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FINAL REPORT

GUIDELINES FOR EXCLUSIVE/PERMISSIVE LEFT-TURN SIGNAL PHASING

by

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(The opinions, findings, and conclusions expressed in this report are those of the author and not necessarily those of the sponsoring agencies.)

Virginia Highway & Transportation Research Council
(A Cooperative Organization Sponsored Jointly by the Virginia Department of Highways & Transportation and the University of Virginia)

In Cooperation with the U. S. Department of Transportation
Federal Highway Administration

Charlottesville, Virginia

January 1985
VHTRC 85-R19

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ABSTRACT

The objective of this research was to develop guidelines for the use of exclusive/permissive left-turn signal phasing. This was achieved by collecting data on traffic and roadway conditions for exclusive, exclusive/permissive, and permissive left-turn phasings and then analyzing the data to identify relationships between the left-turn phasings and traffic and roadway conditions.

The guidelines addressed the following: (1) volume guidelines based on peak hour minimum left-turn volume and the product of the peak-hour left-turn and opposing volumes, (2) annual left-turn accident experience, (3) left-turn traffic conflict experience based on critical number and rates, (4) left-turn delay, and (5) site condition factors identified in the study.

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	Multiply By	To Obtain
feet	0.305	meters
miles per hour	1.607	kilometers per hour

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GUIDELINES FOR EXCLUSIVE/PERMISSIVE LEFT-TURN SIGNAL PHASING

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CHAPTER 1

INTRODUCTION

Problem Statement

Exclusive/permissive (E/P)* left-turn signal phasing is a combination of an exclusive phase, where a green arrow indicates a protected turn, and the permissive phase, where the left-turning vehicles must yield to the opposing traffic during the green ball indication. With a new signal head arrangement and clearance interval, it is a new twist to the advanced-green phasing. The primary intent is to increase the efficiency of traffic flow by left-turning movements through gaps in the opposing traffic at intersections where traffic volumes warrant the phasing. E/P phasing also reduces delay and energy consumption by permitting left turns on the green ball through gaps in the opposing traffic.

On the other hand, two research efforts concluded that accidents involving left-turning vehicles increased after the installation of E/P signals.(1,2) The number of accidents appeared to decrease as drivers became familiar with the signals, and driver understanding of the E/P phasing was identified as an important factor. However, since at some intersections operational and accident problems do not decrease over time, it appears that factors other than unfamiliarity cause problems.

The Virginia Department of Highways and Transportation has been increasing its use of E/P phasing. It is being used extensively for signal modifications from exclusive left-turn phasing and for some new signal systems. In 1982, based on a conservative estimate, there were 130 locations in Virginia with E/P left-turn phasing. This estimate considers only the signals under the Department's control, not those under the control of municipalities. The use of E/P left-turn phasing is increasing nationally. The majority of studies on left-turn phasing have addressed warrants or criteria for the use of exclusive left-turn phasing in lieu of permissive left-turn phasing(3,4) or a study of E/P left-turn phasing. The later studies have concluded that (1) E/P phasing should be considered when left-turn phasing is desired, (2) driver education on E/P phasing is very important, and (3) further

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*Protected is commonly used in lieu of exclusive; e.g., protected/permissive.

evaluation is needed to identify the optimal use of E/P left-turn phasing.

One of the previously cited reports recommended that an evaluation be conducted to compare E/P and other left-turn phasings on the basis of traffic and road conditions and to fill the need for guidelines for the use of E/P phasing.(2)

Objectives and Scope

The objective of this research project was to develop guidelines for the use of E/P left-turn phasing. This was achieved by collecting data on traffic and roadway conditions for the three left-turn phasings, and then analyzing the data to identify relationships between the left-turn phasing and traffic and roadway conditions.

Because the majority (about 95%) of the E/P left-turn signals designed by the Virginia Department of Highways and Transportation contain a leading green arrow, only leading arrow phases were considered. Study sites were limited to signalized intersections along arterial routes because these are of primary interest to the Department.

