
- ☐ Some post-graduate work
- ☐ Graduate degree

What language do you speak at home?

- ☐ English
- ☐ Other (specify:_________)

Thank you very much for taking the time to complete our survey. Your response is an important part of our research project. Please put these forms in the prepaid envelope and drop it in a mailbox.

Figure 3.4. Demographic Information Sheet.

by including as many different zip codes as possible. Since it was believed that inclusion of the demographic questions might affect the response rate, half the preliminary surveys were sent without the demographic sheet. The response rate was about 35% with no statistically significant difference between those with demographic questions and those without. The questionnaire sheets were therefore left unchanged, but the cover letter was revised to better describe the survey.

The full survey was sent to addresses in the nine Texas counties listed in Chapter 1, which ranged from the most populous county in the state, Harris, which includes Houston, to ones containing cities with populations of about 100,000. Assuming a 25% response rate, a 95% confidence interval, and a tolerance of 2.5%, a sample size of 6000 was calculated as shown below:

$$n = \frac{p\,(1-p)\,z^2}{T^2\,R} ,$$

where n = sample size,

p = 0.5 (fraction of incorrect responses, yielding largest variance),

T = 0.025 (tolerance),

z = 1.96 (95% confidence interval), and

R = 0.25 (response rate).

The number of surveys mailed to each county is shown in table 3.2, along with the principal city or cities in each county, each county's population (which was used to proportion the number of surveys mailed to each county (Texas Almanac 1990-91)), and the response rate. The number of surveys mailed to each county was proportioned by the population of the county. The population of each city and town in each of the counties was found from the census data. The number of surveys mailed to each zip code within each county was proportioned by these city and town populations. Surveys destined for cities with more than one zip code were divided evenly among the appropriate zip codes.

County	City	County Population	Surveys Mailed	Respondents*	Response Rate (%)
Harris	Houston	2,782,414	2000	234	11.6
Dallas	Dallas	1,873,624	1300	160	12.3
Bexar	San Antonio	1,186,690	850	148	17.2
Tarrant	Fort Worth & Arlington	1,131,794	800	168	20.9
Travis	Austin	559,173	400	74	18.5
Nueces	Corpus Christi	296,527	200	35	17.5
Cameron	Brownsville & Harlingen	259,409	200	37	18.5
Lubbock	Lubbock	225,527	150	29	19.3
Ector	Odessa	122,309	100	15	15.0
TOTAL			6000	902	15.0

* Four scenarios were mailed to each survey recipient; some respondents did not answer all four scenarios.

Table 3.2. Characteristics of Survey Sample

Survey Quality

There are many different perspectives on the quality of a survey data. The quality of the conclusions and inference from a survey are described by the reliability and validity of the measurements. This is so because high levels of invalidity may be as fatal to the quality of one's inferences as a poor sample or low response rate. However, this should not be construed to mean that good sample sizes and high response rates are not important. Grove (1989) classifies survey errors into the following:

- Coverage error results from failure to include some population elements in the population list.
- Sampling error results from the fact that only a subset of the population was used to represent the population rather than the population itself.
- Nonsampling error results from failure to obtain data from all population elements selected into the sample.
- Measurement error occurs when the recorded or observed value is different from the true value of a variable.

The presence of any of these types of errors can influence the accuracy of the inferences or conclusions made. Attempts must be made to minimize these errors, or their effect on the conclusions drawn, through development and testing techniques that will improve the quality of the collected data. Such techniques as sampling, question-wording effect, and method of measurements are necessary to improve on the quality of the survey and conclusions made.

RESULTS

The quality of a survey is partially judged by the error rate on the questions testing the motorists' understanding. Error rate is defined as the percentage of responses per scenario that were either inconsistent, incompatible, or incomprehensible. Such errors measure the wording-effect and general comprehension of the questionnaire. Inconsistent/incompatible responses include the following:

- Respondent replies "YES" a left turn can be made, but does not indicate if one is allowed to make a protected or permitted left-turn.
- Respondent replies "NO" implying no turning is allowed, but continues to indicate that one can either make a protected or permitted left-turn.

The error rate for the forty scenarios are grouped into three categories: the type of phasing, circular red, and red arrow indications. The results are as shown in table 3.3, with summary statistics presented in table 3.4.

The error rate for the 32 scenarios involving indications and auxiliary signs (other than red arrow or circular red indications alone) had very low error rates. This low error rate (5%) indicates the quality of the survey, in terms of its wording and motorists' comprehension of it.

Protected Only (Special Case)				Permissive Only		Protected/ Permissive		Protected Only	
Red Arrows		Circular Red							
Scenario	%	Scenario	%	Scenario	%	Scenario	%	Scenario	%
34	17	33	16	5	3	1	10	10	2
35	20	36	19	6	4	2	5	19	4
37	15	38	7	7	9	3	3	20	5
39	19	40	15	8	4	4	11	21	6
				9	4	11	2	22	6
						12	5	23	3
						13	6	24	6
						14	6	25	7
						15	2	26	2
						16	1	27	5
						17	1	28	5
						18	1	29	10
								30	6
								31	4
								32	9

Table 3.3. Error Rate for the Forty Scenarios Grouped by Phasing Type and Circular Red and Arrow Indications. Note That These Percentages Include Only Those With Inconsistent Responses.

Group	No. of Scenarios	Mean (%)	Std Dev (%)
Protected Only	15	5	2
Prot/Perm	12	4	3
Permissive Only	5	5	3
Circular Red	4	14	5
Red Arrow	4	18	2
TOTAL	40		

Table 3.4. Summary Statistics on Error Rates for the Forty Scenarios. Note That These Percentages Include Only Those With Inconsistent Responses.

On the other hand those eight scenarios involving either only a red arrow or circular red in the left-turn signal head and circular green for through and right-turning traffic had unusually high error rates: 18% for red arrows and 14% for circular red indications. These eight scenarios signify that no left-turn movement is allowed, while many of the respondents indicated that a permitted turn was possible.

Since the same design was used for all forty scenarios, and the scenarios sent to each recipient were randomly selected, this high error rate can be attributed not to the design of the questionnaire, but rather to the general misunderstanding of red arrows as stop indications. This will be discussed later in this chapter. Analysis of these errors shows that they cannot be neglected by discarding these responses.

The number of responses for each scenario are shown in tables 3.1A through 3.1D. Response to a particular scenario was considered correct only if it was completely free of error. The percentage of incorrect responses for each scenario, broken down into inconsistent and wrong responses, is shown in tables 3.1A through 3.1D. A response was considered wrong only if it was consistent. A discussion of the signs and indications that were particularly misunderstood by many drivers is presented later in this chapter.

Demographic Effects

The demographic factors considered likely to affect the fraction of incorrect responses were

- the number of years of driving experience,
- the age of the respondent, and
- the level of education.

Those who have been driving for 11 to 20 years had the highest percentage of correct responses. Correspondingly, respondents 26-35 years old also had the highest percentage of correct responses. Since the majority of drivers in Texas start to drive in their mid to late teens, this correspondence is to be expected. Higher percentage of incorrect responses were found for less and more experienced drivers (younger and older drivers). Drivers 65 years or older had the highest percentage of incorrect responses. Often these drivers avoid congested traffic areas, since they are generally not working, and may not be as familiar with some indications that have been in use for only a relatively small fraction of their driving life.

A statistical comparison is shown between these categories by the Waller grouping shown in tables 3.5 and 3.6. Waller's test (SAS/STAT 1990) groups categories whose means are not statistically different, thus identifying those which are statistically different. Here the value tested for in each category is the fraction of incorrect responses. All tests were conducted at the $\alpha = 0.05$ significance level. In the case of driving experience (table 3.5), if the groups with higher fractions of incorrect responses are grouped together (group A), only drivers with 11-20 years of driving experience have a significantly lower percentage of incorrect responses.

Similarly, if the categories with lower percentages of incorrect responses are grouped together (group B), only drivers with 41 - 50 years of driving experience have a significantly higher fraction of incorrect responses.

A similar line of reasoning can be followed for the results of Waller's Test on the driver age categories (again at $\alpha = 0.05$), shown in table 3.6. However, the spread in the percent of incorrect responses between categories is large enough to allow three separate groupings, one of lower fraction (group C), one of higher fraction (group A), and one in the middle (group B).

The fraction of incorrect responses with respect to the level of education of the respondent is shown in table 3.7. It should be noted that there is little change in the fraction of incorrect responses once a driver graduates from high school. The drivers with no high school degree belong to one of two groups: very young drivers who are still in high school or drivers who never received a high school degree. Those in the latter group tend to be older drivers, thus both age groups represented here correspond to the higher percent of incorrect responses in tables 3.5 and 3.6. Waller's test is applied here again at $\alpha = 0.05$. In this case, four separate groupings were possible, highlighting, in particular, the higher fraction of incorrect responses by drivers without a high school degree.

Years of Driving	Number of Respondents	Incorrect Responses	Waller Grouping	
≤ 5	33	31%	A	B
6 - 10	74	29%	A	B
11 - 20	226	22%		B
21 - 30	208	24%	A	B
31 - 40	150	26%	A	B
41 - 50	97	32%	A	
≥ 51	96	31%	A	B
No response	18			
TOTAL	902			

Table 3.5. Driving Experience.

Age of Driver	Number of Responsdents	Incorrect Responses	Waller Grouping		
≤ 25	62	25%		B	C
26 - 35	196	20%			C
36 - 45	214	23%			C
46 - 55	147	29%	A	B	C
56 - 65	105	27%	A	B	C
66 - 75	107	35%	A		
≥ 76	47	33%	A		
No response	24				
TOTAL	902				

Table 3.6. Driver Age.

Level of Education	Number of Respondents	Incorrect Responses	Waller Grouping			
≤ 12 years	146	36%	A			
High School	157	28%		B		
Some College	213	22%		B	C	D
Assoc. Deg.	71	28%		B		
Bach. Deg.	121	20%			C	D
Post Grad. Wk.	60	26%		B	C	
Grad. Deg.	107	18%				D
No response	27					
TOTAL	902					

Table 3.7. Level of Education.

Language At Home	Number of Respondents	Incorrect Responses
English	775	24%
Other	100	35%
No response	27	
TOTAL	902	

Table 3.8. Language Spoken at Home.

Sex of Respondent	Number of Respondents	Incorrect Responses
Female	351	30%
Male	524	22%
No response	27	
TOTAL	902	

Table 3.9. Gender.

The language spoken at home was also found to be a significant factor (see table 3.8). While some of the difference may be attributable to a driver's ability to understand an auxiliary sign in English (if present), this factor is likely correlated with the educational level. The fraction of male and female respondents with incorrect responses are shown in table 3.9. These differences are not significant at $\alpha = 0.10$. "No response" in tables 3.5 through 3.9 indicates no response to the particular demographic question.

Discussion of Specific Scenarios

The survey results concerning five separate left-turn indication issues are discussed in this section. They are

1. Use of circular green for protected only left-turns,
2. Simultaneous use of a circular indication and green arrow in a five-section head,
3. Use of auxiliary left-turn signs,
4. Use of red arrows, and
5. Dallas phasing.

1. Use of circular green for protected only left-turns. The circular green indication was used for protected only lefts in scenarios 10 and 23 through 26, and a green arrow was used for protected only lefts in scenarios 19 through 22 and 27 through 32. The percentage of incorrect responses for each scenario are shown in tables 3.10 and 3.11.

Many drivers appear to believe that the circular green indicates a permissive turn, even in the presence of an auxiliary sign indicating left-turn protection. The respondents appear to more consistently understand the use of the green arrow for protected only left-turns.

2. Simultaneous use of a circular indication and green arrow in a five-section head. These indications are used during the protected portion of a protected/permissive operation with a five-section head for the lefts. Some jurisdictions show the same circular indication in all signal heads on the approach, including the five-section head, during the protected turn, while others omit the circular indication in the five-section head. The display of a circular indication and a green arrow can be considered in two cases: (1) protected left when the adjacent throughs + rights have green and (2) protected left

Position of Left Turn Signal Head	Sign	Scenario	Incorrect Responses
Mast arm mounted	LEFT TURN SIGNAL (4)	23	42%
	LEFT TURN SIGNAL (4)	24	65%
	PROTECTED LEFT ON GREEN (3)	25	43%
Post mounted in median	None	10	50%
	None	26	47%

Table 3.10. Use of Circular Green for Protected Only Lefts in Three-Section Heads. Number in Parentheses Following the Sign Legends Refers to the Sign Type in Figure 3.2.

Position of Left Turn Signal Head	Sign	Scenario	Incorrect Responses
Mast arm mounted	None	19	17%
	None	20	16%
	LEFT TURN SIGNAL (7)	21	17%
	LEFT TURN ON ARROW ONLY (1)	22	20%
Post mounted in median	None	27	9%
	None	28	27%
	LEFT TURN SIGNAL (4)	29	17%
	NO TURN ON RED (5)	30	31%
	LEFT TURN SIGNAL (7)	31	14%
	LEFT TURN SIGNAL (7)	32	23%

Table 3.11. Use of Green Arrow for Protected Only Lefts in Three-Section Heads. Number in Parentheses Following the Sign Legends Refers to the Sign Type in Figure 3.2.

when the adjacent throughs + rights have red.

Four scenarios are tabulated in table 3.12 for the first case; scenarios 13 and 15 show a circular green and a green arrow together in a five-section head, and scenarios 12 and 17 show a green arrow alone in the five-section head. When no auxiliary sign was shown, motorist understanding increased when the green arrow was used alone. However, the opposite trend is seen if a sign is used, and no definite conclusion can be drawn.

Four scenarios for the second case, where the adjacent throughs + rights are stopped, are also tabulated in table 3.12. If no sign is used, motorist understanding is relatively unchanged whether or not the circular red is lit in the five-section head. However, a large decrease in incorrect responses are found for the case with a sign. The reduction in the percent of incorrect responses by omitting the circular red indicates that displaying both circular red and green arrow in the same head confuses many drivers. While the entire reduction cannot be attributed to the omission of the circular red indication, it appears that omitting the circular red has a significant positive impact in conveying the meaning of the signal indication to the motorist.

If there is only one three-section head on the approach in addition to the five-section head, then the circular indications in the five-section head must be used at all times to satisfy the requirement in section 4B-12 of the 1988 MUTCD that at least two signal faces must be provided for through traffic.

3. Use of auxiliary left-turn signs. This information is somewhat more difficult to interpret. The survey results for each sign type are shown in table 3.13, where scenarios are paired in order to directly assess the effect of each sign. Scenarios on the same line have the same signal displays and geometric characteristics, the only difference is the presence of the auxiliary sign. Two aspects of this information need to be considered: (1) Which signs have the lowest overall level of misunderstanding? and (2) Which signs show the greatest improvement over their no sign case?

Sign types 2, 6, and 11 show the smallest percent of incorrect responses, and all three types show improvement when the sign is added to a particular scenario. Sign

Description	Green Arrow w/Circular Indication in 5-Section Head			Green Arrow Alone in 5-Section Head		
	Sign	Scenario	Incorrect Responses	Sign	Scenario	Incorrect Responses
Circular Green for Throughs	None	13	19%	None	12	13
	PROTECTED LEFT ON GREEN ARROW (2)	15	8%	PROTECTED LEFT TURN ON ARROW ONLY (9)	17	18
Circular Red for Throughs	None	11	23%	None	14	20
	LEFT TURN SIGNAL (7)	16	34%	PROTECTED LEFT TURN ON ARROW ONLY (9)	18	5

Table 3.12. Inclusion Versus Omission of Circular Indication with the Green Arrow in a Five-Section Head. Number in Parentheses Following the Sign Legends Refers to the Sign Type in Figure 3.2.

	Scenario with Sign		Scenario without Sign	
Auxiliary Sign	Scenario	Incorrect Responses	Scenario	Incorrect Responses
LEFT-TURN ON ARROW ONLY (1)	22	20%	20	16%
	36	21%	33	24%
PROTECTED LEFT ON GREEN ARROW (2)	15	8%	13	19%
PROTECTED LEFT ON GREEN (3)	25	43%	7	22%
LEFT TURN SIGNAL (4)	23	42%	6	31%
	24	65%	5	32%
	29	17%	27	9%
	39	31%	37	29%
NO TURN ON RED (5)	30	31%	28	27%
	40	28%	38	13%
LEFT TURN YIELD ON GREEN ● (6)	3	14%	2	34%
	8	13%	7	22%
LEFT TURN SIGNAL (7)	16	34%	11	23%
	21	17%	19	17%
	31	14%	27	9%
	32	23%	28	27%
	35	52%	34	33%
LEFT TURN PROTECTED ON ARROW ONLY (8)	4	24%	1	25%
PROTECTED LEFT TURN ON ARROW ONLY (9)	17	18%	12	13%
LEFT TURN ON GREEN AFTER YIELD (10)	9	18%	7	22%
PROTECTED LEFT TURN ON GREEN ARROW ONLY (11)	18	5%	14	20%

Table 3.13. Comparison of Scenarios With and Without Auxiliary Left Turn Signs. Number in Parentheses Following the Sign Legends Refers to the Sign Type in Figure 3.2.

types 3, 4, and 7 showed the lowest levels of understanding, and, in each case, driver understanding was either the same or better if the sign was not present. Sign type 7 is a special case, observed only in the City of Austin, and, therefore, was probably unfamiliar to the great majority of the respondents.

4. Use of red arrows. The use of red arrows was tested in eight scenarios, four using a red arrow and four using a circular red to prohibit left-turns. These scenarios are listed in table 3.14, along with their respective survey results. By and large, the fraction of incorrect responses was smaller when a circular red was used to prohibit left turns. This same result was found in every category when similar mounting and sign conditions were paired. A possible explanation is that drivers may be confusing the red indication (meaning a prohibition) with the arrow indication (meaning movement in that direction) and hence believe that upon a red arrow indication they may proceed with caution to make a permissive turn.

It should be noted that red arrows are currently used in only one of the Texas cities included in the survey, Odessa in Ector County, which is believed to be the only use of red arrows in Texas. Therefore, Texas drivers' unfamiliarity with this type indication may have played a key role in the high incorrect response rate.

5. Dallas Phasing is a special phasing used to eliminate the yellow trap, a common cause of left-turn accidents. This is done by displaying a circular green to left turners when the opposing through has a green. This results in the unique display of a circular green for left-turn signals and circular red for the adjacent through signal indications. Basically the Dallas phasing is a modified version of the conventional lead/lag, protective/permissive phasing. The unique indications of the Dallas phasing are given by scenarios 2 and 3 (table 3.1A), the remaining indications of the Dallas phasing are similar to that of the protected/permissive phasing. The difference between scenarios 2 and 3 is the presence of an auxiliary left-turn sign in the case of scenario 3. The addition of the auxiliary sign reduced the incorrect responses from 34% (Scenario 2) to 14% (Scenario 3).

Notice that the accompanying auxiliary sign had some effect as seen by the significantly ($\alpha = 0.05$) lower fraction of incorrect response rate. While the entire

Position of Left Turn Signal Head	Red Arrow			Circular Red		
	Sign	Scenario	Incorrect Responses	Sign	Scenario	Incorrect Responses
Mast arm mounted	None	34	33%	None	33	24%
	LEFT TURN SIGNAL (7)	35	52%	LEFT TURN ON ARROW ONLY (1)	36	21%
Post mounted in median	None	37	29%	None	38	13%
	LEFT TURN SIGNAL (4)	39	31%	NO TURN ON RED (5)	40	28%

Table 3.14. Use of Red Arrow and Circular Red for Left Turn Prohibition. Number in Parentheses Following the Sign Legends Refers to the Sign Type in Figure 3.2.

difference may not be attributed to the presence of the auxiliary left-turn sign alone, the auxiliary sign appears to have a significant positive impact in conveying the meaning of the indication to the motorist.

SUMMARY

At a first glance it may appear alarming that such a large fraction of the drivers misunderstand some of the more commonly used left-turn treatments. However, it should be noted that only a single interval is shown in the questionnaire, and that the respondent is deprived of a large number of visual clues present in actual driving. Nonetheless, since the relative degree of comprehensibility of the signal indications and auxiliary signs is to be examined, the lack or presence of such clues does not invalidate the conclusions.

As mentioned above, a motorist at or approaching an intersection may receive a number of clues as to the meaning of specific signal indications and auxiliary signs. The drivers may observe a sequence of indications and have a better guess as to the meaning of the one shown as they try to negotiate their path through the intersection. Drivers also obtain clues from other drivers: the vehicle in front turns left, the driver behind impatiently honks, and so forth.

On the other hand, each signal indication should be, by itself, comprehensible, regardless of clues which may or may not exist when a driver faces the indications in the field. To this end, the study survey provides a good measure of the relative comprehensibility of the various signal/sign indications and offers recommendations on the use of specific indications, as follows:

1. If red arrows are used, their use should be accompanied by an educational program. They were not as well understood as a circular red in prohibiting left-turns during a particular interval, but red arrows are seldom used in Texas. One advantage of the use of red arrows is that auxiliary signs become unnecessary on the left-turn signal head.

2. A green arrow should always be used for a protected left-turn. Even when an auxiliary sign was used with a circular green intended for left-turns, the fraction of the respondents answering incorrectly was higher than for equivalent cases with green arrows.
3. A circular red and a green arrow should not be shown simultaneously on a five-section head, unless there is only one other signal head for the through traffic. This indication is used to indicate a protected only left while the adjacent through traffic is not allowed to go. When the circular red was removed, the fraction of the respondents answering incorrectly dropped significantly.

A recommendation concerning the auxiliary sign is somewhat more difficult to make. A primary disadvantage of any auxiliary sign is that it is difficult to read at night unless it is directly illuminated. Those which stated that lefts were protected on the green arrow (types 1, 2, 8, 9, and 11) were examined on a case-by-case basis. As shown in table 3.13, the addition of two of these signs (types 2 and 11) increased driver understanding, decreased understanding in one case (type 9), and showed no significant difference in the other two cases (types 1 and 8). In general, drivers appear to have a clear understanding of the meaning of the green arrow, and, as such, the sign does not appear to be necessary. The indication which causes the most confusion in this regard is the circular green when applied to the left-turn: does it provide for protected or permissive operation? Therefore, if a sign is necessary, one which indicates that the left turning traffic must yield on the circular green (providing, of course, that green arrows are used for the protected turn) is to be preferred. The final recommendation is:

4. Sign type 6, LEFT TURN YIELD ON GREEN [circular green], should be used, if necessary, when permissive turning is allowed. Sign type 10 has a similar message, LEFT TURN ON GREEN AFTER YIELD, but is not as clear, since neither circular green nor green arrow is specified.

A new auxiliary sign has been developed for use in conjunction with the Dallas phasing, and is a combination of two of the auxiliary signs included in this study. The legend of sign type 4, LEFT TURN SIGNAL, is compressed into two lines, and added on top of sign type 6, LEFT TURN YIELD ON GREEN [circular green] (see figure 3.2), with a horizontal bar separating the legends. While no data was collected on motorist understanding of this auxiliary sign, it would appear to have two disadvantages. By combining two signs, the text is longer than the two signs individually, requiring either a larger sign or smaller text. In addition, drivers have a longer auxiliary sign to read. The second disadvantage is that the two individual signs have quite different meanings. Sign type 4 is used with exclusive left-turn signal heads, implying that the circular green is used for protected lefts, while sign type 6 is used with permissive lefts on the circular green.

As part of the overall study investigating the left-turn operations at signalized intersections, the survey results have contributed to identifying difficult to understand as well as effective signal indication and auxiliary sign combinations. Field studies at over 100 intersections in the same nine counties and accident studies at many of those intersections have provided further information on operational efficiency and relative safety of the various left-turn treatments. The following three chapters report on experimental design, study findings of the field studies, and the accident/conflict studies, which combined with the results reported in this chapter have led to a number of recommended guidelines for selection of left-turn signal treatments discussed in Chapter 7.

CHAPTER 4

FIELD OBSERVATIONS: DESIGN & REDUCTION

SITE SELECTION

The selection process for data collection covered a wide geographical area, incorporating a number of demographic characteristics such as age and language, which may vary from place to place. Four other important site selection factors were:

- opposing speed limit,
- number of opposing lanes,
- number of left-turn lanes, and
- phasing pattern.

A detailed description of these major factors considered in the site selection is given below:

Geographical Distribution. In all, nine counties were selected for the study. They represented both major population centers as well as rural regions. They also vary in population characteristics across the state in terms of age distribution and language. The nine counties studied were Bexar, Cameron, Dallas, Ector, Harris, Lubbock, Nueces, Tarrant, and Travis. Some variations were also observed in the local left-turn signalization policies in the nine counties.

Speed of Opposing Traffic. The speed of the traffic opposing the left-turning vehicles is an important factor in decisions concerning the safety of left-turners as well as the type of phasing for left-turning vehicles. Studies by Cooper & Wennel (1978) and Bottom & Ashworth (1983) indicate that most drivers underestimate time gaps at high speeds. Six different opposing speed limits are commonly found in urban areas, ranging from 30 to 55 mph in 5 mph increments.

Number of Opposing Lanes. Another important factor that affects the selection of left-turn phasing is the number of opposing lanes that must be crossed. Not only it is difficult for a left-turning driver to find and judge adequate gaps in three or more lanes but also a considerable time is required for such maneuvers. Sites were found with one, two, and three opposing lanes. Only one site with four opposing lanes was found and included in the study.

Number of Left-Turn Lanes. The number of left-turn lanes significantly impacts left-turn operations and thus plays a major role in the selection of the type of left-turn phasing. A considerable reduction in saturation flow is observed for double left-turn lanes as a result of vehicle-vehicle interactions. Also the outer left-turning vehicle blocks the view of the inner left-turning driver impairing his visibility. Sites with single and double left-turn lanes were included in the study. One case with triple left-turn lanes was also found and included.

Phase Patterns significantly affect delay; protected only phasing results in higher delays than protected/permissive. Phase patterns also impact intersection safety. Numerous studies have shown that approaches with protected/permissive phasings have higher left-turn accident rates than those with protected only phasing (Upchurch 1985 and Agent 1985). The phase sequence, in terms of lead, lag, or lead/lag, also has a significant impact on delay and safety at the intersection. A particular phase pattern may be selected for the purpose of achieving progression and coordination along arterials. Five principal phase patterns were considered in this study, namely,

- protected only,
- protected/permissive,
- permissive/protected,
- permissive only, and
- Dallas phasing.

These four factors (speed of opposing traffic, number of opposing lanes, number of left-turn lanes, and phase patterns) at various levels constitute a 6x3x2x7 experimental design with 252 treatments for each of the nine counties. In other words, 252 intersection approaches would have to be found in each county to fully examine all possibilities. In fact, these 252 treatments represent the upper bound and not the actual number of sites studied, as some treatment combinations (intersections) do not exist or were not found. For example, we were unable to find an intersection in Odessa with double left-turn lanes, three opposing lanes, and an opposing speed limit of 55 mph. A tree diagram for the selection of intersections is shown in figure 4.1 for a single left-turn lane and one opposing lane.

Following the above selection procedure, over one hundred intersections were selected for the study. The intersections were largely selected from lists supplied by the District, City, and County traffic engineers in the selected counties. In counties where these lists were not furnished, intersection approaches were selected by the research team. The selected intersections have little or no pedestrian traffic. All the intersections also have exclusive left-turn lanes on the study approaches. A summary of the number of intersections and approaches studied within each county is shown in table 4.1.

County	Number of Intersections	Approaches Studied	Study Date
Bexar	8	16	March 1991
Cameron	7	14	January 1991
Dallas	20	29	June/July 1991
Ector	5	10	April 1991
Harris	12	24	January 1991
Lubbock	5	10	April 1991
Nueces	6	12	February 1991
Tarrant	33	55	June/October 1991
Travis	12	24	November 1991
TOTAL	108	194	

Table 4.1. Number of Intersection Approaches Studied by County.

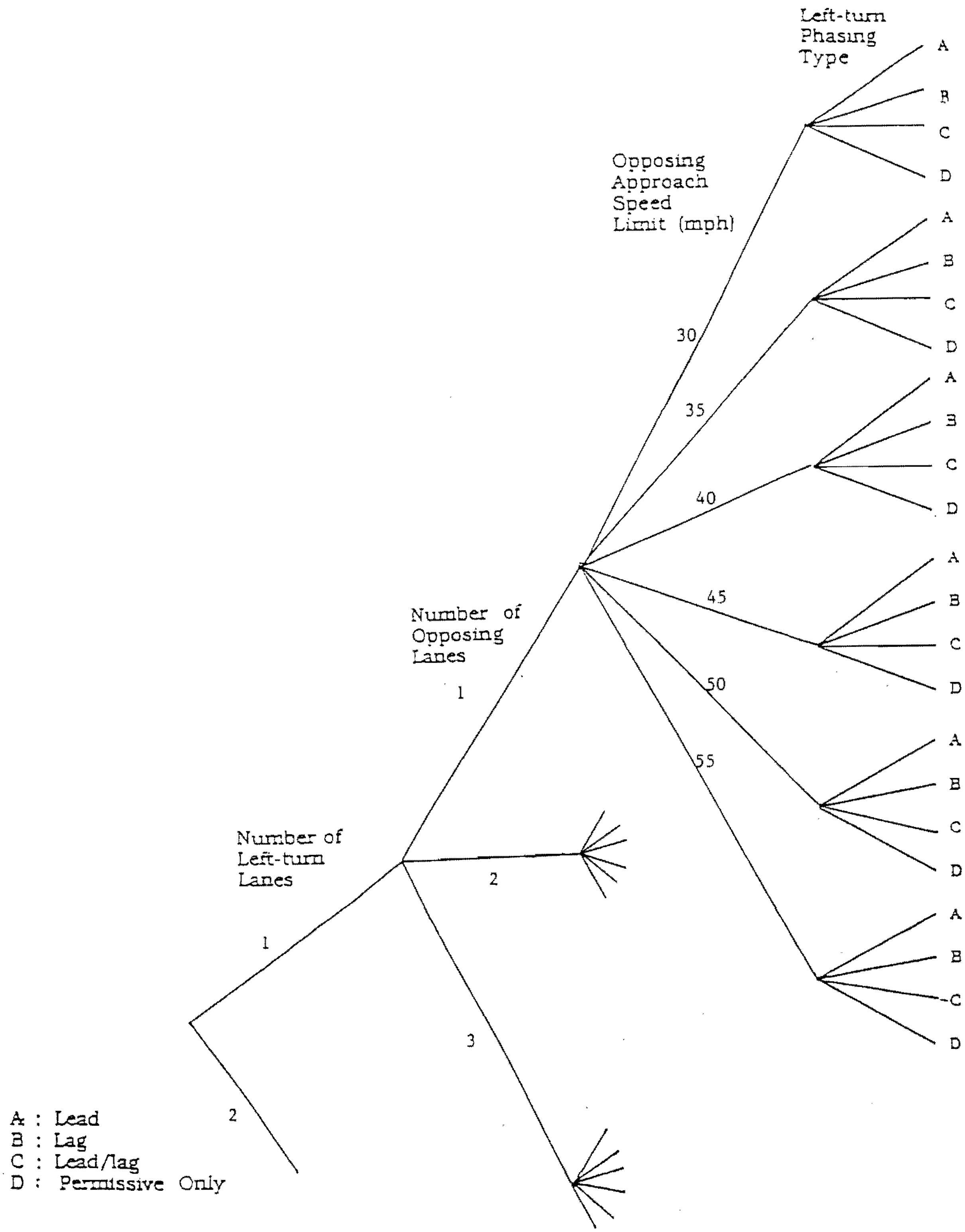


Figure 4.1. Tree Diagram for Selection of Study Sites.

DATA COLLECTION

Traffic and geometric data were collected at all the intersections selected for the study. Since phase patterns, speed limit, and sight distance at an intersection may change from one approach to another, the studies were conducted for approaches rather than intersections as a whole. All approaches were studied during one of the following peak periods:

- morning peak (7:00 - 8:30 am),
- mid-day (12:00 noon - 1:00 pm), and
- afternoon peak (4:30 - 6:00 pm).

All the data were collected on weekdays. Table 4.1 also gives the months during which intersections in each particular county were studied. Data at each intersection was both manually collected and recorded on video tape. One hour of continuous video recording of the approaches of interest was made at each site. The position and height of the camcorder was adjusted and focused on the left-turn operations and their interaction with the opposing traffic, as required for left-turn conflict studies. The indication sequences for signal timing purposes and the phase patterns could also be seen on the video tape. When possible, data was collected from two approaches at a single intersection. In this case, the second camcorder was set up to gather similar data for the second approach. A schematic diagram of the intersection with two camcorder-setup positions is shown in figure 4.2. Both camcorders were equipped with a time base, showing elapsed time to the nearest tenth of a second.

In addition to the video taping, the following geometric and traffic control features were recorded manually at each site:

- number of left-turn lanes,
- number of opposing lanes,
- speed limit of opposing traffic (mph),
- available sight distance (feet),
- phase pattern, and
- indication sequences.

The sight distance was not explicitly addressed in the selection of the intersections. However, it is an important criterion used in selection of left-turn phasing. Approaches

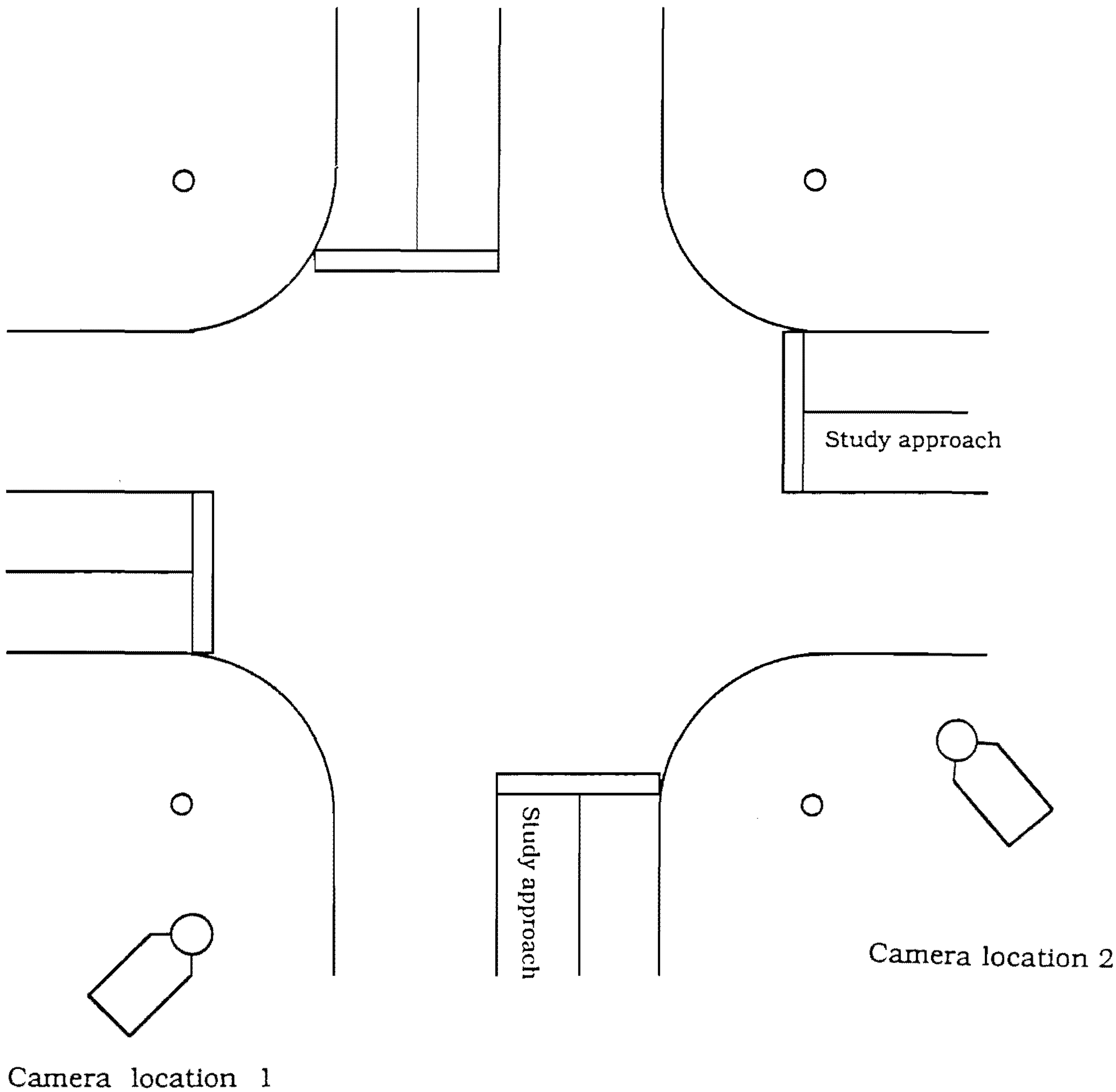


Figure 4.2 Camera data collection locations for study approaches

with poor sight distance for either opposing traffic or left-turning traffic are expected to be protected. The sight distances of all the approaches were therefore recorded for further analysis.

Traffic volume is required in predicting left-turn delays as well as the volume to capacity ratio of the intersection and the allocation of green times. Traffic volumes were obtained from the video tapes. The following volumes were obtained:

- left-turn volume (vph),
- opposing volume (vph),
- vehicle mix (percent of heavy vehicles), and
- through and right turn volumes (vph).

Vehicle mix, defined as the percentage of heavy vehicles in the lane group, is required for assessing the performance of the intersection. The lower acceleration rate of heavy vehicles and their larger turning radii result in more time needed for left-turn maneuvers; in other words, they require larger time gaps. Therefore, protected only phasing may be needed for higher percentages of heavy vehicles in the left-turn traffic. Heavy vehicles were defined as vehicles with more than two axles or four tires.

Signal timings were very crucial in this study. It is important to note that the signal controller settings were not adjusted at any of these sites prior to data collection. Some of the intersections were actuated while others were pretimed. Interval times for the actuated signals were averaged for use in the delay calculations. However, since data were collected during the peak period, most of the actuated signals were effectively operating as pretimed signals. A detailed description of the signal timing measurements are described in the next section (data reduction). The cycle length and green and yellow times were measured from the video tapes. All-red intervals of one second were also found at some intersections.

Field delay data were collected at each intersection for the average left-turn stopped delay (D_{lt}) and the average through stopped delay (D_{th}). These were measured by counting the number of stopped left-turn and through vehicles every fifteen seconds, and summed over the one-hour observation period. The result multiplied by fifteen seconds and divided by the respective left-turn or through volume yields the average stopped delay for the respective lane group. Both left-turn and through + right stopped delays are expressed in seconds per vehicle.

The objective of this field delay study was to compare the results with the delay model in the Highway Capacity Manual (HCM 1985) for permissive only, protected only, and protected/permissive operations, and, if needed, to make adjustments in the model parameters.

DATA REDUCTION

In total, 108 intersections comprising 196 approaches were studied. The data reduction was carried out in three stages. The first stage consisted of volume counts, while the second stage was devoted to signal timing and determination of phase sequences. The third stage of the data reduction process involved conflict counts for the study approaches. Data reduction was time-consuming and demanded a major portion of the project time schedule.

Traffic Volume Counts. Left-turn volume (V_{lt}), opposing volume (V_{op}), and through and right-turn volume (V_{th}) were measured in fifteen-minute intervals. For each intersection, four 15-minute volume counts were obtained for each lane group. Since all the intersections had exclusive left-turn lanes, most approaches consisted of two lane groups: left turns and throughs + rights. There were, however, a few intersections with exclusive right turn lanes, which were treated as separate lane groups. The volume cross product (V_{xp}) was determined as the product of the left-turn volume (V_{lt}) and the opposing through + right turn lane group volume (V_{op}). The volumes were expressed in terms of vehicles per hour (vph). The peak 15-minutes volumes were then selected for analysis. Vehicle classification was also performed.

Vehicle Mix. Heavy vehicles were defined as those with more than two axles or four tires. The vehicular mix for each lane group was determined as the percentage of that traffic that was heavy vehicles, namely,

$$\text{vehicle mix} = \frac{\text{volume of heavy vehicles in a lane group} \quad (100)}{\text{total lane group volume}}$$

Of particular interest to the study was the left-turning traffic mix, which may significantly affect the operation and performance of that lane group.

Signal Timings. The average cycle length was used for those intersections with actuated signals. The cycle lengths were measured at ten points spread evenly within the study period and averaged to find the average cycle length (C).

This approach converts actuated signal settings to pretimed signal settings. It also reduces variability in data and the need to collect cycle-by-cycle signal information. Using this approach, the cycle time (C), the average green time (G), and the yellow interval (Y) were obtained. The time base recorded on the video tapes was capable of timing to the nearest tenth of a second and was used in estimating these time settings.

Conflicts. The left-turn conflict rate (C_{lt}) was also obtained from video tapes. The elapsed time from the start of each study period to the occurrence of the first conflict was used as a surrogate variable to determine the conflict rate. Where no conflict was observed during the whole one-hour observation period, a time value of 60 minutes was used. The number of conflicts is expressed in units of conflicts per million entering squared vehicles as follows:

$$C_{lt} = \frac{(60/T)\ (10^6)}{(V_{lt}/N_{lt})\ (V_{op}/N_{op})} ,$$

where C_{lt} = number of conflicts per million entering squared vehicles per lane (since the volume cross product was used),

N_{lt} = number of left turn lanes,

N_{op} = number of opposing lanes,

V_{lt} = left turn volume (vph),

V_{op} = opposing volume (vph), and

T = elapsed time before first conflict is observed (hr).

Four left-turn conflict types were defined for this study:

Type 1. Left-turn vehicle causes the opposing vehicle to brake or weave to avoid collision.

Type 2. The second through vehicle in the opposing path also has to take an evasive action.

Type 3. Vehicles enter the intersection during any interval and turn left on red.

Type 4. Rear-end conflict in the left-turn lane when the following vehicle brakes after the lead vehicle begins its turning maneuver and then stops.

Estimation of Delays

The measured traffic volumes for the various lane groups together with the signal timings and the geometric features of the intersection were input into the HCS (1985) signalized intersection program to obtain the average stopped delay for the various lane groups. These estimates were termed calculated delays. Saturation flow rates ranging from 1800-2000 vehicles per hour of green per lane were applied to the through traffic and 1600 vphgpl to the left-turn traffic. A peak hour factor of 1.0 was also used to reflect the peak hour conditions.

The following delay variables, all in seconds per vehicle, were obtained from HCS:

- average stopped delay for the left-turning traffic (D_{lt}),
- average stopped delay for the through and the right turn traffic (D_{th}),
- average stopped delay for each approach (D_{ap}), and
- average overall intersection stopped delay (D_{int}).

The calculated delays were obtained from HCS by using the traffic volumes, phase patterns, traffic control, and geometric conditions observed in the field. The calculated delays were compared with the field measured delay to assess the correspondence between the two, and make any adjustment if necessary. The comparison was done for protected only, protected/permissive, and permissive only phase patterns.

Plots of the calculated versus observed delays, presented in figures 4.3 through 4.6, show that slopes do not significantly differ from that of a 45 degree line through the origin. Likewise the intercepts do not significantly differ from zero. From the summary statistics in table 4.2 it is observed that the 95% confidence intervals for the slope and the

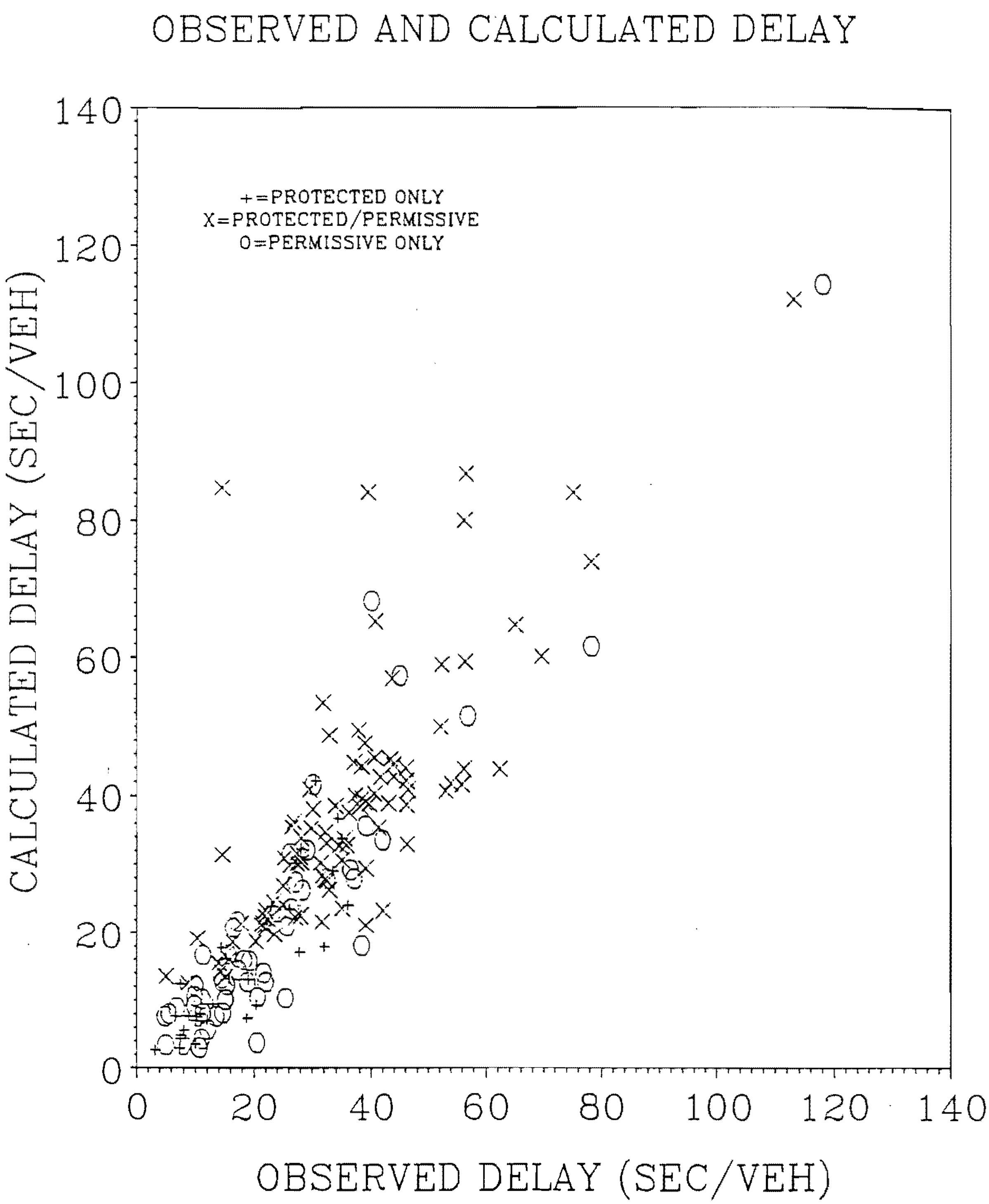


Figure 4.3. Observed and Calculated Left-Turn Delays for All Phasing Types.

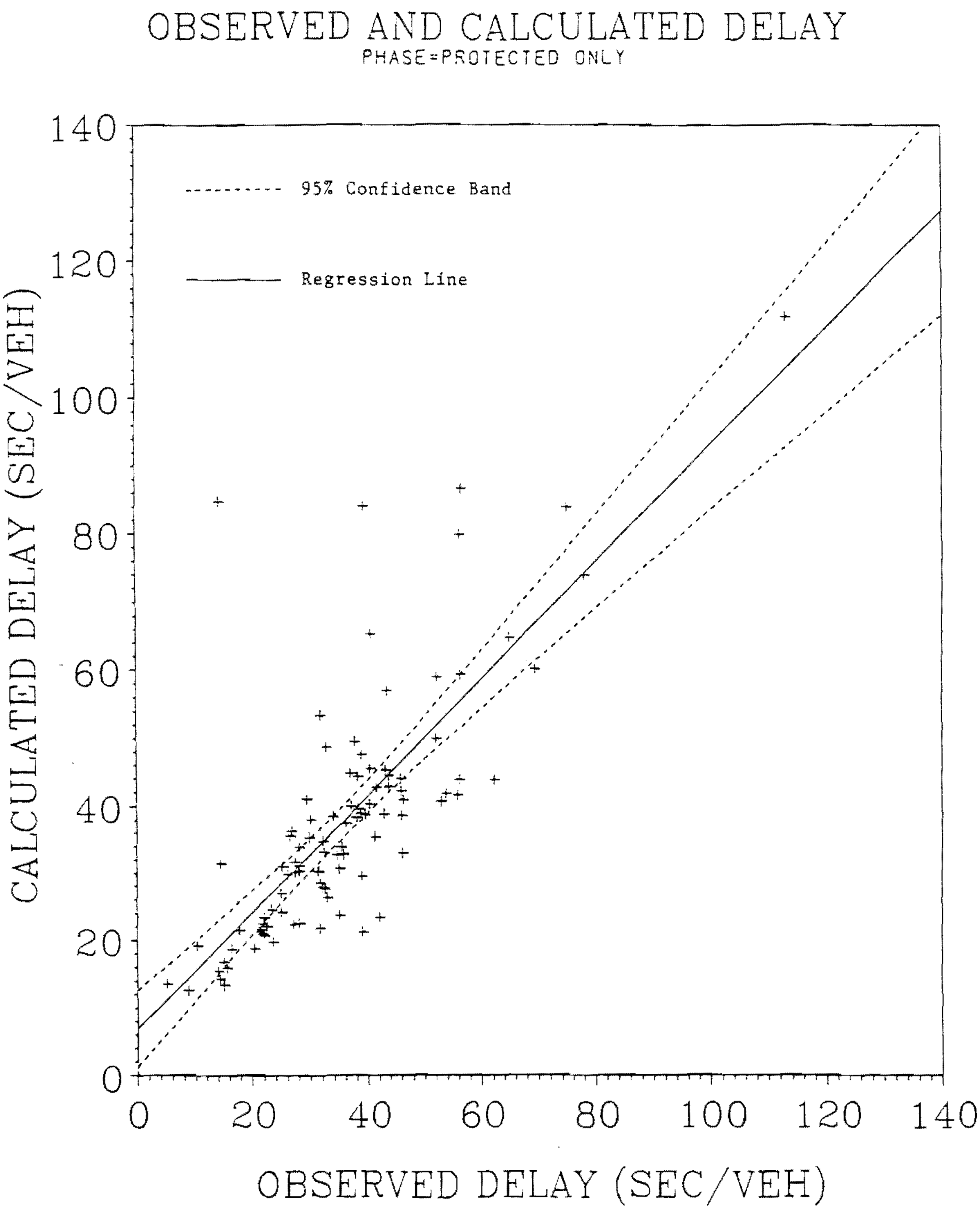


Figure 4.4. Observed and Calculated Left-Turn Delays for Protected Only Phasing.

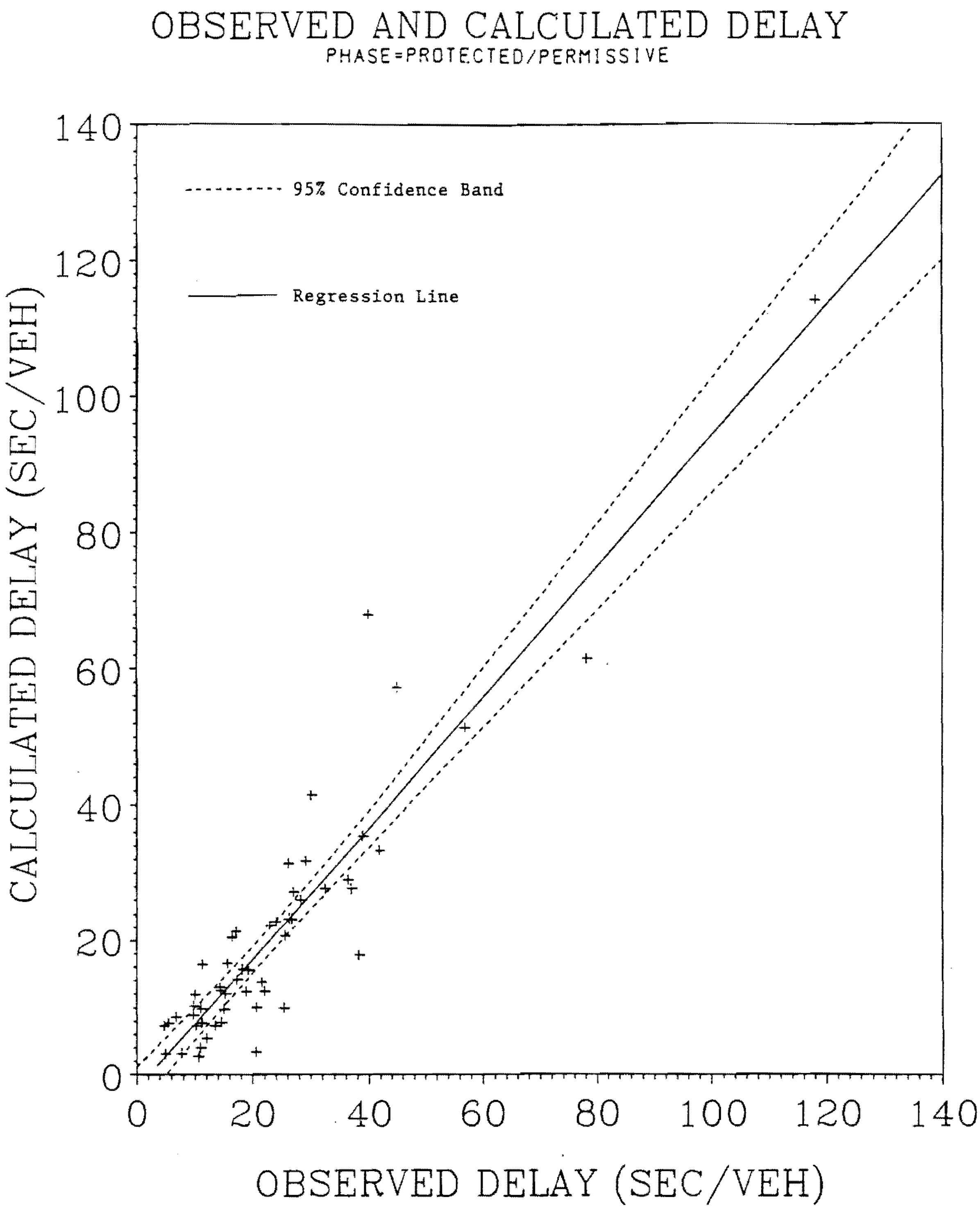


Figure 4.5. Observed and Calculated Left-Turn Delays for Protected/Permissive Phasing.