In establishing the guidelines for use of E/P left-turn phasing, guidelines for the use of permissive and exclusive left-turn phasings were indirectly addressed.

Report Format

The remainder of this report is divided into seven major sections as follows:

1. Literature Review
2. Data Collection Procedure
3. Traffic Engineering Analysis
4. Statistical Analysis
5. Development of Guidelines
6. Conclusions
7. Recommendations

The first four sections describe the tasks leading to the development of the guidelines, which is described in the fifth, or key, section.

CHAPTER 2

LITERATURE REVIEW

Three reports on warrants or guidelines for left-turn signal phasing and five reports on the use of exclusive/permissive left-turn signal phasing are discussed below.

Development of Warrants for Left-Turn Signal Phasing - K. R. Agent(3)

The following warrants were recommended as guidelines when considering adding a separate left-turn phasing with a separate left-turn lane.

1. Accident Experience -- Install left-turn phasing if the critical number of left-turn accidents have occurred. For one approach, 4 left-turn accidents in 1 year or 6 in 2 years are critical. For both approaches, 6 left-turn accidents in 1 year or 10 in 2 years are critical.

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

3. Volumes -- Consider left-turn phasing when the product of left-turning and opposing volumes during peak hours exceeds 100,000 on a 4-lane street or 50,000 on a 2-lane street. Also, the left-turn volume must be at least 50 during the peak-hour period. Volumes meeting these levels indicate that further study of the intersection is required.

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

Parts 1-3 of these guidelines, referred to as the Kentucky method, have been adopted as the left-turn phase criteria included in the Federal Highway Administration's Traffic Control Devices Handbook(4). The minimum left-turn volume must be greater than 2 vehicles per cycle during the peak-hour period instead of 50 vehicles in the peak hour.

Guidelines for Signalized Left-Turn Treatments - Federal Highway Administration(5)

Guidelines addressing the volume to capacity ratio (V/C) and the number of left-turn accidents were developed. Need conditions for exclusive left-turn phasing based on the V/C and the number of left-turns are displayed in Figure 1.

When considered separately, a V/C between 0.7 and 0.9 or from 3 to 4 left-turn accidents per year are considered marginal. It is noted that an indication of a need for exclusive left-turn phasing indicates a problem, and that less restrictive measures (left-turn prohibitions or a separate left-turn lane) should be considered before an exclusive left-turn phasing is justified.

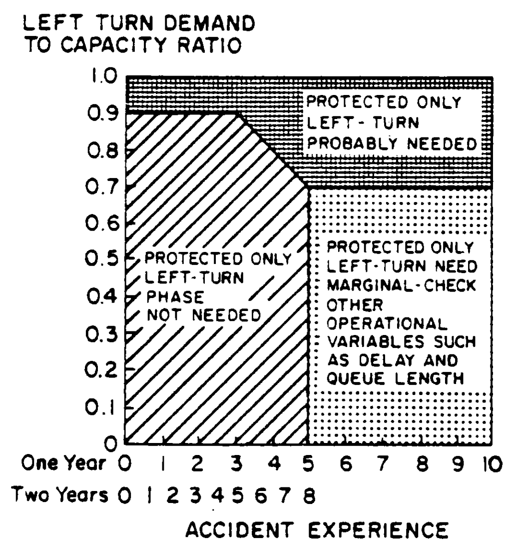


Figure 1. Graph of need conditions for protected only left-turn phasing. (Reference 5)

Guidelines for Use of Left-Turn Lanes and Signal Phases
University of Texas at Austin(6)

A review of existing warrants and guidelines for left-turn signal phasing yielded the following conclusions: (1) volume or capacity warrants are preferred to delay warrants due to the cost of measuring delay; (2) because it fails to reflect the effects of opposing volume, signal-timing scheme, and intersection geometrics on left-turn movements, a single minimum level of left-turn volume is ineffective; (3) a volume-product type of warrant was found inadequate, especially for low left-turn volumes, because it makes no distinction between the left-turn and opposing volume; (4) although the V/C type of warrant appears conceptually sound, it considers only one element, left-turn saturation, out of the many elements that are involved.

Consequently, a warrant for left-turn signal phasing of pre-timed signals was developed using the Texas model, a microscopic traffic simulation package developed at the University of Texas at Austin. The proposed capacity warrant states that a left-turn treatment may be needed if the left-turn demand reaches the threshold located M vehicles lower than the left-turn capacity, where M is a function of the opposing volume, cycle split, intersection geometrics, and the criteria for critical conditions. The four delay criteria for critical conditions are (1) 35 seconds of average left-turn delay, (2) 73 seconds of 90th percentile left-turn delay, (3) 5% left-turning vehicles being delayed more than 2 cycles, and (4) 4 left-turning vehicles in 1 hour being delayed more than 2 cycles. The recommended left-turn warrants for a separate left-turn phase under different levels of opposing volumes and numbers of opposing lanes are given in Table 1.

Table 1

Recommended Left-Turn Warrants for a Separate Left-Turn Phase Under Different Levels of Opposing Volumes and Numbers of Opposing Lanes

Number of Opposing Lanes	Opposing Volume Q_o, vph	Critical Left-Turn Volume Q_w, vph
One	$0 < Q_oC/G < 1000$	$765(G/C) - 0.634Q_o$
	$1000 < Q_oC/G < 1350$	$485\ (G/C) - 0.348Q_o$
Two	$0 < Q_oC/G < 1000$	$855(G/C) - 0.500Q_o$
	$1000 < Q_oC/G < 1350$	$680(G/C) - 0.353Q_o$
	$1350 < Q_oC/G < 2000$	$390(G/C) - 0.167Q_o$
Three	$0 < Q_oC/G < 1000$	$895(G/C) - 0.448Q_o$
	$1000 < Q_oC/G < 1350$	$735(G/C) - 0.297Q_o$
	$1350 < Q_oC/G < 2400$	$390(G/C) - 0.112Q_o$

G/C - ratio of green phasing time, G, to cycle length for 1 phase, C.

Source: Reference 6.

A Study of Clearance Intervals, Flashing Operations, and Left-Turn Phasing at Traffic Signals -- Vol. 4 Left-Turn Phasing - R. H. Mohle and T. K. Rorabaugh(7)

Seven intersections in California were studied. For the study, three were converted from exclusive (E) to E/P, one from E/P to E, one from permissive (P) to E, and 2 E/P signals with blank versus yellow arrow clearance display. Various signal displays and placement and queue detection logic were used for the E/P phasings. The number of left-turn accidents increased with the use of E/P left turns, especially where the phasing was converted from E left turns. It was concluded that the installation of E/P left turns did not cause major changes in conflicts, although the conflicts increased with the accidents. The total intersection delay decreased an average of 36% when E phasings were converted to E/P. A change from E/P to E yielded a 32% increase in the total intersection delay. Although the left-turn delay decreased 52%, the total intersection delay increased 110% when converted from P to E/P.

The decision to implement E/P should be made on a volume basis as opposed to an accident warrant basis. It was recommended that E/P phasing be seriously considered when the installation of left-turn phasing is based on volume conditions.

An Evaluation of Exclusive and Exclusive-Permissive Left Turn Signal Phasing--Travers Associates Consultants, Inc.(8)

After evaluating field data on 8 sites, before and after accident data on 12 sites, and accident experiences at 25 sites, it was concluded that (1) there was not a significant increase in accidents involving left-turn vehicles under E/P phasing compared to E phasing, and (2) an average reduction of 30% in left-turn delay can be expected.

The decision to use E/P phasing should be made by the traffic engineer based on the parameters given below and judgment. "Exclusive-permissive phasing could be advantageously used when:

a) there are considerable delays to left turn vehicles with exclusive phasing.

b) the opposing and left turn volumes are moderate and left turns could penetrate through traffic without great difficulty.

c) the signal is at a moderately traveled intersection where frequent periods free of traffic are experienced.