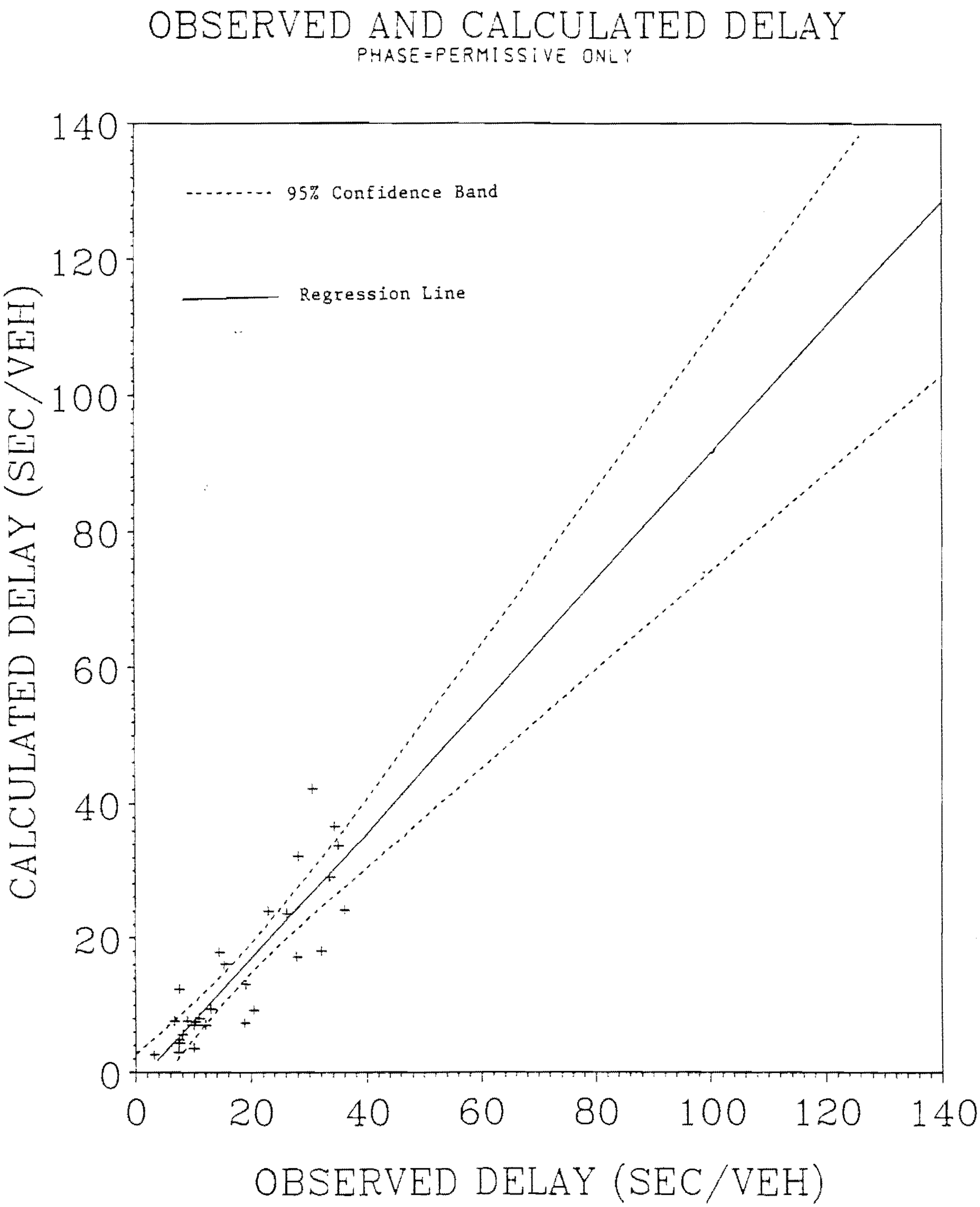


Figure 4.6. Observed and Calculated Left-Turn Delays for Permissive Only Phasing.

Phase Sequence	Parameter	Estimate	Std Error	R^2
Protected Only	β_0	6.60	2.86	0.59
	β_1	0.86	0.07	
Protected/ Permissive	β_0	-2.05	1.57	0.86
	β_1	0.96	0.05	
Permissive	β_0	-1.65	2.10	0.76
	β_1	0.93	0.10	

Table 4.2. Parameter Estimates for the Intercepts and Slopes for the Calculated Versus Observed Left-Turn Delays.

intercept include 1.0 and 0, respectively. This indicates a fairly good agreement between the observed and calculated delays. The intercept for the protected only phasing, was, however, slightly above zero and the relatively low R^2 reflects this variability. The HCM model was therefore used to estimate the total intersection stopped delay which had not been measured at the site.

Left-Turn Accident Data

Left turn accident records on forty-two of the intersections under study were obtained from the Texas Department of Transportation (TxDOT) and selected city traffic engineers. The records represent three successive years from 1988-1990 or 1989-1991. The 1991 records did not include accidents which had occurred in November and December.

The signal timings, phasing, and geometric history of the intersections involved were also obtained from the respective city traffic engineering offices to ensure that no major geometric or signalization changes had taken place that might affect drivers or influence accidents. Two out of the forty-two intersections had undergone changes in the latter part of 1990. However, the field studies related to this project were conducted prior to the changes at these two sites.

For each of the intersections under study, the number of accidents involving left-turn traffic on each approach was determined. These accidents were then matched with the corresponding phase pattern and other characteristics of that approach for analysis.

Left-turn accident totals rather than rates were used in this study due to the ease of their availability and application. Another reason for not using accident rates was the fact that accident rates tend to be biased with low volume approaches having higher rates and high volume approaches lower rates.

Data Classification

The collected data consisted of about 20 variables. To develop a selection criteria based on a systematic procedure which can be easily followed in practice and also for analysis purposes, these 20 variables were further classified into three main groups: design variables, decision variables, and measures of effectiveness.

Decision Variables are defined as those variables that affect the intersection performance; those selected for this study were:

- left-turn volume (V_{lt}),
- opposing volume (V_{op}),
- volume cross product (V_{xp}),
- vehicle mix (Mix),
- G/C ratio for left-turns,
- speed limit of opposing traffic (Spop),
- sight distance (adequate or inadequate) (Diff),
- number of left-turn lanes (N_{lt}),
- number of opposing lanes (N_{op}),
- v/c ratio of the approach, and
- percent of drivers older than 65.

Rather than using available sight distance directly, the difference between available sight distance and required sight distance based on the speed of the opposing traffic was used.

Design Variables are those aspects of the left-turn signal treatment for which guidelines are to be developed:

- the type of left-turn phasing,
- the sequence of the indications, and
- the type auxiliary left-turn signs, if needed.

A set of these design variables must be selected so that it optimizes the intersection operation as a whole, taking into consideration delay and motorists' safety .

Measures of Effectiveness (MOEs) are those variables through which the performance of the signal phasing and indication sequences are assessed. They include:

- left-turn stopped delay (D_{lt}),
- through stopped delay (D_{th}),
- intersection stopped delay (D_{int}),
- left-turn accidents (A_{lt}), and
- left-turn conflicts (C_{lt}).

These three variable classifications define the operation of the signalized intersection and form the basis over which sound guidelines can be developed for the selection of left-turn phasing.

CHAPTER 5

FIELD OBSERVATIONS: DATA ANALYSIS

The data analysis initially involved the examination of the ranges, modes, means, and dispersion of the collected data for each phasing type under study. A correlation analysis of the independent variables was also performed. The objective of this preliminary analysis was to identify any characteristics which could, in a statistically significant fashion, distinguish one phasing type from the others.

Summaries of the general descriptive statistics for the three left-turn phases (protected only, protected/permissive, and permissive only) are shown in tables 5.1 through 5.3. As is easily seen, based on the standard deviations of the variables in these tables, the data covered a wide range of values. It should also to be noted that permissive phases have lower mean values than protected phases. This indicates that permissive signals function more efficiently than protected phasing under certain operating conditions, to be identified and discussed later.

As shown in tables 5.1 through 5.3, there appears to be no definite trend among any of the decision variables due to a wide scatter in the data. This can be further seen in figure 5.1 for two of the main decision variables identified in the previous studies, namely the left-turn and opposing volumes. Such variability has also been previously reported by Upchurch (1985) and Agent (1979). The high variability and the lack of a definite trend in the data calls for a more rigorous statistical data analysis approach. A detailed discussion of the approach used is presented below in the section on statistical analysis.

CORRELATION ANALYSIS

Correlation analyses of the decision variables listed in table 5.1 were performed to determine if any pairs of variables were highly correlated. The objective was to minimize multicolinearity effects in modeling by examining the pairwise correlation

Variable	Sample	Mean	Std Dev	Minimum	Maximum
V_{lt}	98	188	127	8	940
V_{op}	98	629	387	10	1,761
V_{xp}	98	134,185	166,310	80	1,169,454
Mix	98	0.83	1.84	0	12.5
Spop	98	37.7	5.61	20	55
Diff	98	386	307	-225	1,750
Cycle	98	96	25.7	55	190
N_{lt}	98	1.25	0.46	1	3
N_{op}	98	2.08	0.87	1	4
D_{lt}	98	37.7	18.3	12.5	112
D_{int}	98	25.8	14.6	3.1	65.9

Table 5.1. Summary Statistics for Protected Only Phase Sequence.

Variable	Sample	Mean	Std Dev	Minimum	Maximum
V_{lt}	57	174	148.5	12	940
V_{op}	57	689	427	122	2,087
V_{xp}	57	120,393	124,522	2,560	592,956
Mix	57	1.00	1.58	0	7.6
Spop	57	38.9	6.29	30	55
Diff	57	386	307	-225	1,750
Cycle	57	98	33.6	55	190
N_{lt}	57	1.14	0.35	1	2
N_{op}	57	2.4	0.59	1	3
D_{lt}	57	20.3	19.4	2.7	114
D_{int}	57	18.2	10.2	3.1	59.6

Table 5.2. Summary Statistics for Protected/Permissive Phase Sequence.

Variable	Sample	Mean	Std Dev	Minimum	Maximum
V_{lt}	29	62	53	8	266
V_{op}	29	364	324	46	1,256
V_{xp}	29	20,835	29,936	392	161,914
Mix	29	1.4	3.9	0	18
Spop	29	34.4	5.1	30	45
Diff	29	312	278	-100	750
Cycle	29	83.6	19.3	60	120
N_{lt}	29	1	0	1	1
N_{op}	29	1.48	0.68	1	3
D_{lt}	29	14.9	11.2	2.6	42.1
D_{int}	29	9.4	4.1	3.2	20.9

Table 5.3. Summary Statistics for Permissive Only Phase Sequence.

among individual decision variables. The correlation matrix, shown in table 5.4, indicates the following to be highly correlated ($\rho \geq 0.6$):

- left-turn volume and volume cross product,
- opposing volume and volume cross product, and
- opposing volume and number of opposing lanes.

None of the above pairs should therefore appear together as independent variables in any models to be developed.

STATISTICAL ANALYSIS

The statistical analysis was designed to address a sequence of decisions regarding the suitability of the left-turn phasing treatment to be used.

- Is a permissive only left-turn phase adequate or should left-turn protection (green arrow) be provided ?
- If left-turn protection is called for, is a more restrictive protected only phase justified or would protected/permissive pattern suffice?
- If the protected/permissive phase is prescribed, would a lead operation be sufficient or should a lead/lag or Dallas phasing sequence be provided?

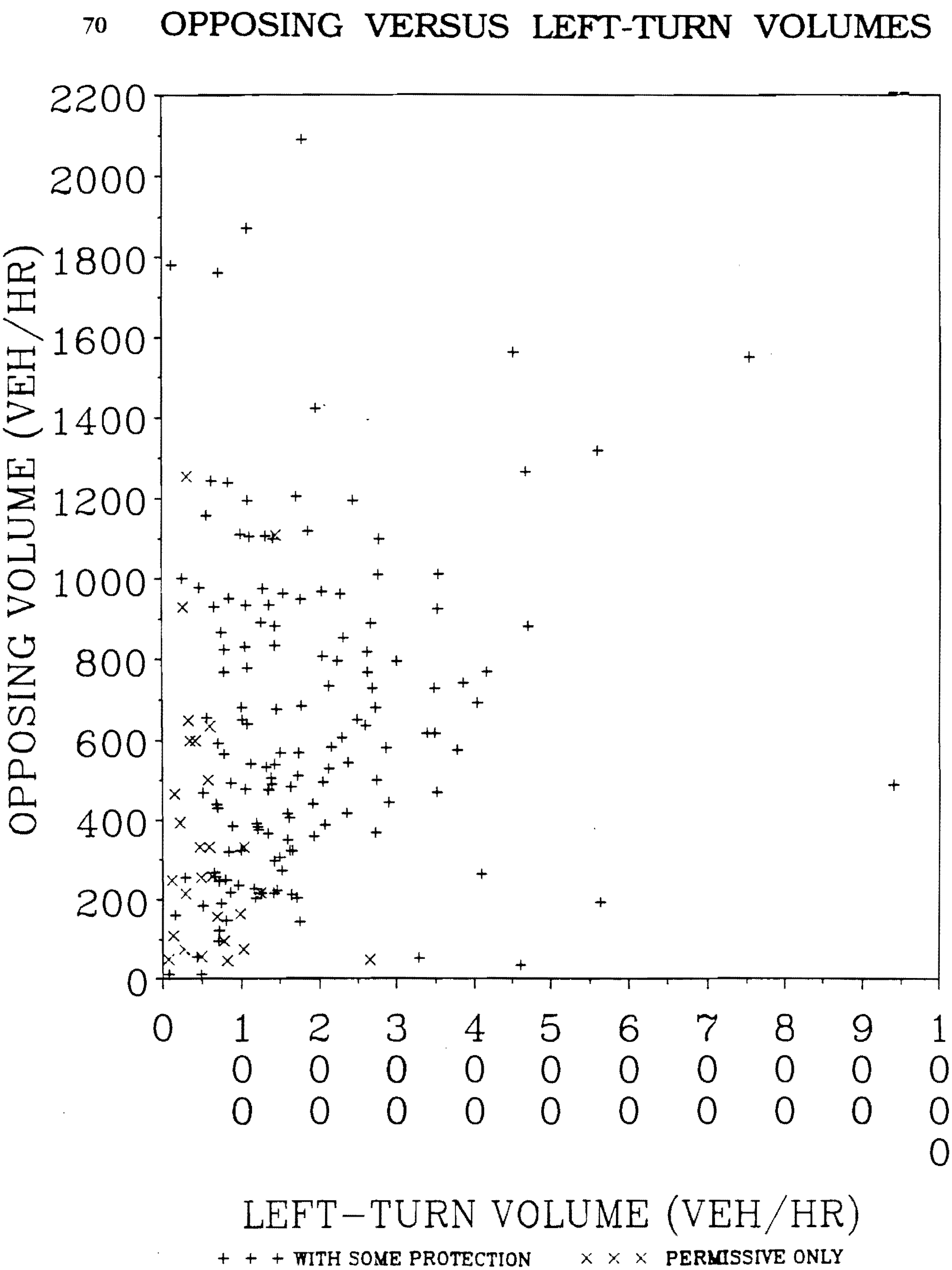


Figure 5.1 Opposing and Left-turn volumes for all phasing types

	V_{lt}	V_{op}	V_{xp}	N_{lt}	N_{op}	Spop	Mix	Diff
V_{lt}	1.00	0.21	0.78	0.48	0.16	0.03	-0.09	-0.03
V_{op}	0.21	1.00	0.60	0.07	0.60	0.15	-0.06	0.31
V_{xp}	0.78	0.60	1.00	0.36	0.34	0.08	-0.05	0.15
N_{lt}	0.48	0.07	0.36	1.00	0.12	-0.05	-0.03	-0.07
N_{op}	0.16	0.59	0.34	0.12	1.00	0.29	-0.18	0.18
Spop	0.03	0.15	0.08	-0.05	0.29	1.00	0.03	-0.01
Mix	-0.10	-0.07	-0.05	-0.03	-0.18	0.03	1.00	0.06
Diff	-0.03	0.31	0.15	-0.07	0.17	-0.01	0.06	1.00

Table 5.4. Correlation Matrix of the Decision Variables.

Two principal statistical analysis techniques were applied to address the above questions. A logistic regression technique was used for the first decision (permissive versus some protection), while statistically significant threshold values for the principal decision variables were developed to analyze higher level decisions regarding the type of protected phasing pattern, should such phasing be needed.

LEVEL 1 DECISION: PERMISSIVE VERSUS SOME PROTECTION

As the volume of traffic and/or accidents increase at intersections with permissive only left turn operation, some form of protection may be justified to improve the safety and operational efficiency of the intersection. These improvements also have their drawbacks, including a potential increase in overall intersection delay and operating cost, as well as a potential increase in certain accident types.

The level 1 decision process was modeled using logistic regression. The preliminary analysis discussed earlier shows that the permissive only phase sequence has distinct characteristics that are markedly different from those with some form of protection. These characterizing variables include:

- left-turn volume,
- opposing volume,
- speed limit on the opposing approach,
- number of opposing lanes, and
- number of left-turn lanes.

The statistically significant higher mean values of these variables for approaches with some form of protection as compared to permissive signals could therefore be used to distinguish the need for one or the other phase pattern. A probabilistic approach using logistic regression was adopted for this purpose.

Given a set of explanatory variables, defined as decision variables, there are probability values associated with the suitability of each phasing type.

Suppose X is a vector of decision variables and

$$p = \Pr(\text{phase} = \Phi \mid X) ,$$

where Φ = type of phase pattern, i.e., the response variable to be modeled. The logistic model has the form

$$U(p) = \log\left(\frac{p}{1-p}\right) = \beta X$$

where U(p) is the logit or the utility function and β is the vector of model parameters. The logistic equation for the probability (p) is:

$$p(\phi) = \frac{e^{U(p)}}{1 + e^{U(p)}} = \frac{e^{\beta X}}{1 + e^{\beta X}} \; .$$

Nine decision variables were used in the analysis. These were:

- left-turn volume (V_{lt}),
- opposing volume (V_{op}),
- volume cross product (V_{xp}),
- vehicle mix (Mix),
- G/C ratio for the protected portion of the left-turns,
- speed limit on opposing approach (Spop),
- sight distance (adequate or inadequate based on approach speed limit) (Diff),
- number of left-turn lanes (N_{lt}), and
- number of opposing lanes (N_{op}).

Of the nine decision variables, three were significant in differentiating permissive phasings from those with some sort of protection, namely,

- left-turn volume (V_{lt}),
- speed limit on the opposing approach (Spop), and
- number of opposing lanes (N_{op}).

The result of the analysis are presented in table 5.5.

Variable	Estimate	Std. Error	P-Value
Intercept	-5.10	1.79	0.005
N_{op}	0.71	0.34	0.039
V_{lt}	0.02	0.01	0.000
Spop	0.09	0.05	0.089

Table 5.5. Parameter Estimates for the Logistic Choice Model.

A common way of summarizing the results of a logistic regression is the use of a classification table. Basically, this table is the result of cross-classifying the observed variable (phase) with a dichotomous variable whose values are predicted from the estimated logistic regression probabilities. Thus to obtain the predicted dichotomous variable, a cut-off point, C, must be defined to which the estimated probabilities are compared. If the estimated probability exceeds the value C then the response variable (representing choice of a particular phase sequence) is allowed to hold a value of one; otherwise it assumes a value of zero. In other words, the estimated probabilities are used to determine the group membership or choice of phase sequence.

If the logistic regression model is the appropriate model and predicts group membership accurately, then it provides evidence that the model fits. However, it must be noted that classification is very sensitive to the relative sizes of the two components being classified, and will always favor classification into the larger group (Hosmer & Lemeshow 1989). Thus, when the group sizes are not equal and where classification is the ultimate goal, it is necessary to examine the estimated probabilities graphically before setting the cut-off value C.

The estimated probabilities for permissive only phasing and those with some form of protection are shown in figure 5.2. The plot shows a cut-off point of 0.7 to be suitable for classification to account for the unbalanced data.

From the parameter estimates given in table 5.5, the utility (U) for some protection is given by

$$U = -5.10 + 0.705(N_{op}) + 0.024(V_{lt}) + 0.085(Spop) \ .$$

The positive coefficients for the decision variables indicate preference for some protection for higher values of the decision variables. Low values of these variables, on the other hand, imply preference for permissive only operation.

Using the cut-off point probability of 0.7, the corresponding utility (U=0.85) is obtained

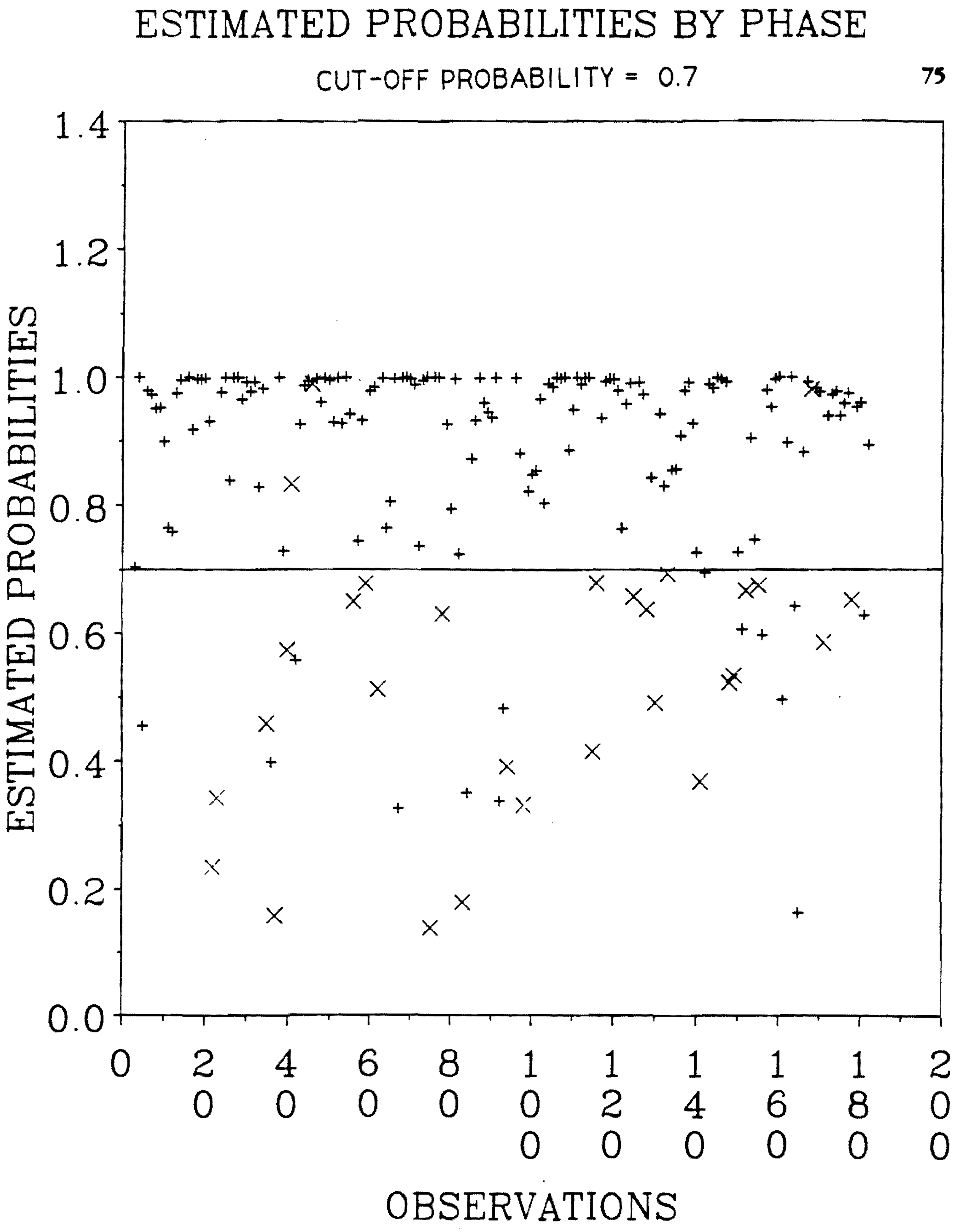


Figure 5.2 Estimated probabilities for permissive only phasings and with some protection.

$$0.85 = -5.10 + 0.705(N_{op}) + 0.024(V_{lt}) + 0.085(Spop) \ ,$$

which yields the utility lines

$$V_{lt} = 220 - 3.54(Spop) \quad \text{for} \quad (N_{op} = 1) \ ,$$
$$V_{lt} = 190 - 3.54(Spop) \quad \text{for} \quad (N_{op} = 2) \ , \text{ and}$$
$$V_{lt} = 160 - 3.54(Spop) \quad \text{for} \quad (N_{op} = 3) \ .$$

Figures 5.3 through 5.5 are the plots of the left-turn volume versus speed limit on the opposing approach for one, two, and three opposing lanes, respectively. The lower portion (shaded in each plot) indicates preference for a permissive only operation while the upper portion (unshaded) signifies the need for some protection.

LEVEL 2 DECISION: PROTECTED ONLY VERSUS PROTECTED/PERMISSIVE

The analysis approach for the level 2 decision comprises of setting threshold values which could be used as criteria to distinguish between the two forms of protected operation. Since these two types of phasings display very similar characteristics in terms of the decision variables, the logistic approach cannot be effectively applied here. The level 2 decision takes place only when it has clearly been established that some form of protection is necessary. As shown in table 5.6, the number of left-turn lanes (N_{lt}) and the number of opposing lanes (N_{op}) significantly differ for the protected only versus protected/permissive operation. All other variables have mean values which are not significantly different for the two types of phasings. The t-value probability compares means while the F-value probability compares variances of the two types of phasing.