"Exclusive-permissive phasing might result in operational difficulties when:

a) the median between the left edge of opposing left turn lanes exceeds 20 feet.

b) there is a median between left turn lanes and the lane opposite the permissive phase has more than approximately 20 percent trucks large enough to obstruct the view of oncoming traffic.

c) there is not sufficient sight distance downstream for a motorist making a left turn to see an adequate gap in the opposing traffic stream.

d) the Safe Stopping Sight Distance for the opposing through traffic meets or exceeds the distance it would travel during an acceptable gap. (A Policy on Geometric Design of Rural Highways by the American Association of State Highway Officials, 1965, was used to determine the sufficient sight distance for the left turning vehicle and the safe stopping sight distance for the opposing through volume.)

e) the speed of opposing through traffic is high or is subject to considerable fluctuations. In this case, the capability of the driver to judge an acceptable gap might be limited.

f) double left turn lanes are operating. The added capacity compromises safety in the permissive phase. Exclusive phasing should be considered."(8)

Left Turn Phase Design in Florida--Florida Section Institute of Transportation Engineers(9)

Before and after accident data were studied at 17 sites changed from E to E/P and 11 sites changed from E/P to E. Delay studies were conducted at 1 intersection. A survey of traffic engineers in Florida was conducted.

The following guidelines were recommended.

"A. Protected/permissive [E/P] left turn phasing should be provided for all intersection approaches that require a left turn phase unless there is a compelling reason for using another type of left turn phasing. Protected/permissive left turn phasing is the most common type of left turn phasing currently in use in the State of Florida. Drivers favor this type of left turn phasing because the reduction in intersection delay is very noticeable. If the decision between providing protected/permissive or protected only left turn phasing is not obvious, the traffic engineer should initially operate the left turn phase as protected/permissive on a trial basis. If satisfactory operation results, the protected/permissive left turn phasing should be retained. If unsatisfactory operation results, the protected/permissive left turn phase should be converted to another type of left turn phasing.

B. Protected only left turn phasing should be provided for an intersection approach if any of the following conditions exist:

1) Double left turn only lanes are operating.

2) Intersection geometrics force the traffic engineer to provide the left turn driver with an exclusive signal head that cannot be shared with adjacent through drivers.

3) Sight distance to opposing traffic is less than 250 ft. when the opposing traffic is traveling at 35 MPH or less, or less than

400 ft. when the opposing traffic is traveling at 40 MPH or more. This represents approximately five seconds of travel time which was the first gap size universally accepted by all left turn drivers in the California research project. [Mohle, R. H. and T. K. Rorabaugh, "A Study of Clearance Intervals, Flashing Operations, and Left-Turn Phasing at Traffic Signals - Volume 4 Left-Turn Phasing" prepared for the Federal Highway Administration, U. S. Department of Transportation, Washington, D.C., May 1980.]

4) The approach is the lead portion of a lead/lag intersection phasing sequence.

C. <u>Protected only left turn phasing</u> might be appropriate for an intersection approach if any of the following conditions exist and the traffic engineer, using his best professional judgment, has the opinion that allowing permissive left turns will be unduly hazardous:

1) Poor sight distance to opposing traffic because of roadway curvature (horizontal or vertical) or opposing left turn vehicles.

2) Speed limit of opposing traffic is higher than 45 MPH.

3) Left turn traffic must cross three or more lanes of opposing through traffic.

4) Protected/permissive left turn phasing is currently in use and the number of left turn angle accidents caused by left turn drivers on this approach exceeds six per year.

5) Unusual intersection geometrics exist that will make permissive left turning particularly confusing or hazardous."(9)

Guidelines were also provided for P/E and split phasing. Recommendations were made on left turn signal displays.

An Evaluation of Permissive Left-Turn Phasing--K. R. Agent(1)

The impacts of left-turn phasing changes at 4 T intersections in Kentucky were studied. Of the 4 E left-turning phasings, 2 each were converted E/P and P/E phasings. It was concluded that (1) compared with E phasing, left-turn delay and total intersection delay were reduced by 50% and 24% respectively, (2) 37% of the left turns were made on the green ball phase, (3) very few left turns were made on the green ball for opposing volumes over 1,000 vehicles per hour on a 4-lane road, (4) the number of left-turn accidents increased with P phasing but decreased with driver familiarity, and (5) 3 of the 4 locations had a benefit-cost (delay reduction cost savings - accident cost) ratio much higher than one after 1 year.

It was recommended that (1) this type of phasing be considered at all new left-turn phasing locations and at locations once considered for E phasing but denied due to increased delays, (2) adequate sight distance should be ensured, especially when the speed limit is greater than 45 MPH, (3) signing (e.g., left turn must yield on green ball) should always be used, and (4) advance publicity should precede installation.

An Assessment of Exclusive/Permissive Left-Turn Signal Phasing--M. A. Perfater(2)

A study analyzing traffic volumes, conflicts, and accidents, and a survey of individuals residing near the intersection were conducted for 10 E/P intersections. More than one-third of the survey respondents were confused by E/P signals the first time they were encountered. The survey respondents implied that familiarity with the E/P signal tended to reduce apprehension about it and that advance publicity had merit. Traffic conflicts were most frequent at intersections with high left-turn volumes and multiple movements.

Summary of the Literature

Existing guidelines for left-turn signal phasing consider the following factors: volume, delay, accidents, conflicts, and site conditions such as sight distance, speed, number of lanes of opposing volume, and road geometrics.

The guidelines for a separate left-turn signal vary considerably; therefore, no clear, consistent set of guidelines may be derived from a synthesis of the literature. Moreover, the quantitative guidelines are only for a separate left-turn phase and do not specify the selection of E/P versus E phasing. The E/P guidelines lack quantitative measures that would eliminate much of the judgement and potential for error involved in selecting an E/P phasing.

Compared to E phasing, E/P phasing is effective in reducing delay; however, traffic conflicts and accidents tend to increase with E/P phasing. Therefore, when a separate left-turn phasing is needed based on safety considerations, E phasing should be recommended, and when the need is based on volume and delay, E/P phasing should be recommended.

CHAPTER 3

DATA COLLECTION PROCEDURE

The data collection was divided into five parts: selection of sites, traffic volumes and conflicts, delay, site conditions, and accidents. The procedures and measures of performance used are discussed below.

Selection of Sites

The selection of sites is divided into two areas: sample size and criteria for sites.

Sample Size

The selection of a sample size is among the most difficult, yet important, tasks of many applied research efforts. In the case at hand, the desire for precision and the identification of sampling errors must necessarily be examined in light of the constraints of manpower, time, and cost. Data collection costs for this study were a major item; nevertheless, the potential safety and other user cost impacts of the employment of guidelines based upon the findings of the study suggested that the sample size be large enough to provide significant confidence in the estimated effects of signal type on key traffic factors such as conflicts, delay, and user costs.

The normal procedure for selecting sample size is to establish the size of the population under study, determine the parameter of interest (such as the mean), determine the standard deviation of this parameter, establish a level of precision for the sample estimate, establish a confidence level in the sample estimate of the population parameter, and calculate sample size.(10)

There were a total of 130 E/P signals within the scope of the study; for the other types, no accurate estimate of the population size could be obtained. Nevertheless, one may quite reasonably argue that within the arterial system there are very few P signals, largely because of the traffic volumes typical of this system. Furthermore, experience with and warrants for E phasing suggest that even though the number of signals in this category is relatively large, careful selection of sites from which data were collected enabled the drawing of reasonable inferences about these signals for comparison with the E/P type. Consequently, the total sample size for the E and the P signals was limited to 25.