The threshold values were determined by establishing the 85th-percentile values of each decision variable for the protected/permissive phasings. These values correspond to the threshold levels exceeded only 15% of the time by the protected/permissive phasings. The threshold values are given in table 5.7.

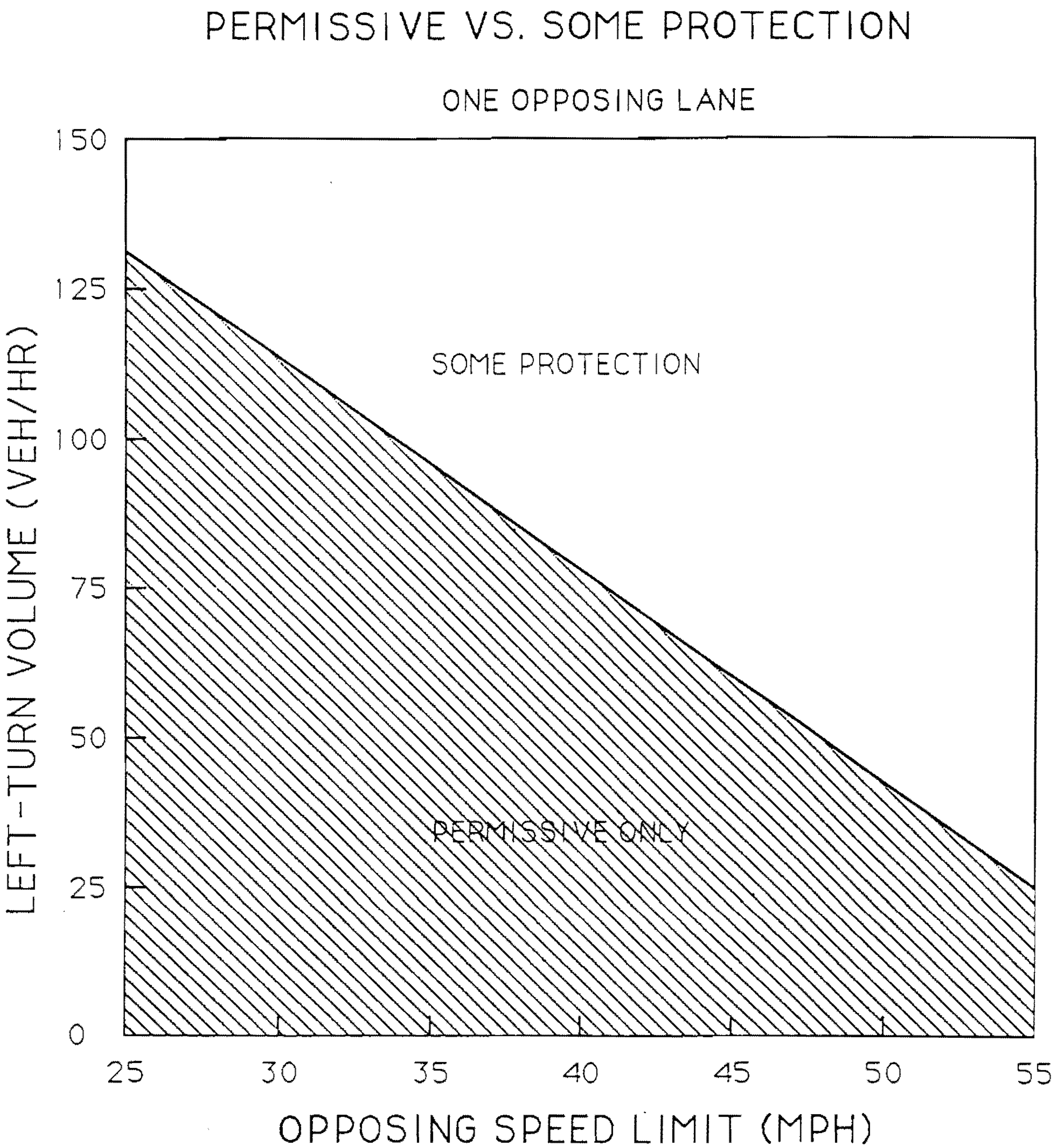


Figure 5.3. Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face one opposing lane.

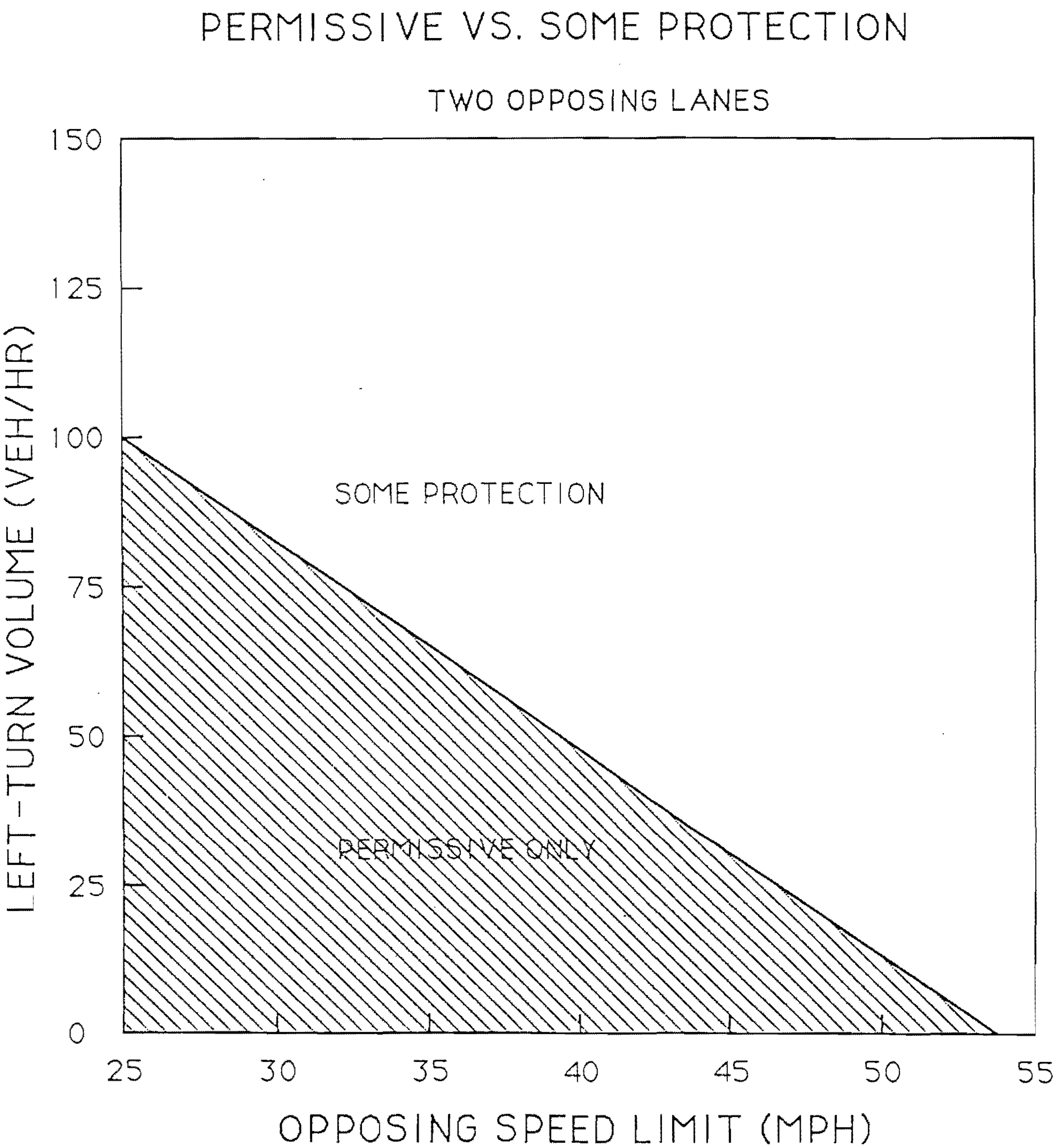


Figure 5.4. Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face two opposing lanes.

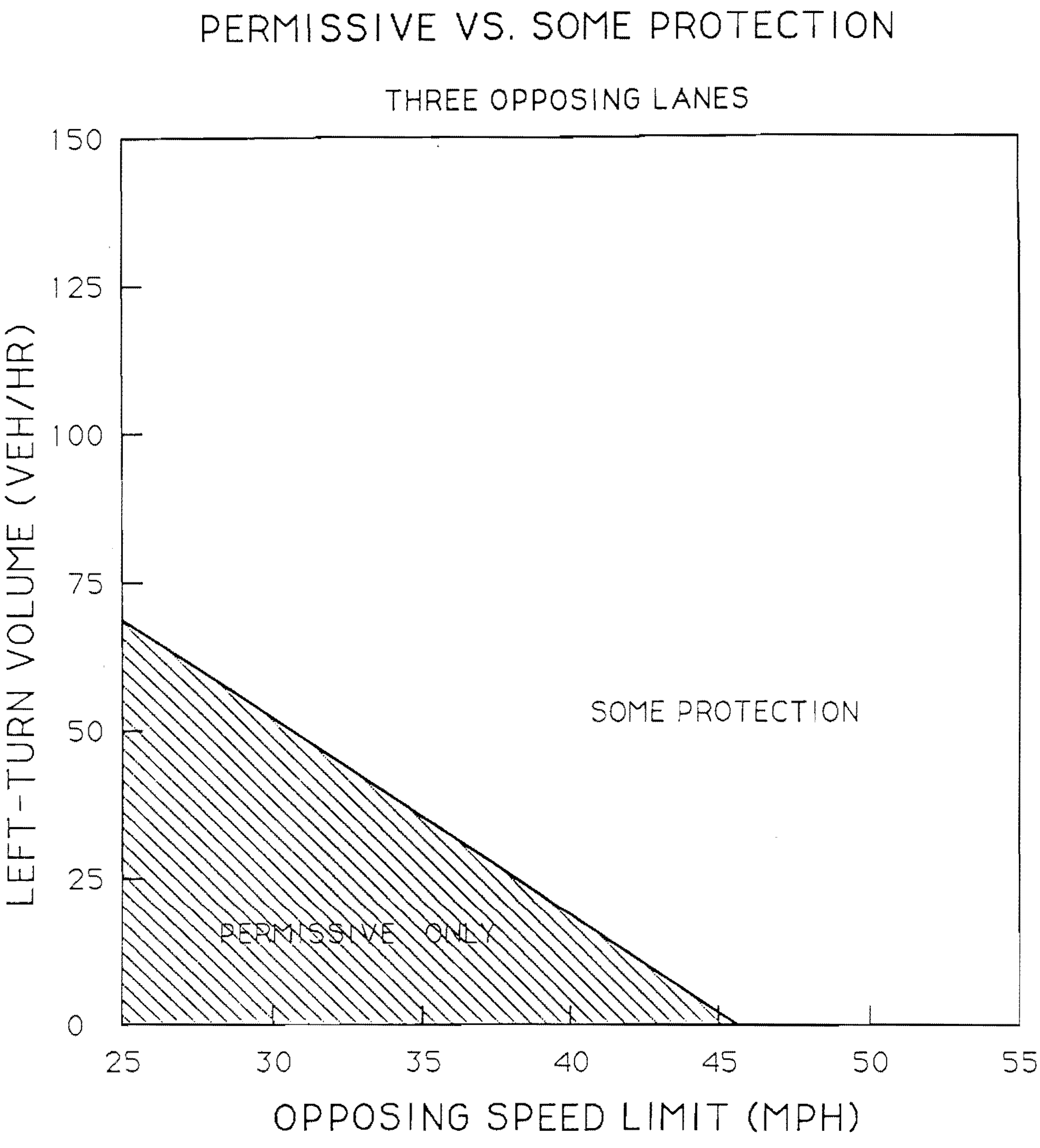


Figure 5.5. Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face three opposing lanes.

Variable	Phase	Mean	Std Dev	P > F	P > |t|
V_{lt}	PTO	188	127.5	0.19	0.54
	P/P	174	148.5		
V_{op}	PTO	630	387.5	0.40	0.40
	P/P	689	427.5		
V_{xp}	PTO	134,190	166,310	0.02	0.57
	P/P	120,393	124,222		
Mix	PTO	0.83	1.85	0.20	0.52
	P/P	1.00	1.59		
Spop	PTO	37.7	5.62	0.40	0.21
	P/P	38.9	6.18		
N_{lt}	PTO	1.26	0.46	0.02	0.08
	P/P	1.14	0.35		
N_{op}	PTO	2.08	0.87	0.00	0.01
	P/P	2.40	0.59		
Cycle	PTO	96.6	25.7	0.02	0.01
	P/P	98.6	33.6		

Table 5.6. Comparison of Means and Standard Deviations for Protected Only (PTO) Versus Protected/Permissive (P/P) Operations.

Decision Variables	Threshold Value
Left-Turn Volume (V_{lt})	> 320 vph
Opposing Volume (V_{op})	> 1100 vph
No. of Opposing Lanes (N_{op})	≥ 3
No. of Left-Turn Lanes (N_{lt})	≥ 2
Sight Distance (Diff*)	< 0 ft
Left-Turn Mix (% Hv. Veh.)	> 2.5%
Opposing Speed Limit (Spop)	≥ 45 mph
Volume Cross Product (V_{xp})	> 250,000 $(vph)^2$

* The difference between the available and required sight distance based on the speed limit.

Table 5.7. Threshold Values for Protected/Permissive Phasings.

The number of approaches under each of these two phase sequence types which meet the threshold values and the percent of these approaches that have protected only are presented in table 5.8. Table 5.8 clearly shows that none of the eight decision variables, with the exception of restricted sight distance and number of left-turn lanes greater than or equal to two, could, by themselves, be used as criteria for left-turn phase selection.

In most cases, two or more conditions are required to justify use of protected only phasings. Any two combinations of the eight decision variables above which satisfy the threshold values will constitute a critical operating condition under which the approach must be protected only. Pairwise combinations of the above eight variables are therefore used, as shown in table 5.9.

In determining the conditions under which protected only phasing is recommended, all combinations of the decision variables for which 80% or more of the approaches studied had protected only phasing were identified. A sensitivity analysis identified the 80th-percentile as the point of diminishing returns for the selection and conditions under which protected only is recommended. The analysis indicated that if a lower than 80th-percentile value is used, very few additional conditions for protected only phasing will be added. For example, using the 70th- or 75th-percentile will only result in one added condition for protected only, i.e., more than two left-turn lanes. On the other hand, considering a higher value than the 80th-percentile will exclude a large number of conditions for which protected only should be recommended. For example, considering the 85th-percentile will exclude four of the eight conditions identified under the 80th-percentile criterion, including inadequate sight distance, for which protected only phasing should definitely be considered. Based on this criterion and the data presented in tables 5.7 through 5.9, conditions for the use of protected only phasing are listed below.

1. Use protected only phasing for:

    - approaches with restricted sight distance, and
    - approaches with four or more opposing lanes.

Decision Variable	Threshold	No. of Approaches Exceeding Threshold P/P	PTO
Left-Turn Volume (V_{lt})	> 320 vph	11 (37%)	19 (63%)
Opposing Volume (V_{op})	> 1100 vph	11 (29%)	27 (71%)
No. of Opposing Lanes (N_{op})	≥ 3	25 (43%)	33 (57%)
No. of Left Turn Lanes (N_{lt})	≥ 2	12 (29%)	30 (71%)
Sight Distance (Diff*)	< 0 ft	5 (21%)	19 (79%)
Left-Turn Mix (% HVs)	> 2.5 %	6 (38%)	10 (62%)
Opposing Speed Limit (Spop)	≥ 45 mph	12 (25%)	36 (75%)
Volume Cross Produce (V_{xp})	> $2.5\text{x}10^5$ $(\text{vph})^2$	7 (44%)	9 (56%)

* The difference between the available and required sight distance based on opposing speed limit.

Table 5.8. Number and Percent of Approaches Exceeding the Threshold Values (PTO: Protected Only, P/P: Protected/Permissive, HV: Heavy Vehicles).

Combinations	No. of Approaches Exceeding Threshold P/P	PTO
V_{lt} > 320 vph & V_{op} >1100 vph	2 (22%)	7 (78%)
V_{lt} > 320 vph & Spop ≥ 45 mph	2 (17%)	10 (83%)
V_{lt} > 320 vph & Mix > 2.5%	0 (0%)	3 (100%)
V_{op} > 1100 vph & Spop ≥ 45 mph	2 (10%)	18 (80%)
V_{op} > 1100 vph & Mix > 2.5%	0 (0%)	2 (100%)
N_{lt} ≥ 2 & Spop ≥ 45 mph	4 (20%)	16 (80%)
N_{op} = 3* & Spop ≥ 45 mph	1 (9%)	10 (91%)

* Only one intersection was studied with more than three opposing lanes.

Table 5.9. Number and Percent of Approaches Which Meet the Pairwise Threshold Combinations.

2. Use protected only phasing when any two of the following conditions are met:
   - left-turn volume > 320 vph,
   - opposing volume > 1100 vph,
   - opposing speed limit ≥ 45 mph, and
   - left-turn lanes ≥ 2.
3. Use protected only phasing when one of the following combination of conditions exists:
   - $N_{op} = 3$ & Spop ≥ 45 mph,
   - $V_{lt} > 320$ vph & Mix > 2.5%, and
   - $V_{op} > 1100$ vph & Mix > 2.5 %.

LEVEL 3 DECISION: PHASING SEQUENCE (LEAD, LAG, OR DALLAS PHASING)

In order to increase safety and reduce left-turn delay some special phasing types not included in the current MUTCD have been developed. These phasing types are a modification of the conventional lead/lag phasing. The special Dallas phasing (de Camp & Denney 1982) which has been in operation in the city of Dallas for some years is presented.

The Dallas phasing has the advantage of eliminating yellow traps which are a potential cause of left-turn accidents. In this phase sequence, shown in figure 5.6, the permitted green indication for the left-turn movement is allowed to end at the same time as the opposing through traffic, thus avoiding the yellow trap.

Detailed study of this special phasing has been reported by Collins (1988) and Fambro (1991). These studies indicate that the Dallas phasing results in less left-turn delay when compared to conventional lead/lag phasing types. Also the leading left phase of the Dallas phasing inflicts less delay to left turners compared to the lagging left phase. The leading left phase allows left-turn sneakers while this is not possible in the lagging left phase. The reports also show that for high opposing volumes there is no significant difference in left-turn delay between the Dallas and the conventional lead/lag phase. In other words, the Dallas phasing is suitable for low to moderate opposing flows and will work as well as conventional lead/lag in heavier volume conditions. The peak period left-

DALLAS PHASING

Green ball confusion

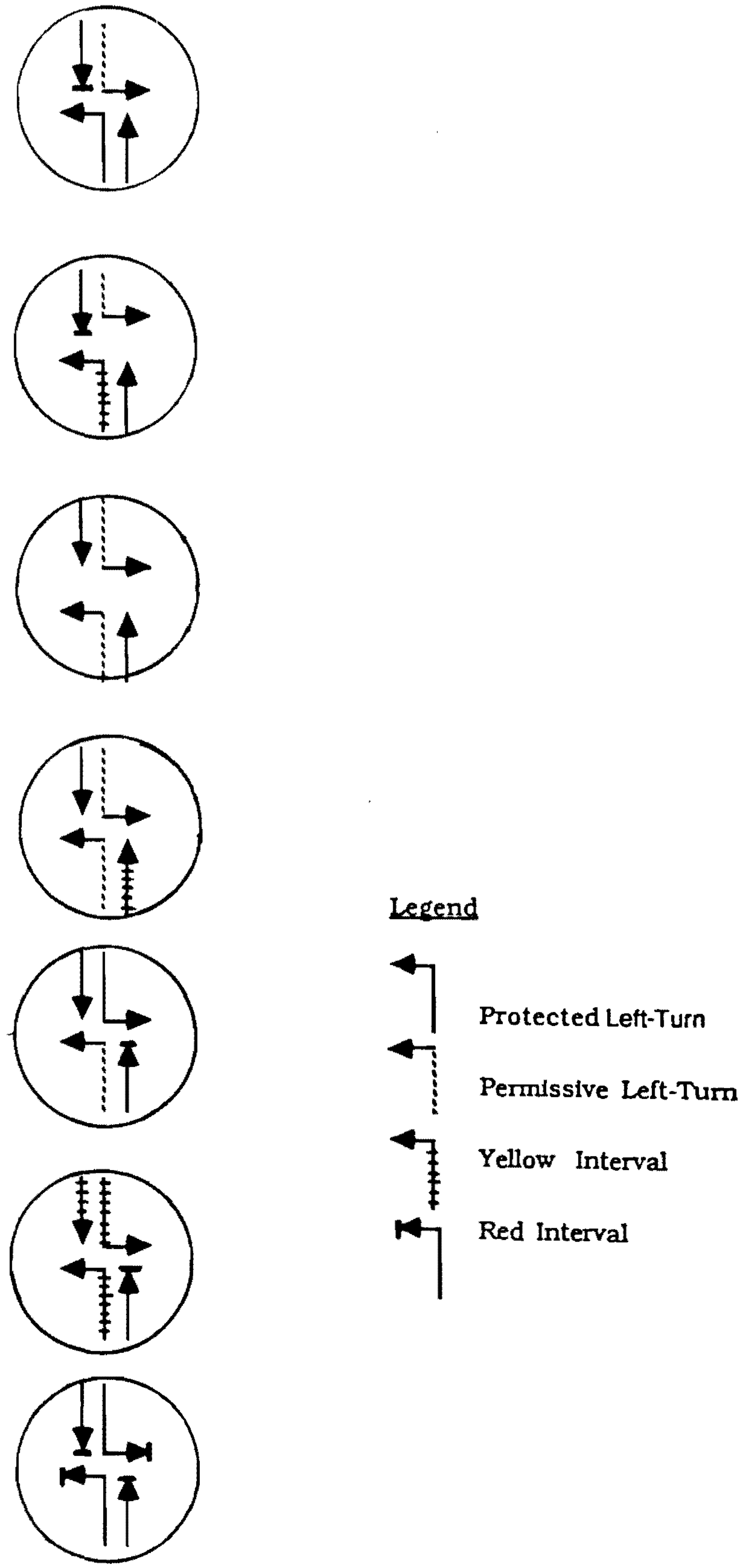


Figure 5.6 Dallas Phasing

turn delay results for the Dallas phasing found in the field studies performed for this study are shown in table 5.10.

A concern related to the Dallas phase sequence is that the approach with the lagging protected left-turn phase will initially receive a circular green (permissive indication) when green is terminated for the cross street (see figure 5.6). At the same time, the adjacent through approach continues to have a red indication since the opposing left-turn has a leading green arrow. Thus, there is a potential for drivers on the lagging left-turn approach to misinterpret the leading circular green as a protected phase. As discussed earlier, neither the motorist surveys nor the accident studies indicate this to be a problem, since a great majority of drivers always interpret the circular green over a left-turn lane as a permissive indication.

To address this concern, however, a variation of the Dallas phasing, to be referred to as the Arlington phasing, has been implemented in Arlington (figure 5.7). In the Arlington phasing, the lagging left-turn approach receives a circular green (permissive) indication only after the green arrow (protected phase) for the leading left (opposing) approach has expired. Consequently, the left-turning driver on the lagging left approach will not be displayed a permissive circular green when the adjacent through traffic faces a red indication.

Sequence	Mean	Std Dev	$P > \|t\|$
Lead	29.3	16.3	0.046
Lag	36.0	16.7	

Table 5.10. Mean Peak Period Left-Turn Stopped Delay and Standard Deviation for the Lead and Lag Sequence of the Dallas Phasing.

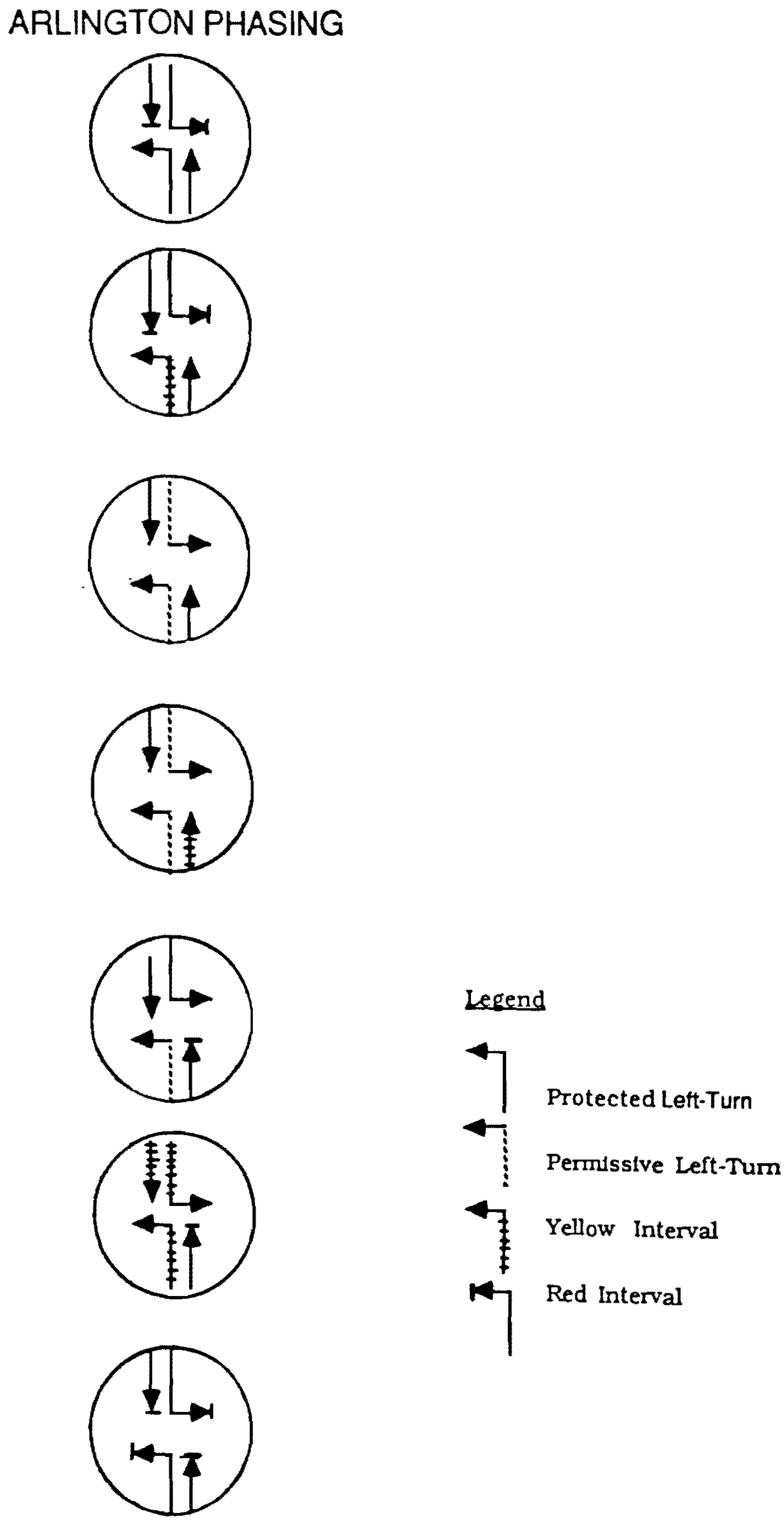


Figure 5.7 Arlington Phasing

The approach with the leading left in the Dallas phasing results in significantly less left-turn delay than the approach with the lagging left. This suggests that the lead portion should be allocated to the heavier left-turn traffic approach and, whenever possible, alternated to reflect the directional change in traffic volume.

DELAYS

Delay as a measure of effectiveness is the direct result of the interaction between the design and decision variables. The objective is to find a set of design variables that would minimize delay without sacrificing safety. Basically the three most common phasing types are protected only, protected/permissive, and permissive only. The special phasing types such as the "Dallas phasing" and its modified version, the "Arlington phasing," are also classified as protected/permissive phasings, but will be discussed separately. Decisions on the use of such special phasings are discussed under the Level 3 decisions. For each of the above phasing types, the following sequence of left-turn operations can be implemented:

- lead,
- lag, and
- lead/lag.

Combining the phasing types and the sequence of operations results in the following seven phase sequence combinations:

- permissive only,
- leading, protected only,
- lagging, protected only,
- leading, protected/permissive,
- lagging, protected/permissive,
- leading, protected/permissive with Dallas display, and
- lagging, protected/permissive with Dallas display.

The expected peak period left-turn delay values for the commonly observed phasing types and sequences are shown in tables 5.11 and 5.12.

As can be seen, protected/permissive approaches are generally associated with lower left-turn delays compared to protected only; and this difference is statistically significant. This observation may be somewhat intuitive as in protected/permissive

Phase	Mean	Std Dev	P > |t|	P > F
Protected Only	37.7	18.3	0.001	0.60
Protected/Permissive	20.3	19.3		

Table 5.11. Mean Peak Period Left-Turn Stopped Delay (secs/veh) and Standard Deviations for Protected Only Versus Protected/Permissive Phasing.

Sequence	Mean	Std Dev	P > |t|	P > F
Lead	29.3	18.3	0.06	0.006
Lag	39.4	26.4		

Table 5.12. Mean Peak Period Left-Turn Stopped Delay (secs/veh) and Standard Deviations for Lead and Lag Phasing Sequences.

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phasing the left-turn traffic has the opportunity to filter through gaps in the opposing traffic. Thus, protected/permissive phasings can be employed to reduce delay to left-turning vehicles significantly. Lower left-turn delays are also observed for leading as compared to lagging sequences.

Lead/lag operation (whether protected/permissive or protected only) may be implemented for reasons other than local reduction in left-turn delay. Arterial progression is often greatly improved by the use of lead/lag operation, since the two through green times are not constrained to occur at the same time. In addition, an intersection may not be large enough to accommodate both opposing lefts occurring together, particularly if one or both of them are turning out of double left turn lanes. In this case, a lead/lag phase pattern would be necessary in order provide protected turning in both directions.

CHAPTER 6

ACCIDENT AND CONFLICT STUDIES

ACCIDENTS

The type of phasing and sequence not only affects delay, but also accidents and conflicts. In addition, the motorists' relative understanding of the various forms of phasing differ significantly. While motorists easily understand protected only operation, many have problems correctly interpreting some of the more elaborate protected/permissive phasing types. Auxiliary signs are used to improve motorists' understanding but they do not entirely alleviate the problem. As part of this research a survey was conducted, as described in Chapter 3, to examine the motorists' understanding of left-turn traffic signal indications and associated auxiliary signs. The results clearly show that motorists have problems interpreting some of these left-turn signs and signals.

To assess the safety aspects of these phasing types, forty-two intersections were selected for accident studies. Accident data on these intersections were obtained from the Texas Department of Transportation (TxDOT) and the traffic engineering departments of the cities of Arlington, Dallas, and Fort Worth. The records represent three successive years from 1988-1990 for the data from TxDOT, Dallas and Fort Worth and 1989-1991 for the data from Arlington. Accident data for November and December was not included in the 1991 records for Arlington.

Signal timings, phasing, and geometric history of the intersections involved were also obtained from the city traffic departments to ensure that no major geometric or signalization changes had taken place which might have influenced accidents. Two intersections were reported to have undergone such changes; however, they took place shortly after those intersections had been studied by the research team.

The detailed accident records furnished information on the direction of movement, type and cause of accident, accident location, and type of movement for all vehicles involved in the accident. Only accidents involving left-turns were extracted for analysis. For each of the 42 intersections the following data were recorded:

- number of accidents involving left-turns,
- phasing type of the approach from which the left-turn entered,
- phasing sequence, and
- number of left-turn lanes.

The analysis was individually performed for each intersection approach. The left-turn accident total for each approach was then matched with the corresponding phase pattern and other characteristics of the approach such as opposing traffic speed limit and number of lanes for the left-turn and opposing traffic.

As described in Chapter 4, accident totals rather than rates were used in the study because of their availability and ease of application. Accident rates tend to be biased with low volume approaches having higher rates and vice versa. In addition, the best measure of exposure would be a volume cross product, which would require an estimate of the turning movement volumes at each intersection, while most cities only maintain fairly current ADT estimates for the intersecting streets. Average numbers of left-turn accidents for the various phases and sequences at the intersections in this study are shown in tables 6.1 and 6.2.

The large standard deviation shows the high variability in the left-turn accident data. However, on the average, protected/permissive approaches have significantly higher left-turn accident totals than protected only approaches. The p-value for comparison between protected only and protected/permissive phasings was 0.10, i.e., a 10% level of significance.

Besides phase patterns, a number of other factors affect left-turn accidents and could account for the large standard deviations observed. Among them are intersection geometry, sight distance, approach speeds, traffic volume, and weather conditions. The smaller number of intersections with lagging sequences in our study may also be a contributing factor in the large variation in the data.

However, regardless of the above-mentioned factors, the higher standard deviation and mean left-turn accident totals for the protected/permissive approaches suggest consistently higher left-turn accident totals for protected/permissive as compared to protected only phases. It should also be noted that higher accident rates for left-turning

Phase Sequence	Mean	Std Dev	Approaches Studied
Protected Only	2.57	3.16	77
Protected/Permissive	3.69	3.96	36
Permissive Only	1.27	1.66	26
Dallas	2.92	4.60	18

Table 6.1. Three-Year Left-Turn Accident Totals for Left-Turn Phasing Types.

Sequence	Mean	Std Dev	Approaches Studied
Lead	2.9	3.5	102
Lag	2.8	2.9	11

Table 6.2. Three-Year Left-Turn Accident Totals for Lead and Lag Sequences.

vehicles at protected/permissive approaches have also been reported by Upchurch (1985) and Agent (1985) in their studies on left-turn phasing treatments.

Thus, protected only phase patterns can be used to reduce left-turn accidents at protected/permissive approaches with an excessive number of left-turn accidents. The focus of the accident analysis in this study has been to establish what constitutes an "excessive" number of left-turn accidents for protected/permissive operation. The 85th-percentile (mean + one standard deviation) accident numbers were selected as a criterion.

The 85th-percentile 3-year accident totals for left-turns was eight accidents for approaches with protected/permissive and six for protected only approaches. Consequently, protected/permissive approaches with seven or more left-turn accident totals over a three year period could be considered to have an exceptionally high number of left-turn accidents. In such cases, a protected only phase pattern could be used to reduce the number of left-turn accidents.

The safety of leading and lagging sequences, as measured through the number of left-turn accidents, are not significantly different, as shown in table 6.2. However, leading sequences are likely to have higher left-turn accident totals as indicated by their large variance. (Although, an F-test showed these differences not to be significant.) Hummer, et al. (1991), also reported higher left-turn accidents for approaches with leading as compared to lagging sequences (although not significantly so). (Lee, et al. (1991), also found no significant differences between the accident rates for leading and lagging operation for both total intersection and left-turn accident rates.) This higher number of left-turn accidents at approaches with the leading sequence of a lead/lag pattern may be partly attributed to the so-called "yellow trap" phenomenon, i.e., the yellow interval which ends the protective portion of the protected/permissive phase. The yellow trap will also occur when overlaps are used with the lagging protected/permissive sequence. The problem with yellow trap is the false impression that the yellow interval gives the left-turn traffic, that the opposing traffic is also displayed a yellow indication when the left-turn approach has yellow.

The Dallas phase pattern was developed to eliminate yellow traps, and is a modified form of conventional lead/lag phase patterns. The Dallas phasing, and its derivative, the Arlington phasing, are described in greater detail in Chapter 5, and shown in figures 5.6 and 5.7.

Recent studies by Collins (1988), Brookes, et al. (1990), and Fambro (1991) indicate that the Dallas phasing does not reduce intersection safety but does increase intersection capacity. The studies also indicate that Dallas phasing produces less delay when compared with the traditional phasing types. Also the leading left phase of the

Dallas phasing incurs less delay when compared to the lagging left phase. This was attributed to the fact that the leading left phase allows left-turn sneakers during the yellow interval while this is not possible for lagging left approaches.

CONFLICTS

Another measure of effectiveness of intersection performance is the number of conflicts per approach. Although data are not readily available on conflicts, as they are not documented, such data may easily be obtained from the field. Conflict analysis can be a powerful tool in determining the relative safety of intersections. Many latent risk factors at intersections are not reflected in accident records and can only be identified and extracted from conflict studies. Most left-turn conflicts of near-miss type do not result in accidents and hence are not recorded. The safety of an approach or intersection may therefore be better assessed through conflict studies.

In this study, the left-turn conflict rate (C_{lt}) was determined from video tapes. The elapsed time from the start of each study period to the occurrence of the first conflict was used as a surrogate variable to determine the conflict rate. Where no conflict was observed during the whole one-hour observation period, a time value of 60 minutes was used. The number of conflicts was expressed in units of conflicts per million squared vehicles/lane (generally referred to as million squared vehicles in this report):

$$C_{lt} = \frac{(60/T)\ (10^6)}{(V_{lt}/N_{lt})\ (V_{op}/N_{op})} \ ,$$

where C_{lt} = number of conflicts per million squared vehicles,

N_{lt} = number of left turn lanes,

N_{op} = number of opposing lanes,

V_{lt} = left turn volume (vph),

V_{op} = opposing volume (vph), and

T = time to first observed conflict (minutes).

The four left-turn conflict types used in this study were:

Type 1. Left-turn vehicle causing the opposing vehicle to brake or weave to avoid collision.

Type 2. The second through vehicle in the opposing path also having to take an evasive action.

Type 3. Vehicles entering the intersection during any indication and turning left on red.

Type 4. Rear-end conflict in the left-turn lane when the following vehicle brakes after the lead vehicle begins its turning maneuver and then stops.

The result of the conflict study for the various phasing types and sequences are shown in tables 6.3 and 6.4. It should be noted that most of the observed conflicts were of types 1 and 3.

Phase Type	Approaches Studied	Mean	Std Dev	85th Percentile
Protected Only	62	146	146	262
Protected/Permissive	47	176	272	448
Permissive Only	29	914	1130	2044

Table 6.3. Conflict Rates (Conflicts per Million Squared Vehicles) for Left-Turn Phasing Types.

Phase Sequence	Approaches Studied	Mean	Std Dev	85th Percentile
Lead	86	156	230	386
Lag	23	90	101	191

Table 6.4. Conflict Rates (Conflicts per Million Squared Vehicles) for Lead Versus Lag Phasing Sequence.

The p-value for the hypothesis that the leading and lagging sequences result in the same number of conflicts was 0.04, thus lending statistical significance to the alternate hypothesis that lagging sequences result in significantly fewer conflicts. Note that the corresponding result was not clearly visible in the accident data analysis as reported in table 6.2. However, the vehicles creating the type 3 conflicts are sneakers, which, buy definition, are turning at the end of a permissive green (not followed by a protected green). Thus, leading protected/permissive operations will always have more conflicts.

The conflict studies do confirm the inferences made from the accident studies, that lagging sequences have a smaller accident potential than leading sequences. Table 6.4 shows that lagging sequences result in fewer than 191 conflicts roughly 85% of the time (i.e., mean + standard deviation), thus, if a leading sequence results in more than 191 conflicts, then a lagging sequence is bound to result in fewer conflicts. Table 6.3 also shows that permissive approaches, as expected, have the highest conflict rates followed by protected/permissive approaches, while protected only approaches have the lowest conflict rates. Table 6.3 shows that protected/permissive sequences result in fewer than 448 conflicts roughly 85% of the time (i.e., mean + standard deviation). Thus, if a permissive only approach is experiencing more than 448 conflicts, then a protected/permissive operation is bound to result in fewer conflicts. By the same token, if an existing approach with protected/permissive operation experiences more than 262 conflicts (table 6.3), then protected only operation is likely to reduce the number of conflicts.

In summary, it has been determined that protected only approaches have higher delays (Chapter 5), however, they experience fewer accidents. Protected only approaches have both the lowest conflict and accident rates. Protected/permissive approaches, on the other hand, have lower delay but produce higher accident and conflict rates as compared to protected only phasing. Permissive only approaches are associated with the lowest delay but very high conflict rates. The low accident totals for permissive only approaches stem from the fact that they are generally low volume intersections, i.e., for a given accident rate, the lower volumes (and, thus, lower exposure) imply a smaller number of accidents. These approaches were not problematic, otherwise they would have already been corrected by some form of left-turn protection.

Based on the results of the accident and conflict studies presented above, the following recommendation can be made:

1. Use protected only phasing when

    - seven or more left-turn accidents in a three-year period are reported for a protected/permissive approach, and the expected delay for protected only phasing is acceptable (within the desired level of service), or

    - 260 or more left-turn conflicts per million squared vehicles are found for a protected/permissive approach.

2. Use Dallas phasing when

    - the use of protected only phasing will result in high delays but the 3-year accident total exceeds seven or more for a single approach for an existing protected/permissive operation; although not specifically studied, the Arlington phasing could be used in this situation as well.

3. Use lagging sequences for left-turns where

    - the use of leading sequences have resulted in more than 190 left-turn conflicts per million squared vehicles (mean + standard deviation for lag sequence in table 6.4), or

    - the use of lagging sequence is necessary as part of an overall network progression scheme.

CHAPTER 7

SUMMARY OF GUIDELINES

The guidelines presented in the preceding four chapters are summarized below. Full details regarding their development are described in Chapters 3 through 6 of this report.

ENGINEERING STUDY NEEDS

A number of site conditions and characteristics are required when considering the appropriate left-turn signal treatment. A comprehensive list of data needs for such a study is provided below. However, only a subset of these data may be necessary for any particular intersection.

Vehicular volumes

- peak hour volume measured at fifteen-minute intervals for the left-turning traffic, expressed in vehicles per hour,
- peak hour volume measured at fifteen-minute intervals for the opposing traffic, expressed in vehicles per hour, and
- the percentage of heavy vehicles (vehicles with more than 2 axles or four tires) in the left-turning traffic.

Intersection geometrics

- available stopping sight distance for the left-turning and opposing traffic based on the approach speed limits (current AASHTO standards recommended),
- number of opposing lanes that the left-turning traffic must cross,
- number of left-turn lanes in the left-turn bay, and
- availability of adequate intersection width and area to allow for operation of dual left-turn movements.

Average Stopped Delay

- the average stopped delay to left-turning traffic at peak hours for each approach in seconds per vehicle, and
- the overall stopped delay for the intersection in seconds per vehicle.

Opposing Traffic Speed Limit

- the posted speed limit of the opposing approach, or, if no speed limit is posted, the 85th-percentile speed for the approach.

Accident Totals

- a 3-year accident history involving left-turning vehicles for each approach of the intersection.

Conflict Rates

- left-turn conflict rate expressed in conflicts per million entering squared vehicles for each approach.

System Consideration

- existence of a signal coordination scheme on either of the streets.

GUIDELINES

The guidelines developed for phase selection address a number of decisions regarding the suitability of left-turn phasing treatments to be used. In all cases it is assumed that a separate left-turn bay exists for use by left-turning vehicles. The guidelines are based on threshold values designed to determine what constitutes an "excessive" value of any particular variable, beyond which a specific left-turn phasing treatment may be justified. The decisions to be made are classified into three levels:

Level 1. Is a permissive only left-turn phase adequate or should some form of protection (green arrow) be provided?

Level 2. If protection is called for, is a more restrictive protected only phase justified or would a protected/permissive phase suffice?

Level 3. If protected/permissive phase is to be used, would a lead operation be sufficient or should a lead/lag or Dallas phasing sequence be provided? Also, if a protected only phase is prescribed, could a lead sequence be used or should a lag option be considered?

Level 1. Permissive Only versus Some Protection

This is intended for application where the decision entails determining whether a permissive only phase is appropriate or some protection (green arrow) is necessary. It is recommended that a permissive only phase pattern be replaced by a phase pattern with some left-turn protection when any one of the following conditions exist:

- the plotted point representing the peak period volume in vehicles per hour (based on the peak 15-minute) and the corresponding opposing traffic speed limit (in mph) falls above the line (in the unshaded portion) in figures 7.1 through 7.3 for the existing number of opposing lanes.
- sight distance for the left-turning vehicle is restricted, based on the posted speed limit for the opposing traffic; in such cases, full protection is recommended; recommended sight distances are provided in AASHTO (1990).
- more than eight left-turn related accidents have occurred within the last three years at any one approach with permissive only phasing.
- more than 450 left-turn related conflicts per million entering squared vehicles (i.e., $vphpl^2$) is observed at an approach with permissive only phasing.

Level 2. Protected/Permissive versus Protected Only Phase Patterns

Once the decision is made to provide some left-turn protection, it must be determined whether a protected/permissive phasing would suffice or a more restrictive, protected only phase pattern be prescribed. A number of factors are involved in determining which phase pattern to use. If possible, the more efficient protected/permissive phasing should be used unless a protected only phasing is absolutely necessary. Protected only phase patterns are recommended under any of the following conditions:

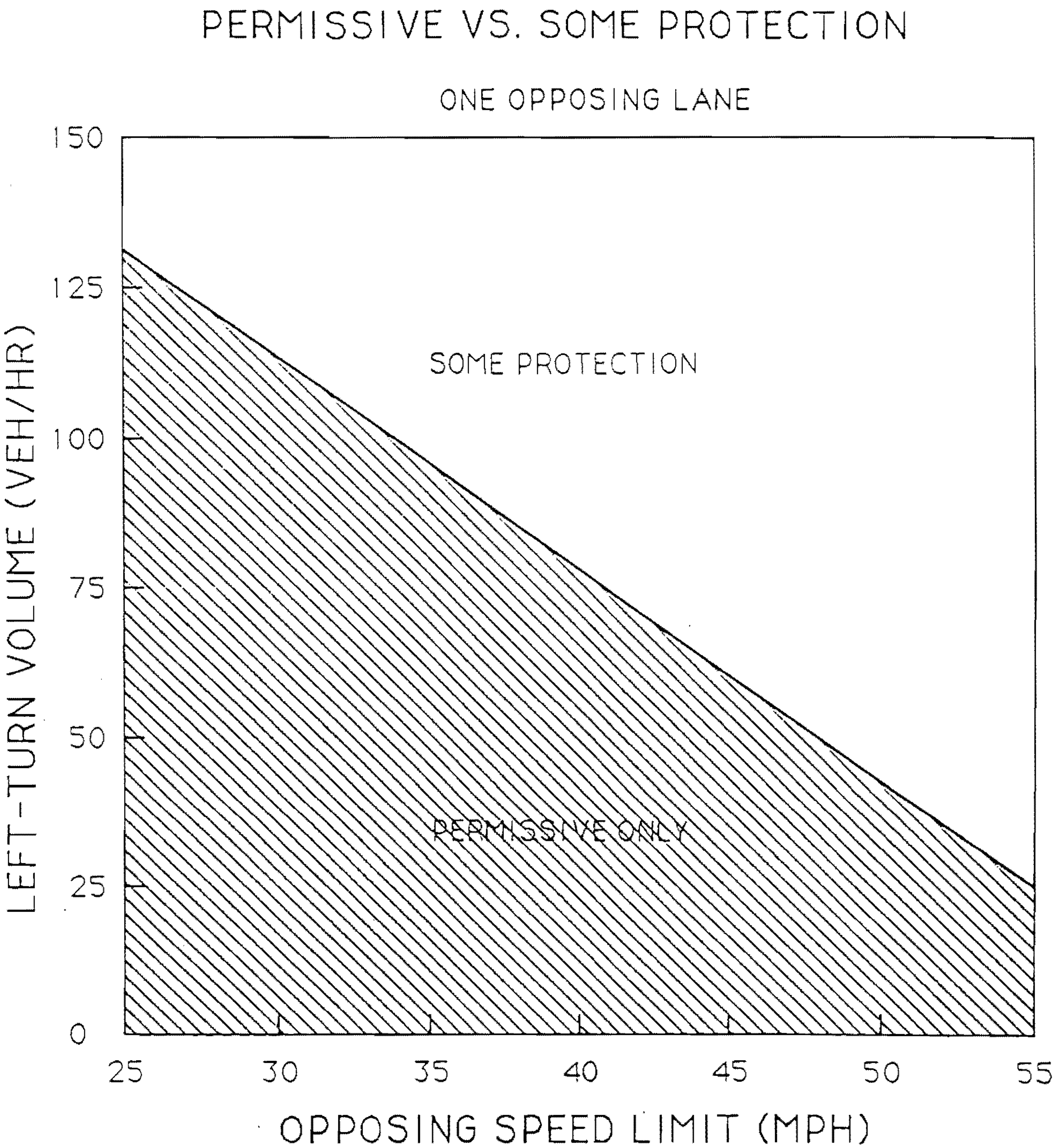

Figure 7.1 Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face one opposing lane.

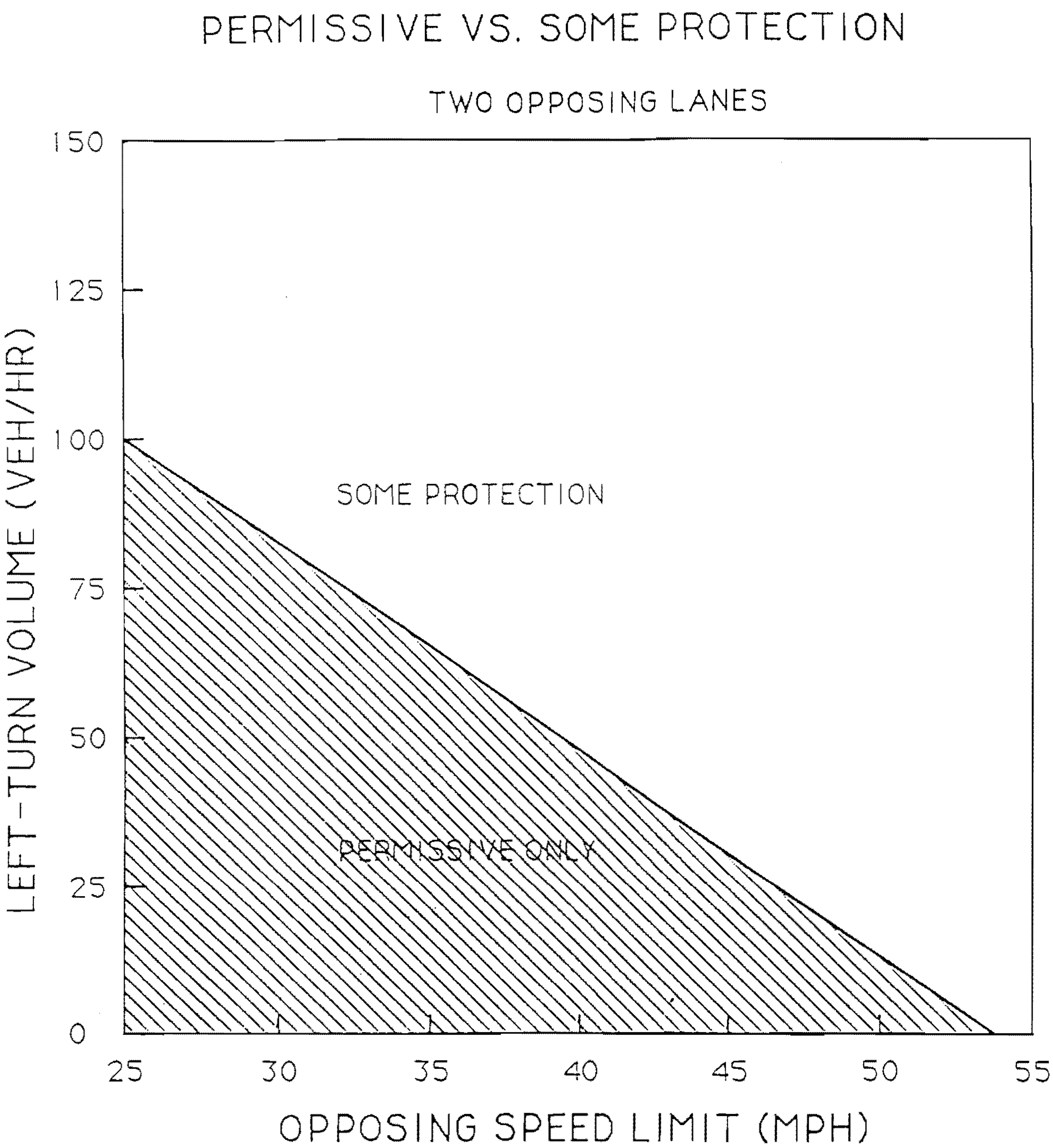

Figure 7.2 Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face two opposing lanes.

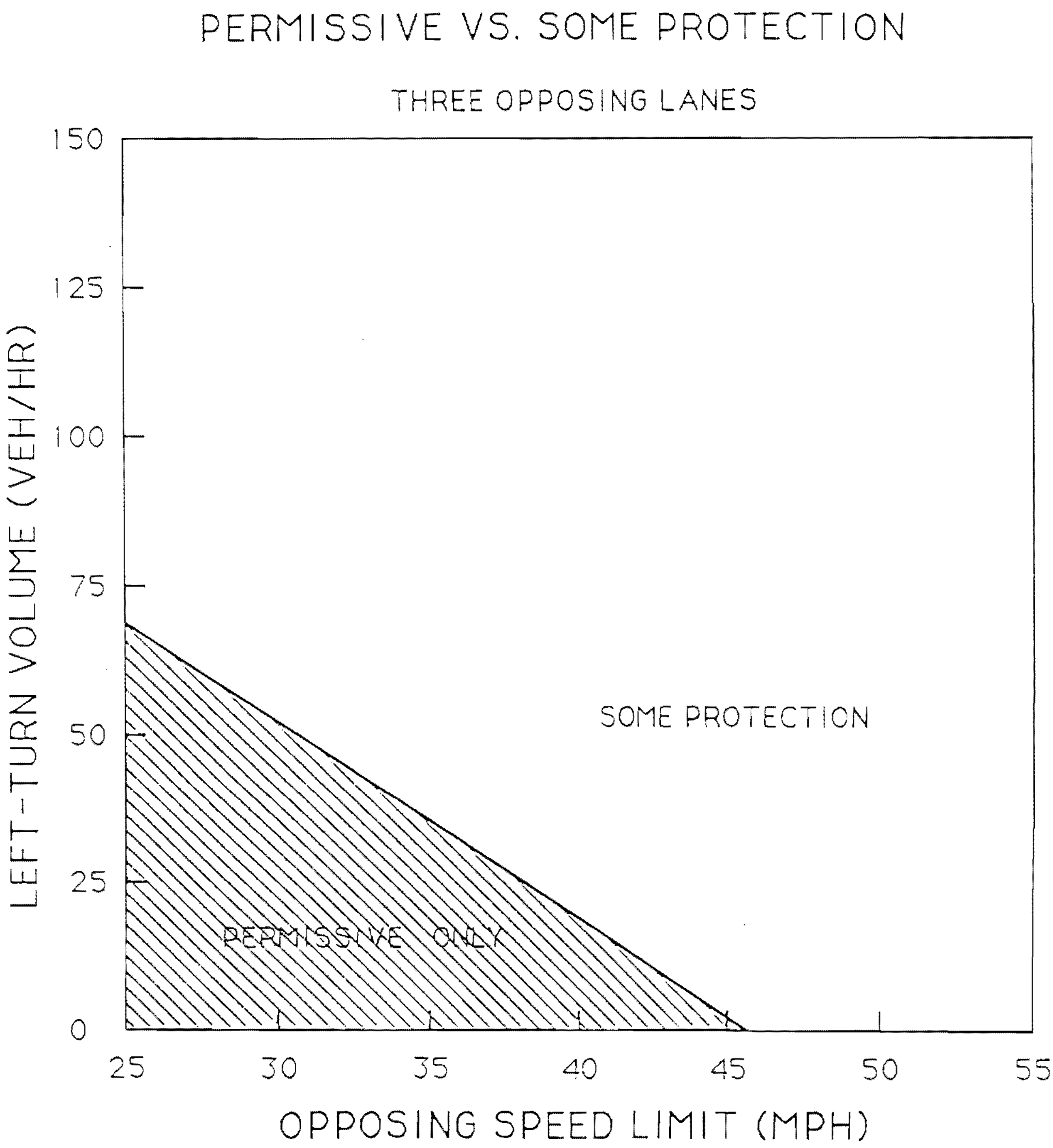

Figure 7.3 Selection guide for the choice between permissive only versus some left-turn protection when the left-turning vehicles face three opposing lanes.

- Use protected only phasing for:
  - approaches with restricted sight distance, determined by the posted speed limit on the approach opposing the left-turn traffic, or
  - approaches with four or more opposing lanes that must be crossed by the left-turn traffic.
- Use protected only phasing when any two of the following conditions are met:
  - peak fifteen-minute flow rate for the left-turning traffic is greater than 320 vph,
  - peak fifteen-minute flow rate for the opposing traffic is greater than 1100 vph,
  - opposing speed limit is greater than or equal to 45 mph, or
  - left-turn lanes are two or more in number.
- Use protected only phasing when any one of the following conditions exist:
  - number of opposing lanes equals three and the opposing speed limit is greater than or equal to 45 mph,
  - left-turn volume is greater than 320 vph and the percent of heavy vehicles in the left-turn traffic exceeds 2.5%,
  - opposing volume is greater than 1100 vph and the percent of heavy vehicles in the left-turning traffic exceeds 2.5%,
  - seven or more left-turn related accidents have occurred within a 3-year period for a protected/permissive approach,
  - more than 260 left-turn related conflicts per million squared vehicles are observed for a protected/permissive approach, or
  - the average stopped delay to left-turning traffic is acceptable (within the desired level of service) for protected only phasing and it is the judgement of the traffic engineer that the use of protected/permissive phasing will result in a greater number of left-turn accidents.

Unless one of the above criteria is met, a protected/permissive phase pattern should be used. They increase intersection capacity and reduce delay significantly as compared to protected only phasing.

Level 3. Sequence of Phasing - Lead or Lag?

The level 3 decision is intended for the selection of the appropriate phase sequence once the type of phasing to be used has been determined.

Leading sequences are, from the efficiency standpoint, more desirable, since they are associated with lower delays and increased intersection capacity. Lagging sequences, on the other hand, appear to be potentially safer compared to leading sequences. The following recommendations are made in deciding between a lead or a lag sequence for a single approach:

- A leading sequence is recommended for:
  - protected/permissive phase that has been determined to be suitable under the guidelines outlined above, provided that it will not disrupt a progression scheme on either street, or
  - a protected only phase that has been determined to be suitable under the guidelines outlined above, provided that it will not disrupt a progression scheme on either street.
- Dallas phasing is recommended under the following conditions:
  - where a protected/permissive has been determined to suffice but the resulting level of service is not within acceptable levels, or
  - where the 3-year accident total equals or exceeds seven but the use of a protected only phase will result in unacceptably high delays.
- A lagging sequence is recommended where:
  - it is intended to improve the safety of an already installed leading sequence, under which more than 190 conflicts per million squared vehicles are experienced, or
  - the lagging left-turn sequence is necessary as part of an overall network or arterial progression scheme.
- A lead/lag sequence is recommended for intersections where:
  - there is inadequate space within the intersection to safely accommodate dual left operation, or
  - it is necessary for the progression scheme.

The guidelines developed provide a simple three-level procedure to aid in the selection of the appropriate left-turn signal treatment. The data requirements for each decision level are different, reflecting the different objectives to be dealt with at each level.

These guidelines also reflect a selection process which recognizes the trade off between operational efficiency and safety. More than one condition is required in some cases to justify the selection of a particular phase so as to ensure an optimum solution.

SIGNAL INDICATION AND AUXILIARY SIGNS

Operational efficiency and safety can be further enhanced by the use of appropriate signal indications and auxiliary signs that are well understood by the driving public. The following recommendations, concerning signal indications and auxiliary signs, in conjunction with the above-mentioned guidelines, are made:

- Use of red arrows should be accompanied by a public educational program. While the red is the prohibition color, an arrow indication implies movement. Hence a red arrow may be interpreted as "proceed with caution."
- A green arrow should always be used to indicate left-turn protection. Circular green with or without an auxiliary sign should never be used to indicate a protected left-turn.
- A circular red and a green arrow should not be shown simultaneously in a five section head (for dual left-turn operation), as the circular red indicates a strong prohibition, while the green arrow indicates an allowable movement. When these indications are shown simultaneously on a single head, drivers may misinterpret the indication as a permissive rather than a protected turn.
- LEFT TURN YIELD ON GREEN [symbolic green ball] (auxiliary sign type 6 in this study, or R10-12 in the MUTCD) should be used, if necessary, when permissive turning is allowed.
- LEFT TURN YIELD ON GREEN [symbolic green ball] (auxiliary sign type 6 in this study, or R10-12 in the MUTCD) should always accompany the left-turn signal head if the Dallas phasing is used.

CHAPTER 8

CONCLUSIONS AND RECOMMENDATIONS

Guidelines have been developed for the selection of left-turn phase patterns, indication sequences, and auxiliary signs. The guidelines developed incorporate operational efficiency and safety as well as motorists' understanding of signal indications and auxiliary signs and are based on extensive field studies, motorist surveys, and accident studies. A three-level decision process is devised to assist the traffic engineer in selecting appropriate left-turn treatment at a signalized intersection. The guidelines and recommendations are based on threshold values designed to determine what constitutes an "excessive" value for any particular variable/factor beyond which a specific left-turn treatment can be justified. The conventional logistics choice model has also been employed.

It has been determined that the selection of any particular phase pattern is a multi-objective process involving a number of factors. In many cases, more than one condition must be met to justify the selection of a particular phase pattern and to ensure an optimal solution. Recommendations on the use of indication sequences and auxiliary signs are also made to further enhance left-turn operational efficiency and safety.

Further research on safety and motorist preferences for different left-turn signal treatment options is required. In addition, more field data would improve the accuracy of the threshold values and strengthen the results. Special emphasis on the safety aspects of leading and lagging sequences must also be addressed. Further research is also required to study the special Dallas phasing as more cities adopt this phasing type, more drivers are exposed to it, and other variations such as the Arlington phasing evolve. The Arlington phasing has been designed to remove the leading permissive green confusion for left turns with lagging protection in the Dallas phasing, as shown in figures 5.6 and 5.7. In the Arlington phasing scheme, the approach with lagging left protection receives a permissive green indication only after the green arrow displayed to the leading left approach and its clearance interval have expired. Therefore, the left-turning driver will never be displayed a permissive green when the adjacent through traffic faces a red display at the beginning of the main street green phases. The operational safety and efficiency of the Arlington phasing and the conventional Dallas phasing also need to be compared.

The guidelines developed and the recommendations set forth as part of this study can be disseminated within the Texas Department of Transportation by their incorporation into the departmental design and operations manuals, and possibly as an appendix to the Texas MUTCD. Immediate benefit to drivers, once the guidelines are implemented, will be increased safety as a direct result of consistency in design and motorist understanding. As drivers become more accustomed to particular phase sequences and signal indications, vehicular flows through the intersections are also expected to increase, thereby providing a more efficient intersection operation.

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APPENDIX A

MOTORIST SURVEY FORMS

AND SCENARIOS

Note: The survey forms are reproduced in this appendix without color; the appropriate colors were used on the mailed survey forms.

THE UNIVERSITY OF TEXAS AT ARLINGTON

8 March 1991

DEPARTMENT
OF CIVIL
ENGINEERING

Dear Motorist:

We are investigating drivers' understanding of left-turn traffic signal displays and signs. This research is sponsored by the Texas State Department of Highways and Public Transportation and the Federal Highway Administration. Its main objective is to identify the left-turn signal indications and signs that are most easily understood.

As part of this research effort, we are mailing survey forms to a number of randomly selected drivers across the state. The survey is multiple choice, and should not take more than a few minutes of your time.

A sketch at the top of each page of the survey shows what you might see if you wanted to turn left at the intersection and were in the left-turn lane. Immediately below the sketch, the traffic signal lights that you might see as you approach the intersection are shown followed by two multiple-choice questions. Below these two questions, a different combination of traffic signal lights (and signs) are shown for the same intersection approach, followed by the same two questions. Please note that all the combinations of traffic signal lights shown on the survey forms are currently in use in Texas.

The second page shows a different type of intersection, and two possibilities for the traffic signal lights. On the last page, there are a few questions to help us classify your responses. Please do not sign the survey form.

Please take a few minutes now to complete this survey, place it in the enclosed self-addressed, prepaid envelope, and drop it in any mailbox. Your assistance in this research is greatly appreciated.

Sincerely,

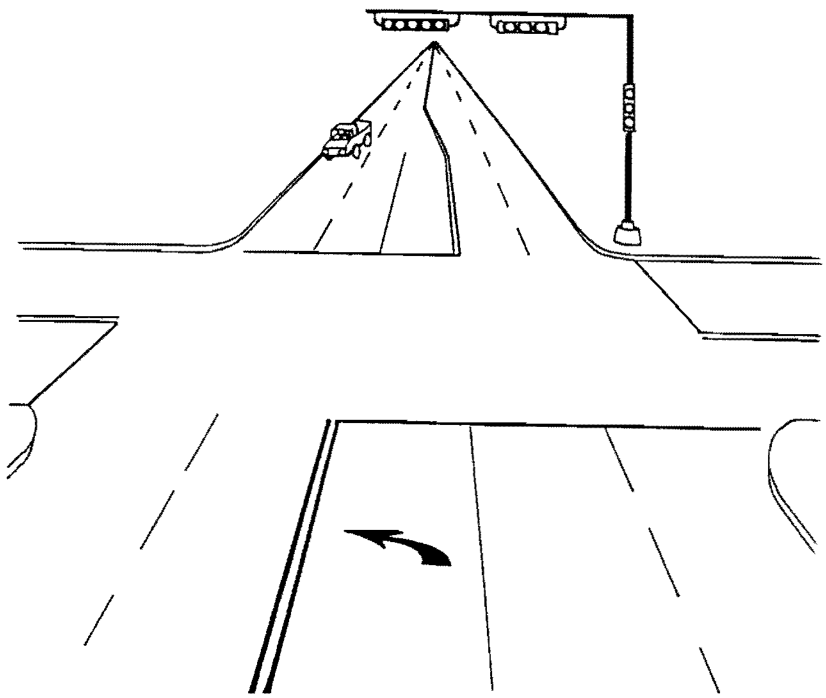
S. Ardekani

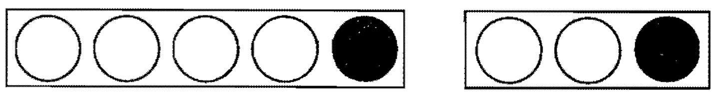
Sia Ardekani
Assistant Professor

James C. Williams

James C. Williams
Assistant Professor

1-1-0
1-3-0





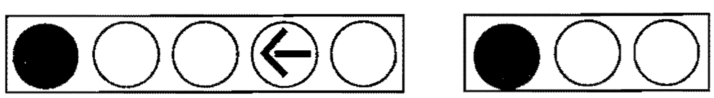
If you are waiting to turn left and see the above signal indication:

1. Are you allowed to turn left?   Yes   No   (please circle)

2. If you can turn left,

   ☐ You must wait for a large enough opening in the oncoming traffic.

   ☐ You may turn if the intersection is clear, since the oncoming traffic must stop.



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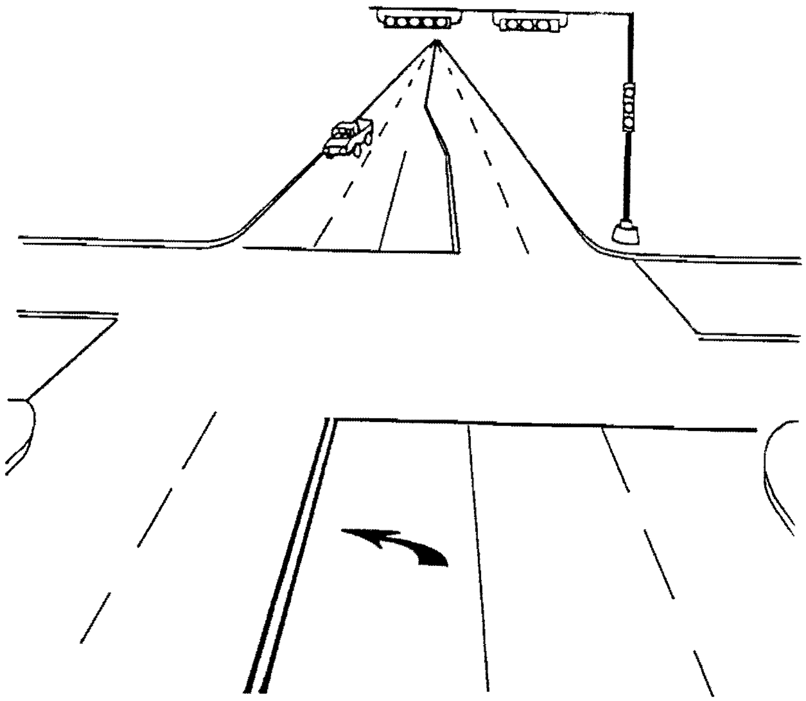

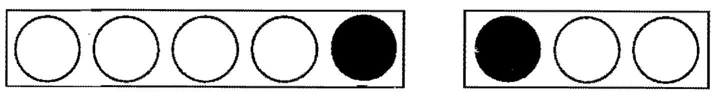

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1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

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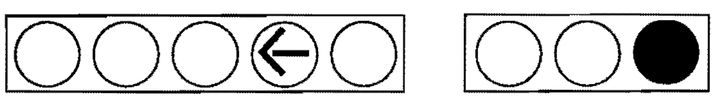

If you are waiting to turn left and see the above signal indication:

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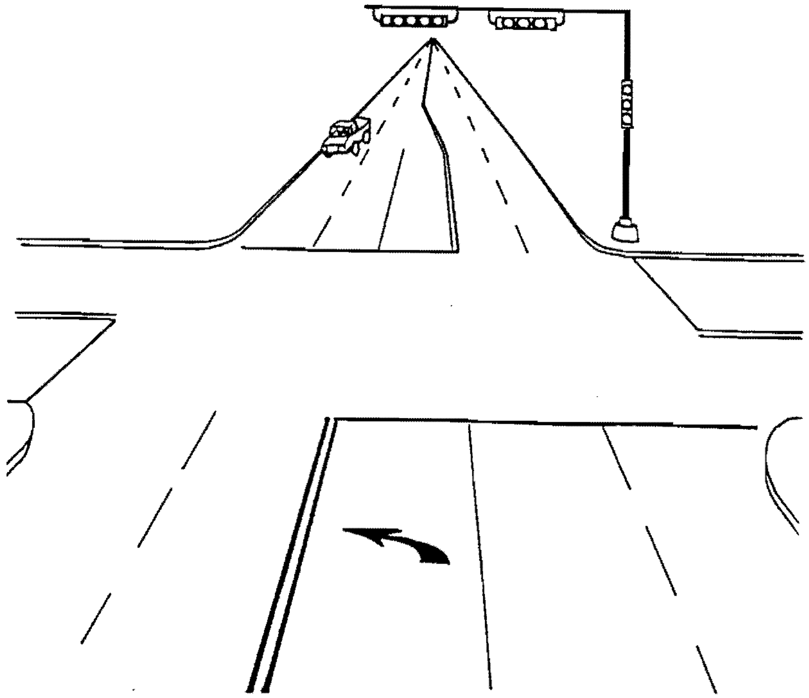
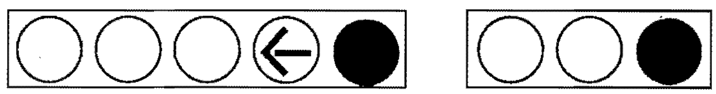
2. If you can turn left,

   - ☐ You must wait for a large enough opening in the oncoming traffic.
   - ☐ You may turn if the intersection is clear, since the oncoming traffic must stop.

1-5-0
1-6-0





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1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

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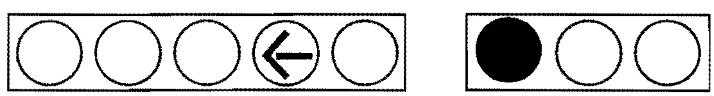

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2. If you can turn left,

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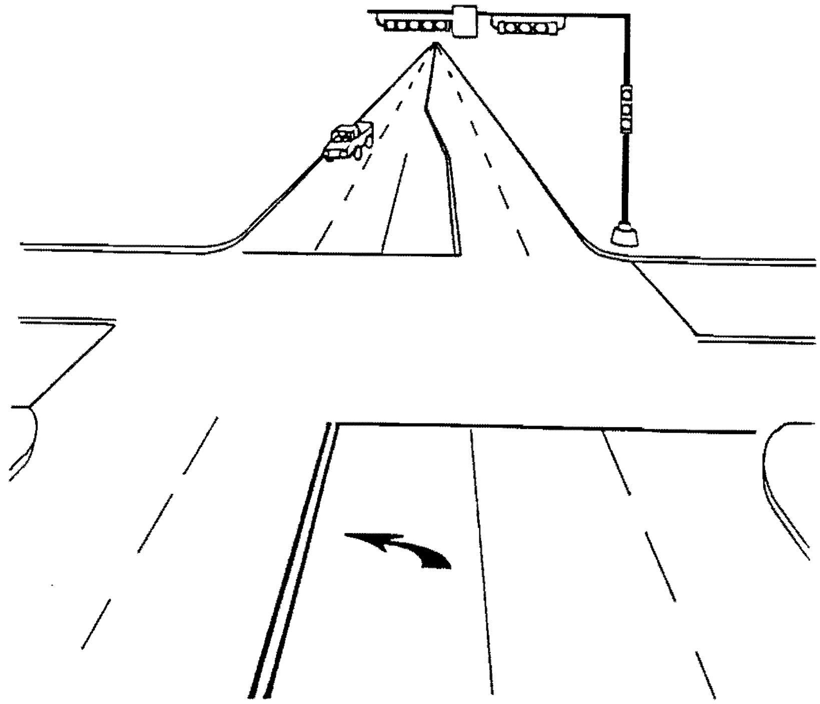
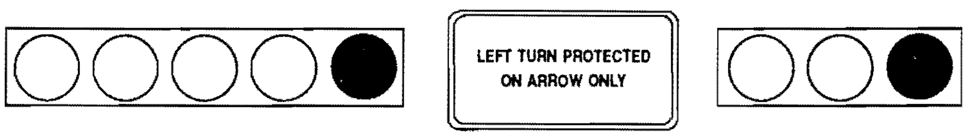
☐ You may turn if the intersection is clear, since the oncoming traffic must stop.

2-1-3
2-6-11





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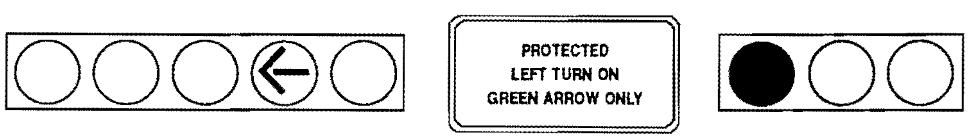

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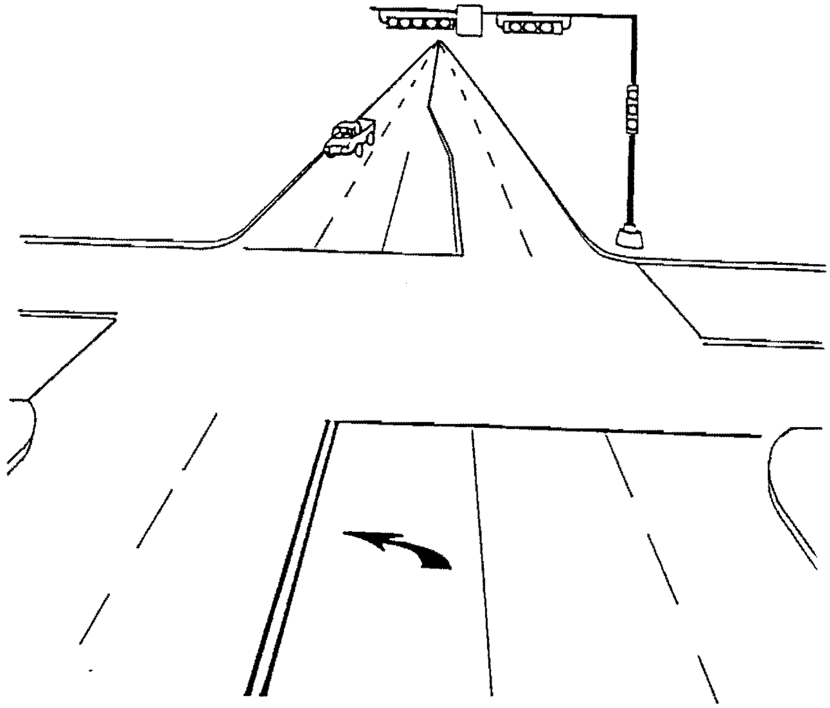
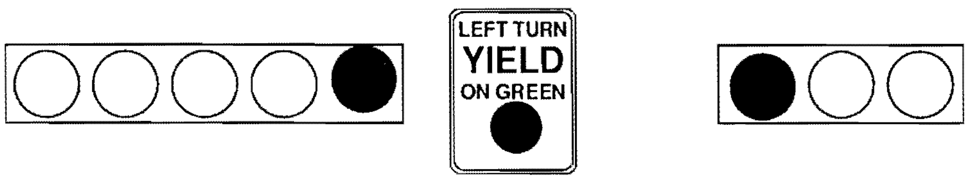
2-2-6
2-5-2

118





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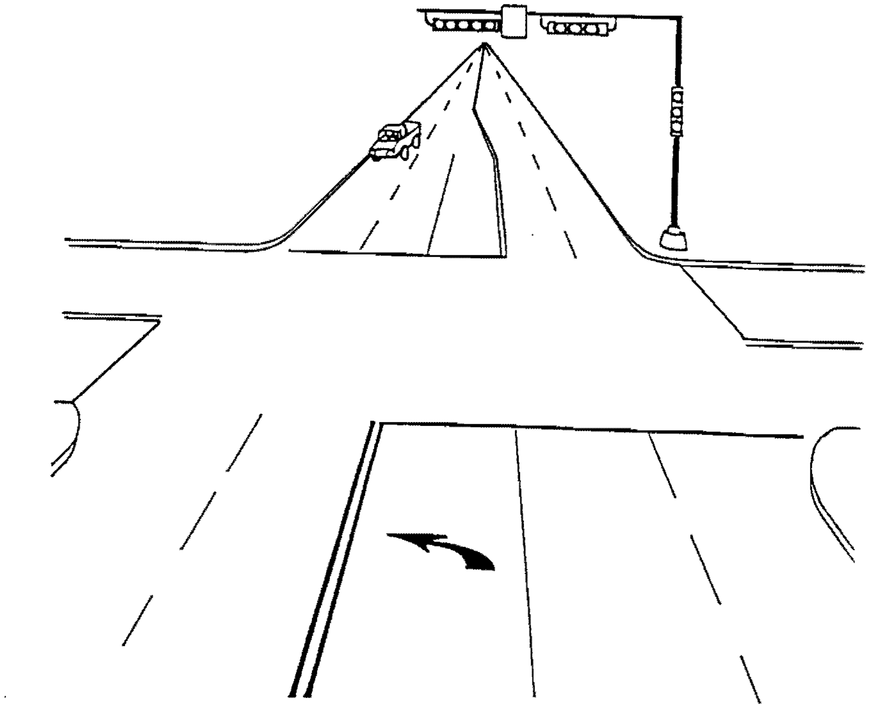
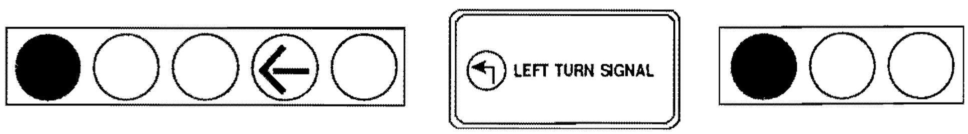
2-3-7
2-4-9





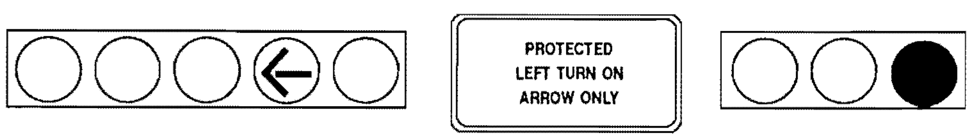
If you are waiting to turn left and see the above signal indication:

1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

   - [ ] You must wait for a large enough opening in the oncoming traffic.

   - [ ] You may turn if the intersection is clear, since the oncoming traffic must stop.



If you are waiting to turn left and see the above signal indication:

1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

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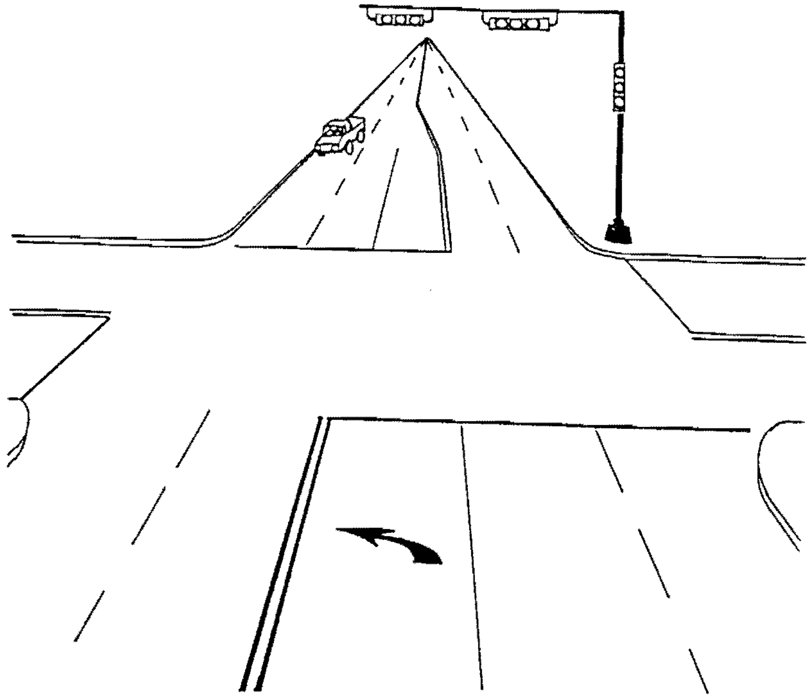
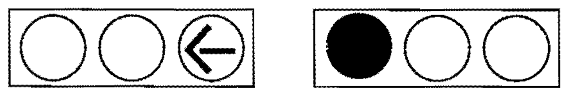
   - [ ] You may turn if the intersection is clear, since the oncoming traffic must stop.





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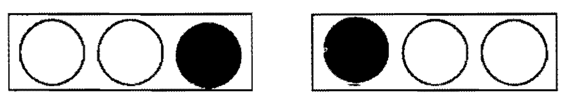

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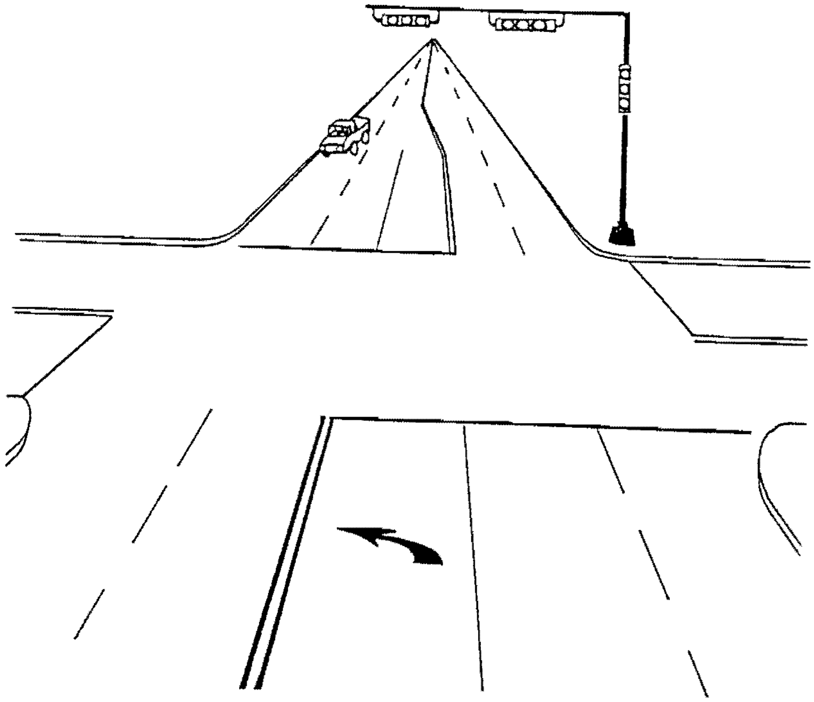
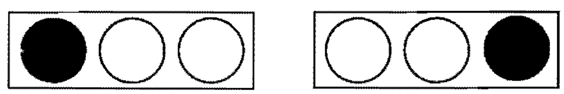
3-9-0
3-10-0





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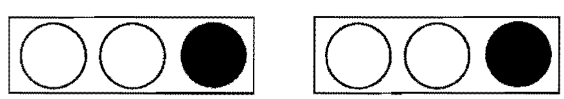

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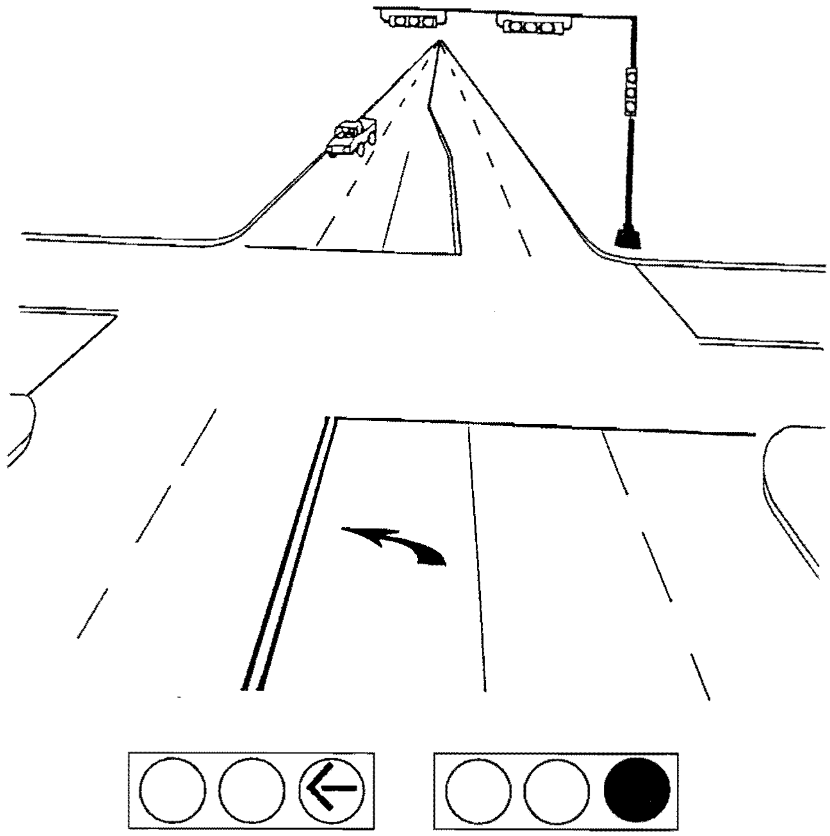
3-12-0
3-8-0



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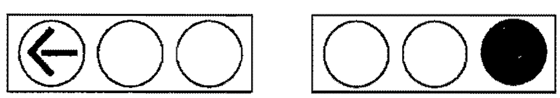

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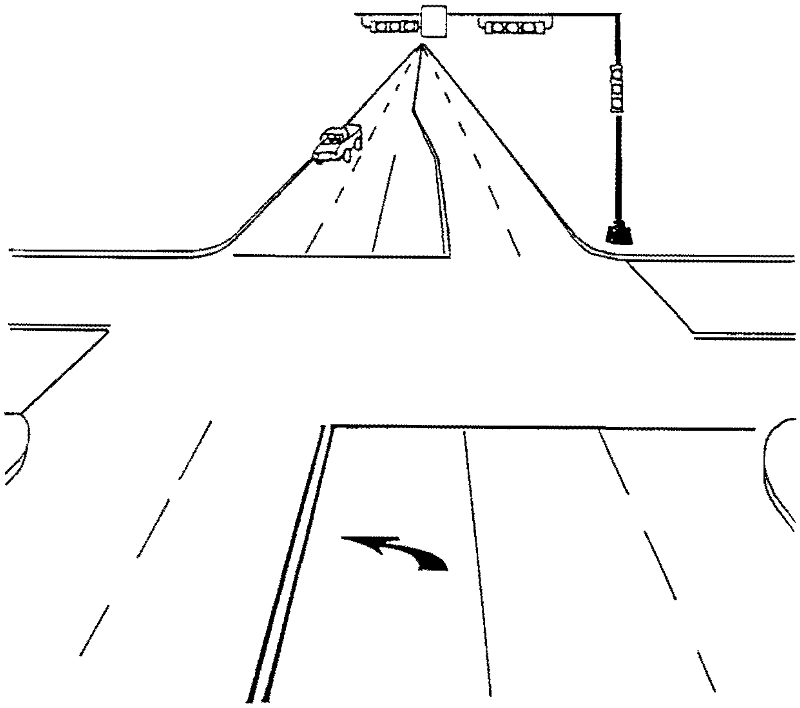

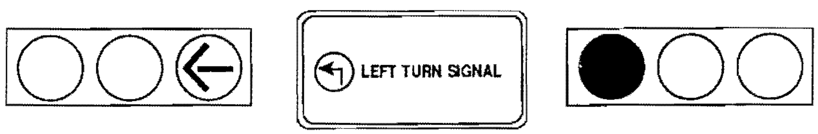

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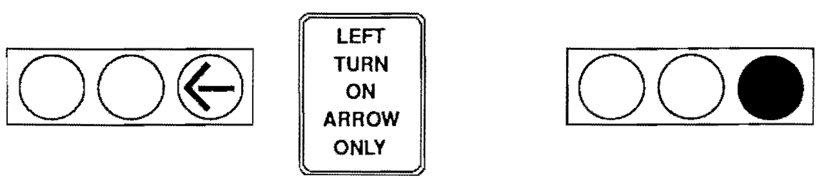

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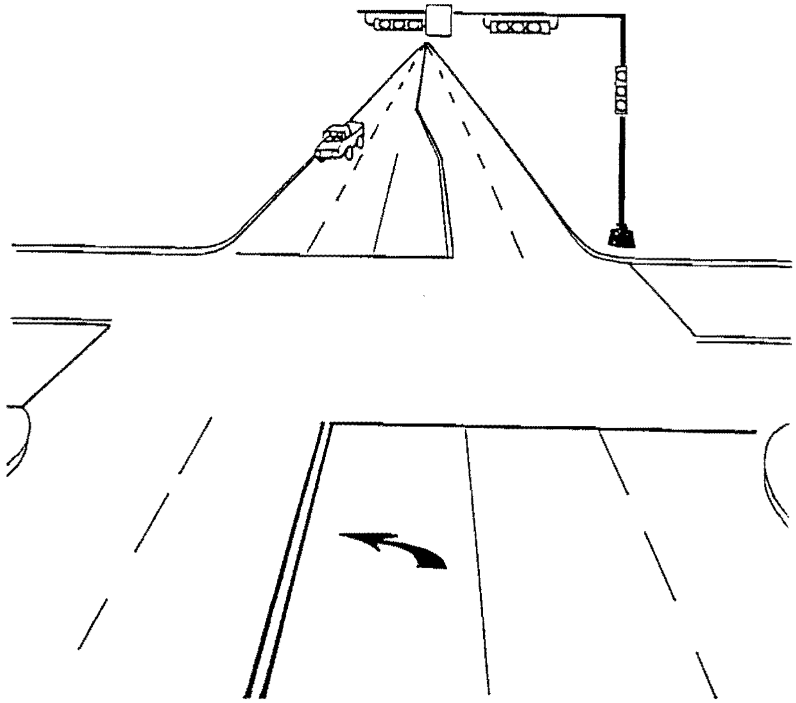
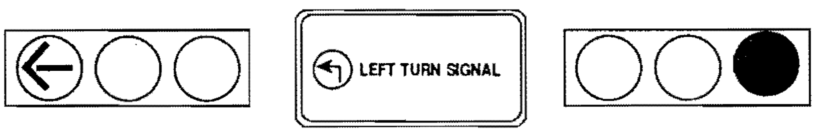
4-8-7
4-11-4





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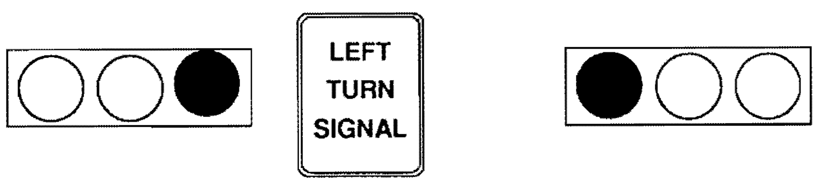

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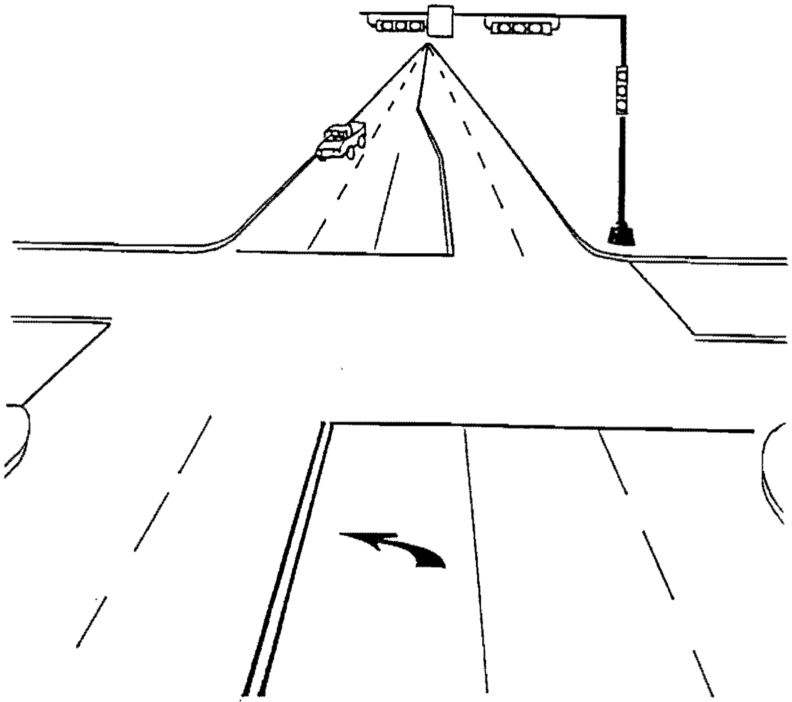

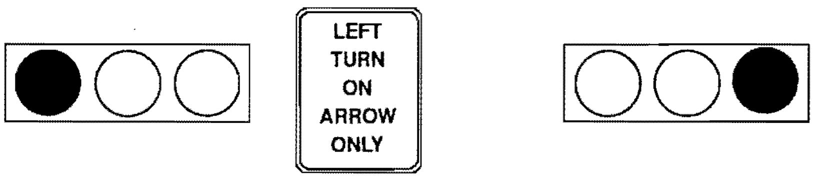

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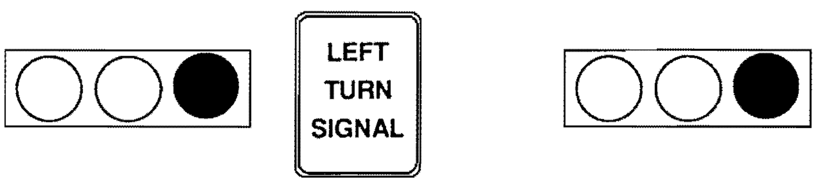

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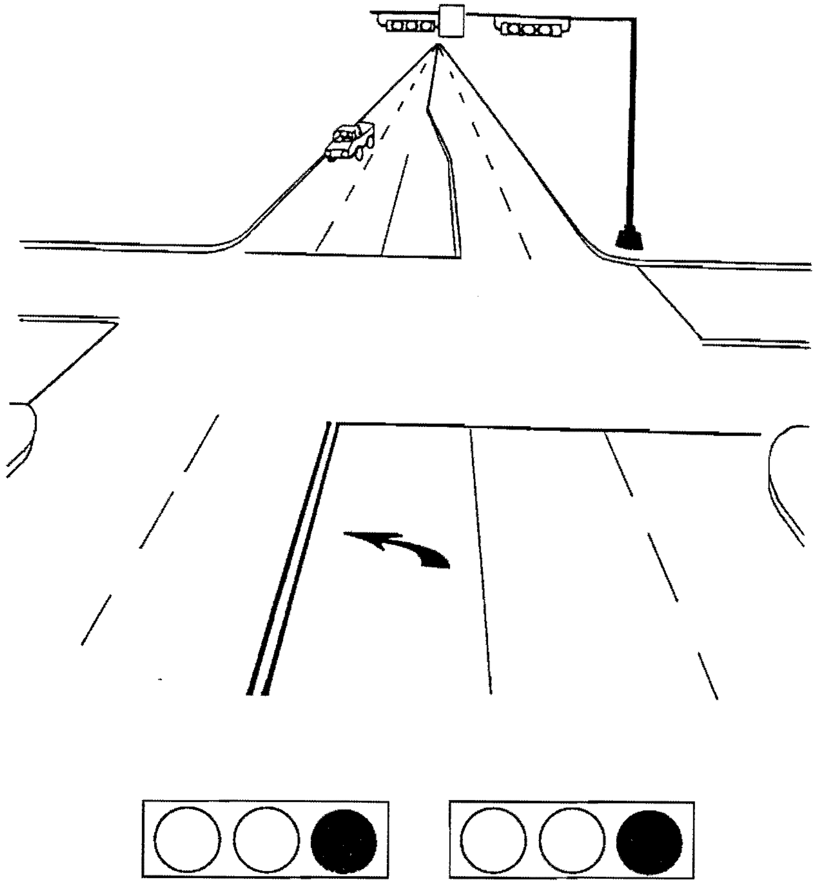
   ☐ You may turn if the intersection is clear, since the oncoming traffic must stop.

6-10-0
6-10-3



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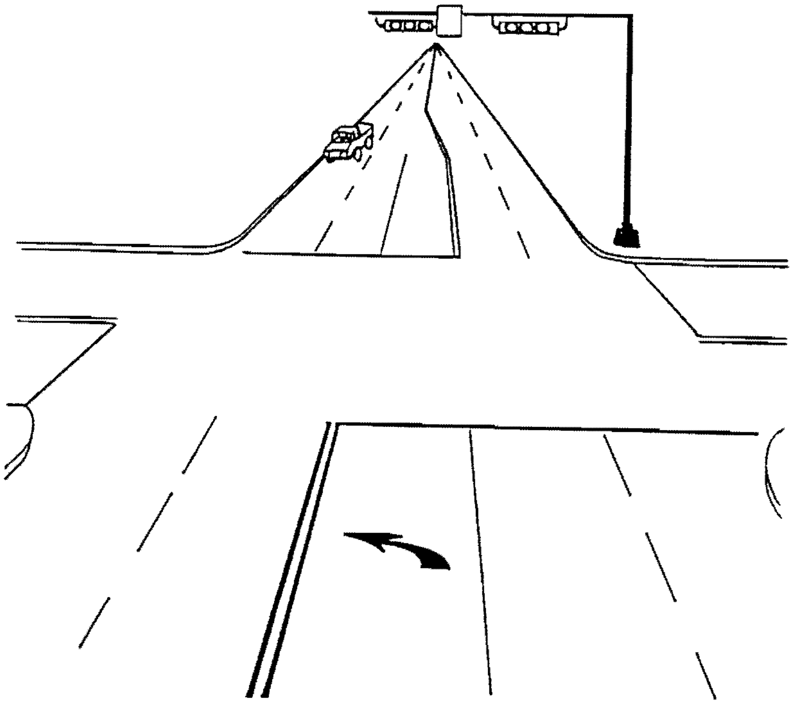
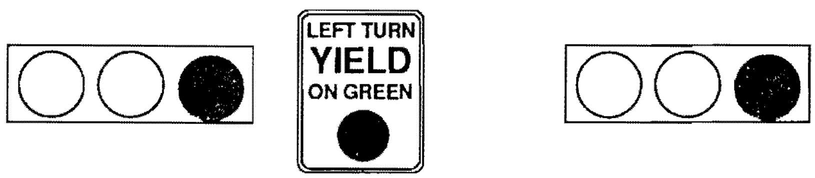
6-10-6
6-10-10





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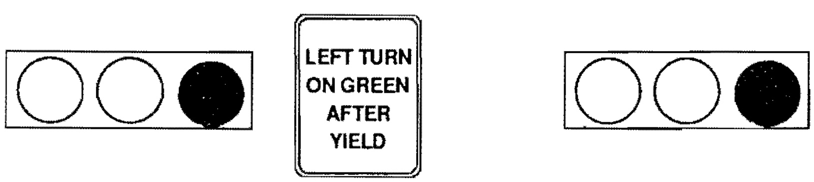

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   ☐ You must wait for a large enough opening in the oncoming traffic.

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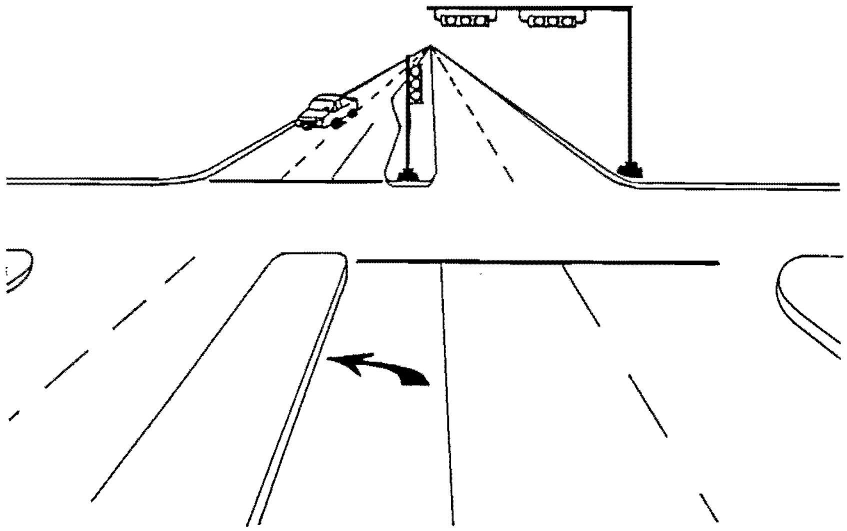
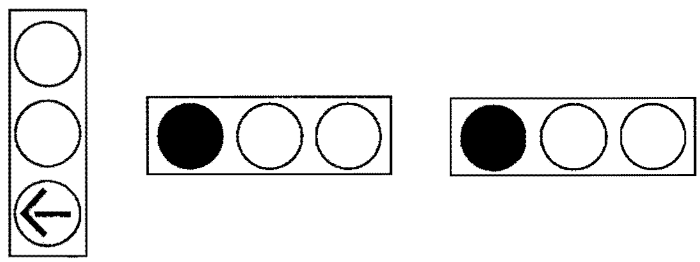
7-13-0
7-18-0





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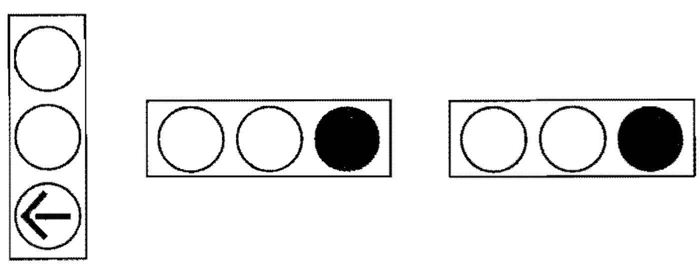
1. Are you allowed to turn left? Yes No (please circle)

2. If you can turn left,

   ☐ You must wait for a large enough opening in the oncoming traffic.

   ☐ You may turn if the intersection is clear, since the oncoming traffic must stop.



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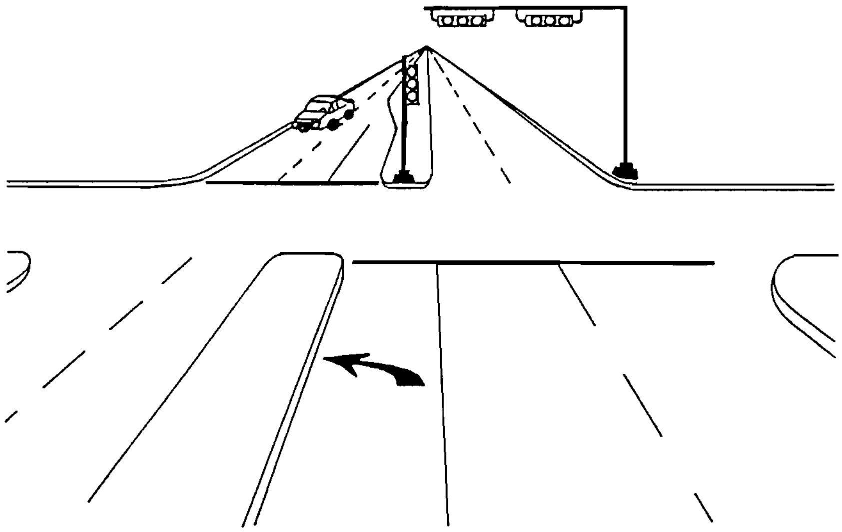
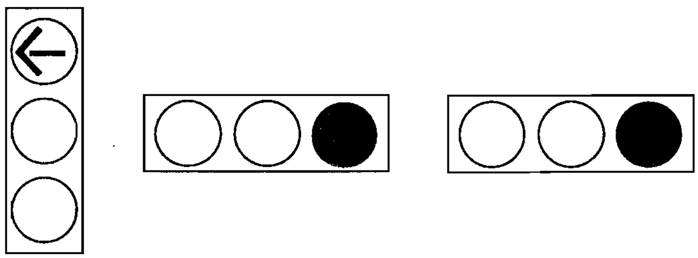
7-14-0
7-17-0





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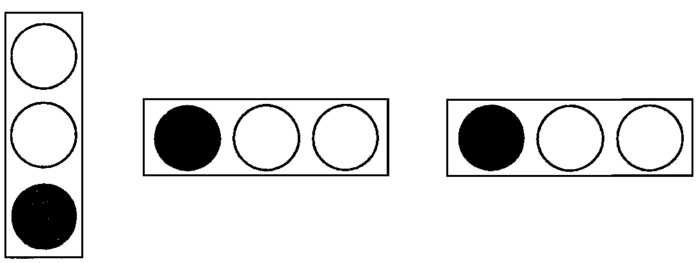

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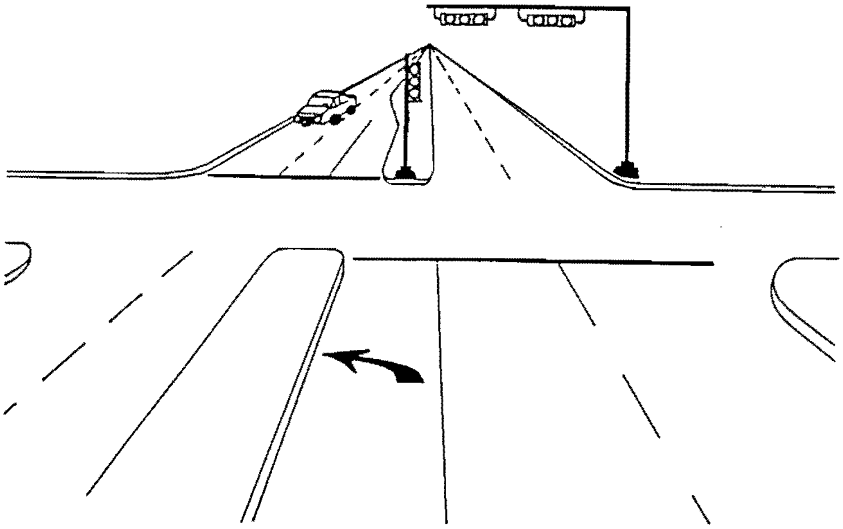
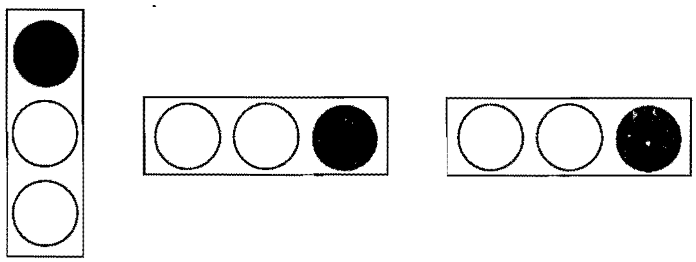
7-15-0
7-16-0





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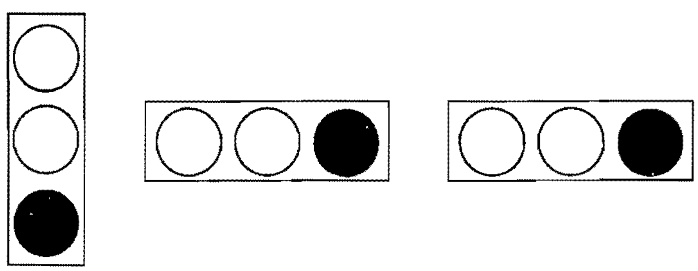

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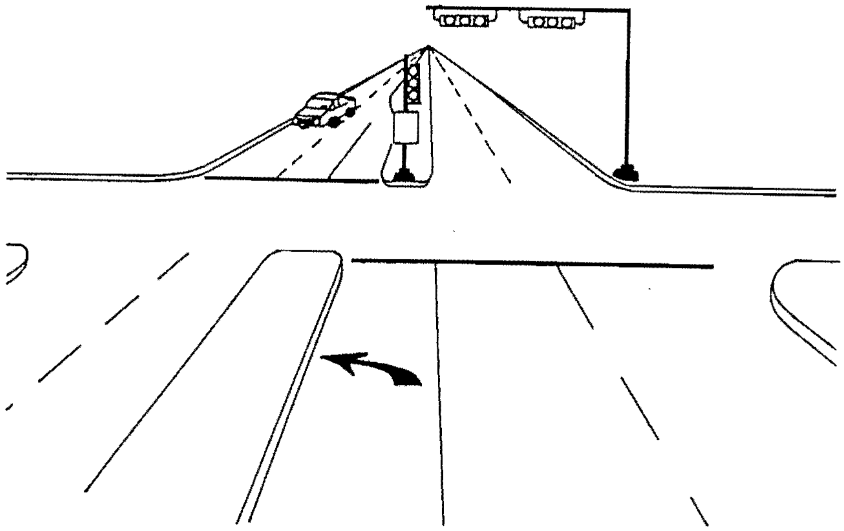
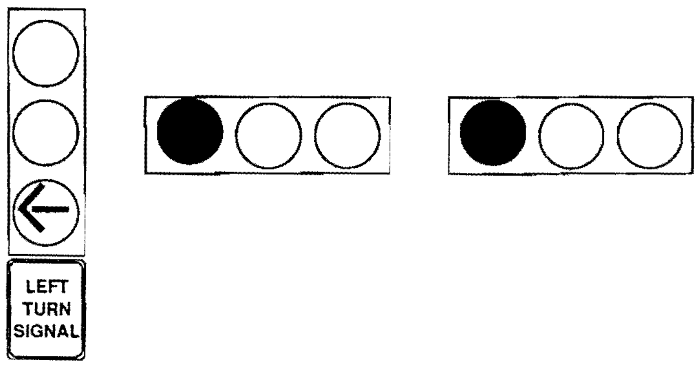
8-13-4
8-18-5





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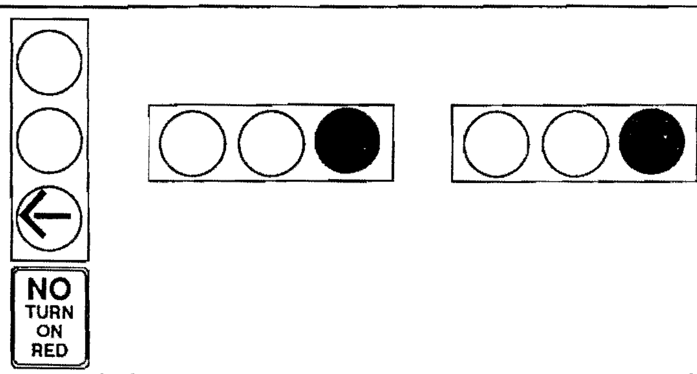

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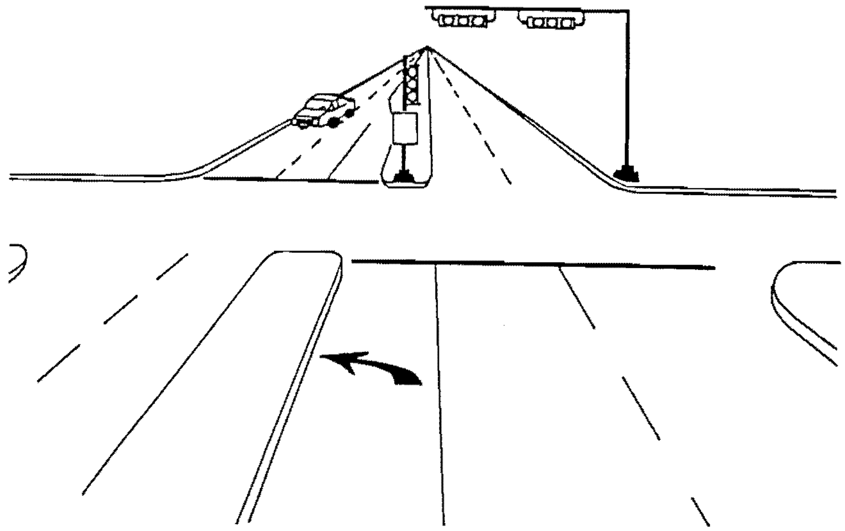
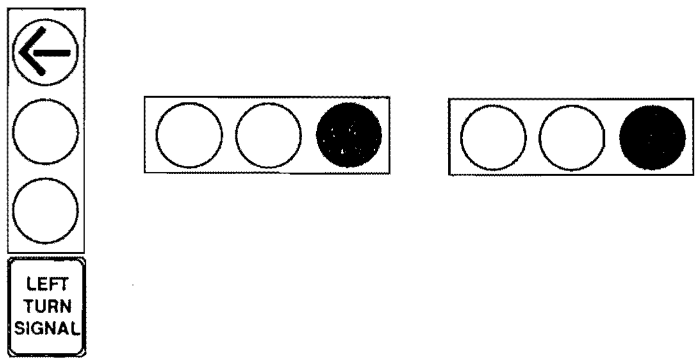
8-14-4
8-17-7





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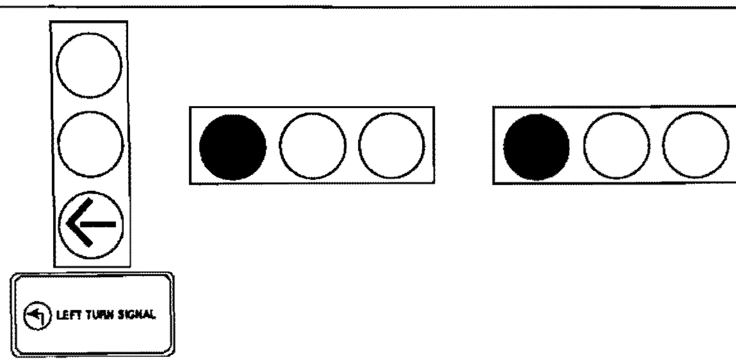

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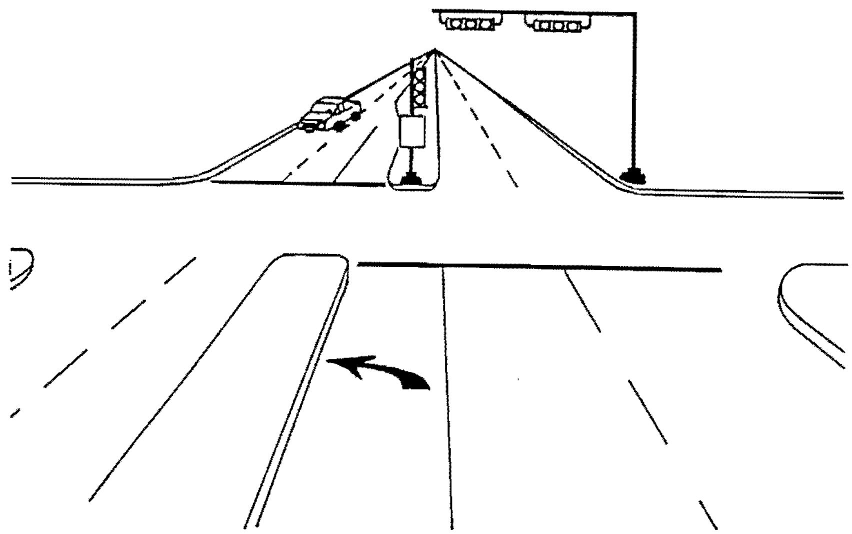
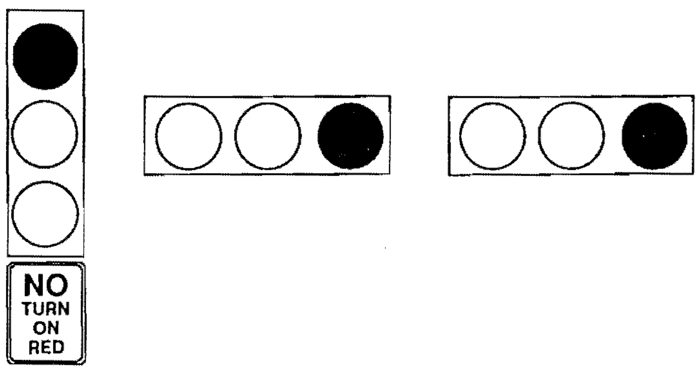
8-15-5
8-16-7





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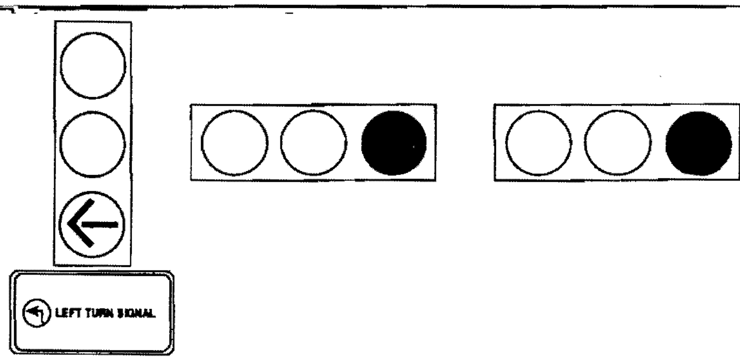

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Finally, we need some general information about you to help us classify your responses. Remember, do not sign this form.

Sex

- ☐ Female
- ☐ Male

Age

- ☐ 25 or under
- ☐ 26 to 35
- ☐ 36 to 45
- ☐ 46 to 55
- ☐ 56 to 65
- ☐ 66 to 75
- ☐ 76 or over

How many years have you been driving?

- ☐ 5 or less
- ☐ 6 to 10
- ☐ 11 to 20
- ☐ 21 to 30
- ☐ 31 to 40
- ☐ 41 to 50
- ☐ 51 or more

How many years of school have you attended?

- ☐ Less than 12 years
- ☐ High school degree
- ☐ Some college work
- ☐ Associates degree
- ☐ Bachelors degree
- ☐ Some post-graduate work
- ☐ Graduate degree

What language do you speak at home?

- ☐ English
- ☐ Other (specify:_________)

Thank you very much for taking the time to complete our survey. Your response is an important part of our research project. Please put these forms in the prepaid envelope and drop it in a mailbox.

APPENDIX B

LIST OF

STUDY

INTERSECTIONS

INTERSECTION	Nlt	Nop	Vlt	Vop	Spop	Diff*
<u>Fort Worth, Tarrant County</u>						
SB Altamesa & Hulen	1	2	291	445	35	R
EB Ephraim & Jacksboro	2	2	275	500	45	S
NB Jacksboro & Ephraim	2	3	216	583	45	R
WB US 80 & Altamere	2	3	386	742	40	S
SB Altamere & Hwy 80	2	3	144	882	40	S
EB Hulen & Altamesa	1	2	150	306	40	S
NB Altamesa & Hulen	1	2	79	823	35	S
WB Berry & Cleburne	1	3	205	808	35	S
NB Cleburne & Berry	1	3	132	1106	35	S
NB Crowley & Altamesa	1	3	140	491	40	S
EB Altamesa & Crowley	1	2	207	388	40	S
WB Camp Bowie & Bernie Anderson	1	3	204	968	35	S
NB Bernie Anderson & Camp Bowie	1	1	104	332	30	S
EB Rosedale & Forest Park	1	3	66	929	35	R
NB Forest Park & Rosedale	1	2	250	651	30	R
WB Rosedale & Forest Park	1	3	133	532	45	R
SB Forest Park & Rosedale	1	2	197	1421	30	S
EB Magnolia & Hemphill	1	1	70	157	30	S
NB McCart & Walton	1	2	100	1110	35	S
NB Granbury & Bilgrade	1	1	23	394	45	S
WB Lancaster & Rivers	2	3	252	448	55	S
SB Jacksboro & Long Ave.	1	2	100	1624	45	S
WB Lancaster & Sandy	1	2	64	408	55	S
SB Jacksboro & Riverwood	1	2	36	2028	45	S
<u>Euless, Tarrant County</u>						
WB Euless & Raider	1	2	224	1096	50	S
EB Hurst & Preccint	1	2	192	1456	40	S
EB Euless & Industrial	1	2	296	796	45	S
WB SH 114 & FM 1709	1	2	316	1544	55	S
WB SH 114 & Dove St.	1	2	180	160	55	S
<u>Arlington, Tarrant County</u>						
NB Collins & Abrams	1	2	48	978	35	S
EB Abrams & Collins	1	2	139	506	35	S
WB Abrams & Center	1	2	61	635	35	S
EB Green Oaks Blvd. & Collins	1	2	172	204	40	R
NB Collins & Green Oaks Blvd.	1	2	106	479	35	S
WB Pioneer & Matlock	1	2	187	1118	40	S
SB Matlock & Pioneer	1	2	75	190	35	S
NB Collins & Timberview	1	2	43	598	40	S
WB Pioneer & Park Springs	1	2	274	681	45	S
NB Park Springs & Pioneer	1	2	29	256	40	S
EB Pioneer & Cooper	1	3	245	406	35	S
NB Cooper & Pioneer	1	3	162	406	35	S
WB Mansfield & Cooper	1	2	89	384	35	S

* R: Restricted; S: Satisfactory

INTERSECTION	Nlt	Nop	Vlt	Vop	Spop	Diff*
Arlington, Tarrant County (cont)						
SB Cooper & Mansfield	1	3	108	1872	40	S
WB Pioneer & Collins	1	2	268	889	40	S
SB Collins & Pioneer	1	3	245	1194	35	S
SB Cooper & Bardin	1	2	468	1267	40	S
EB Center & Collins	2	2	329	52	35	R
NB Collins & Center	1	2	12	1267	40	S
WB Pioneer & Green Oaks	2	2	754	1551	45	S
EB Lamar & Collins	2	2	261	636	40	R
NB Collins & Lamar	2	2	561	1319	35	S
EB Pioneer & Corn Valley	2	1	252	88	40	S
EB Pioneer & SE 8th	1	2	880	212	45	S
EB Pioneer & New York	1	2	272	1155	45	S
WB Pioneer & Susan	1	2	164	1592	45	S
Austin, Travis County						
EB Riverside & Barton Springs	1	2	66	268	35	S
NB Barton Springs & Riverside	1	2	378	576	35	S
WB Barton Springs & Lamar	2	2	352	472	35	S
NB Lamar & Barton Springs	1	3	84	1240	35	S
EB St Elmo & 1st	1	1	52	184	35	S
NB 1st & St Elmo	1	1	48	332	30	S
NB Lamar & Justin	1	2	111	1104	30	S
EB Stassney & Congress	1	2	160	417	40	S
SB Congress & Stassney	1	2	84	320	40	S
EB William Cannon & Congress	1	3	106	830	40	R
SB Congress & William Cannon	1	2	86	218	40	S
WB William Cannon & Congress	1	3	106	830	40	S
WB Oltorf & Congress	1	2	121	383	40	S
SB Congress & Oltorf	1	2	71	592	40	S
WB Riverside & Congress	1	2	79	565	35	S
NB Congress & Riverside	2	3	193	358	35	S
SB Congress & 1st	1	3	173	512	35	S
NB Burnett & Anderson	1	2	224	796	35	S
WB Anderson & Burnett	1	2	263	768	45	S
WB BenWhite & Burleson	1	2	129	975	50	S
SB Congress & BenWhite	1	2	178	1284	40	S
SB Burleson & BenWhite	1	2	121	368	35	R
EB McNeil & Parker	1	2	88	300	45	S
SB Parker & McNeil	1	2	272	424	55	R
Dallas, Dallas County						
EB Northwest & Buckner	1	3	278	1372	45	S
SB Buckner & Northwest	3	1	564	193	45	S
WB Beltline & Garland	1	2	490	488	40	R
NB Garland & Beltline	1	2	80	250	45	S
SB Garland & Beltline	2	2	117	227	45	S

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INTERSECTION	Nlt	Nop	Vlt	Vop	Spop	Diff*
Dallas, Dallas County (cont)						
EB Beltline & Garland	1	2	113	542	40	S
WB Spring Valley & Coit	2	3	238	545	35	S
SB Coit & Spring Valley	2	3	354	1010	40	S
EB Spring Valley & Coit	2	3	232	853	35	R
NB Coit & Spring Valley	1	4	142	1100	40	R
WB Forest Lane & Preston	1	3	263	817	35	S
NB Preston & Forest Lane	1	3	353	924	35	S
EB Oaklawn & Lemmom	1	3	109	1195	35	S
NB Lemmon & Oaklawn	1	2	405	693	35	S
EB Cedar Springs & Fairmount	1	1	28	74	30	R
NB Fairmount & Cedar Springs	1	2	16	467	35	S
EB Northaven & Preston	1	1	50	56	30	S
NB Preston & Northaven	1	3	32	1256	35	S
EB Northwest & Midway	1	3	155	962	35	S
SB Midway & Northwest	1	2	142	216	35	S
EB Forest Ln. & Greenville	1	3	340	617	40	R
SB Greenvile & Forest Ln.	2	3	179	2089	45	S
EB Forest Lane & Plano Rd	2	3	444	744	45	S
WB Forest Lane & Central Park	2	2	372	110	40	S
WB Forest Lane & Hillcrest	2	2	336	1036	40	S
WB Northwest Hwy. & Hillcrest	2	2	348	400	40	S
EB Northwest Hwy. & Audelia	2	3	412	1680	45	S
WB Beltline & Preston	2	2	392	952	45	S
WB Beltline & Momfort	2	3	332	2040	40	S
San Antonio, Bexar County						
EB Durango & Santa Rosa	2	2	410	264	35	R
SB Santa Rosa & Durango	2	3	118	204	35	S
WB Durango & Santa Rosa	1	2	71	95	35	S
NB Santa Rosa & Durango	1	2	96	236	35	S
EB Durango & Flores	1	2	60	333	30	S
SB Flores & Durango	1	2	64	259	35	S
EB Oblate & San Pedro	1	1	126	216	35	R
SB San Pedro & Oblate	1	3	57	1158	40	R
EB Hilberand & San Pedro	1	1	69	441	35	S
NB San Pedro & Hilberand	1	2	87	493	40	S
NB Wurzbach & Medical	1	2	108	779	40	S
WB Fredricksburg & Wurzbach	1	2	192	442	40	R
NB Wurzbach & Fredricksburg	1	2	174	568	40	R
NB Blanco & West	1	2	230	607	40	S
WB West & Blanco	1	2	213	529	40	S
SB San Pedro & McCarthy	1	3	72	1761	45	S

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INTERSECTION	Nlt	Nop	Vlt	Vop	Spop	Diff*
Houston, Harris County						
WB Woodway & Chimney Rock	1	2	278	1010	35	R
NB Chimney Rock & Woodway	1	1	100	323	35	S
EB Memorial Dr. & San Felipe	1	2	146	677	40	S
SB San Felipe & Memorial Dr.	1	2	8	10	35	R
WB Woodway & Post Oak Ln.	2	2	301	795	35	S
NB Post Oak Ln. & Woodway	1	2	82	46	30	S
NB Veteran Memorial & FM 1960	1	2	236	417	40	S
WB FM 1960 & Veteran Memorial	1	3	172	1205	40	S
NB Veteran Memorial & Mt. Houston	1	2	120	392	40	S
WB Mt. Houston & Veteran Memorial	1	3	101	681	55	S
EB San Felipe & Post Oak	1	3	279	1098	35	S
NB Post Oak & San Felipe	2	3	417	770	35	S
SB Fannin & Holyhall	1	3	228	962	40	S
EB Westheimer & Voss Rd.	2	4	452	1564	35	S
NB Voss & Westheimer	1	4	177	949	35	S
WB Richery & North Bammel Rd	1	2	146	223	35	S
SB North Bammel Rd. & Richery	1	2	34	650	35	S
WB Aldine & Green Rd	1	1	50	256	45	S
SB Green Rd. & Aldine	1	1	165	212	45	S
WB N. Bammel Rd & Veteran Memo.	1	2	57	655	40	S
NB Veteran Memo. & N. Bammel Rd.	1	1	165	212	35	S
SB Post Oak & San Felipe	1	3	117	968	35	S
WB San Felipe & Post Oak	1	3	250	1115	35	S
EB Woodway & Post Oak Ln.	1	2	14	826	35	S
Lubbock, Lubbock County						
WB 4th & Indiana	1	2	144	540	55	S
WB 4th & Boston	1	1	99	164	30	S
NB Boston & 4th	2	1	44	55	20	S
WB 19th & University	1	3	213	734	40	S
SB University & 19th	1	3	102	650	30	S
EB 19th & University	2	3	471	883	35	S
NB University & 19th	1	3	205	496	35	S
SB Ave Q & Main	1	3	146	1109	40	S
EB 50th & Ave Q	2	3	349	728	40	S
SB Ave. Q & 50th	1	3	151	569	40	S
Odessa, Ector County						
EB University & US 385	1	2	350	617	35	S
SB US 385 & University	1	3	137	935	40	S
WB 31st St. & US 385	1	1	99	164	30	S
SB US 385 & 31st St.	1	2	27	930	40	S
EB University & Grandview	1	2	135	477	35	S
WB Grandview & University	1	2	126	891	40	S
WB Yukon & US 385	1	2	216	160	55	S
SB US 385 & Yukon	1	2	143	297	45	S

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INTERSECTION	Nlt	Nop	Vlt	Vop	Spop	Diff*
Odessa, Ector County (cont)						
WB 42nd St. & Grandview	2	3	178	685	55	S
SB Grandview & 42nd St.	2	3	122	376	45	S
Brownsville, Cameron County						
EB Price & Paredas	1	2	70	431	35	S
NB Paredas & Price	1	2	164	485	40	S
EB Jefferson & Central Blvd.	1	1	14	109	30	S
NB Central Blvd. & Jefferson	1	2	160	351	35	S
NB Elizabeth & Palm	1	2	164	485	40	S
NB Boca Chica & Simpson	1	3	63	1244	40	S
WB Simpson & Boca Chica	1	1	103	75	30	S
NB Central Blvd & Price Rd.	1	3	108	640	40	S
EB Boca Chica & 14th St.	2	3	270	728	40	S
SB 14th St. & Boca Chica	1	2	144	834	40	S
WB Boca Chica & Central Blvd.	1	2	163	323	35	S
SB Central Blvd. & Boca Chica	1	2	52	469	35	S
NB 14th St. & Boca Chica	1	1	52	757	40	S
WB Boca Chica & 14th St.	2	2	435	306	40	S
Corpus Christi, Nueces County						
EB Horne & Ayers	1	2	166	323	30	S
NB Ayers & Horne	1	2	136	477	30	S
WB Saratoga & Ayers	1	2	72	122	55	S
SB Ayers & Saratoga	1	2	175	144	55	S
EB Saratoga & Staples	1	2	274	369	55	S
SB Staples & Saratoga	1	2	67	258	55	S
NB Ocean Dr. & Elizabeth	1	3	75	866	35	S
EB Elizabeth & Ocean Dr.	1	1	49	10	30	S
NB Ocean Dr. & Ayers	2	3	85	951	35	S
EB Baldwin & Staples	1	2	12	248	35	S
NB Staples & Baldwin	2	2	288	580	35	S
SB Staple & Baldwin	1	2	27	876	35	R

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