For the E/P signal type, an attempt was made to obtain a 15% sample, in addition to examining before/after installations when such opportunities arose. There is some justification for this sample size. While very little was known about the distribution of key traffic variables for the 130 E/P signals within the scope of the study, information from a study by Perfater(2) indicates that the range of basic left-turn conflicts is 0.7-14.3$\overline{3}$ per 1,000 left-turn vehicles. Assuming the population is normally distributed, 99.7% of the values of conflict rates lie between the sample mean and $\pm$ 3 standard deviations (σ), that 6 σ = 14.33, or σ = 2.39. Using equations (1), (2), and (3), the sample size required for a predetermined level of confidence and degree of precision with respect to the conflicts rate which might be expected was calculated; this is suggestive of reasonable sample size. For a 90% level of confidence and a precision of $\pm$ 1 conflict per 1,000,

$$n = \frac{Z_\alpha \sigma^2}{2 E^2}, \tag{1}$$

where

n = required sample size,

Z_α = standard normal variable for (100-α)% level of confidence, and

E = desired precision or error limit.

Thus,

$$n = \frac{1.68 (2.39)^2}{2(1)^2} = 16.16. \tag{2}$$

For a 95% level of confidence and the same degree of precision,

$$n = \frac{1.96 (2.39)^2}{2(1)^2} = 21.92. \tag{3}$$

Finally, to increase the level of confidence to 99%, the sample size would need to be increased by 100% to a total of 40 for E/P signals only.

Consequently, a 15% sample (20 E/P sites), which is well within the range of sample sizes suggested by reasonable levels of statistical confidence and precision for estimating traffic conflict rates, was selected.

Criteria for Selecting Sites

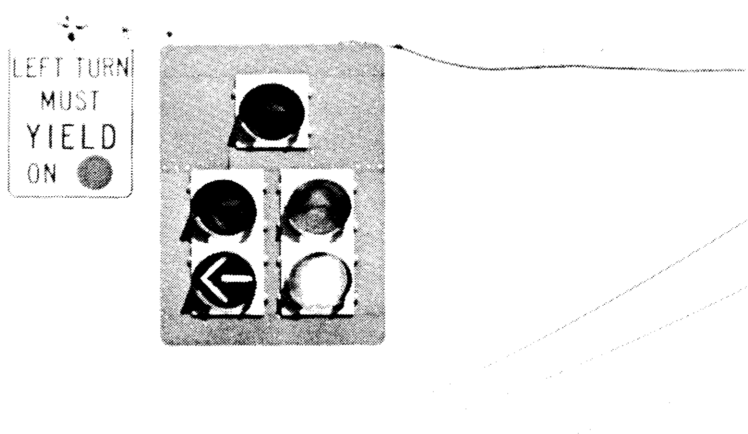
A total of 45 sites were examined; 20 sites for E/P, 15 sites for E, and 10 sites for P left-turn phasings. Emphasis was placed on arterial routes in suburban areas because these are of primary interest to the Department. It was desirable to select intersections with different types of left-turn signal phasings along one arterial since the intersections should have many similar site conditions and similar traffic conditions such as opposing through volumes and driver aggressiveness. A wide geographic distribution of sites was preferred. A range of left-turn and opposing through volumes was desired for each left-turn phasing.

Each study site satisfied the following requirements: (1) the signal display and placement conformed to Department standards, and (2) a left-turn lane was provided. The first requirement was intended for E/P signals under the control of municipalities. The E/P signal should (1) be of the 5-section house design, (2) have the sign "Left Turn Must Yield on (green ball)" mounted near the signal, and (3) be installed overhead on the left-turn lane line extended. Figure 2 displays the standard E/P signal installation. It is noted that since the field study, the standard sign legend has been changed to "Left Turn Yield on Green (with a green ball symbol)."

Four limitations were encountered in selecting sites. There are very few P left-turn signals with left-turn lanes, because left-turn lanes are most commonly used when there is a need for a separate left-turn phase. There weren't many arterials that have all three left-turn phases along a section of roadway. Since urbanized areas have more signalized intersections, more potential sites were located in or near urban areas. The sites were concentrated in 4 of the 9 highway construction districts in Virginia, and, since the majority of signalized arterials are on 4-lane roads, the majority of the study sites were on 4-lane roads.

The 45 study sites are described in Table 2. Information on the site number, intersection, location, and signal type is provided.

E/P signal placement



E/P signal head

Figure 2. Standard E/P installation.

Table 2

Listing of the Study Sites

Site No.	Intersection	County or City	Signal
1	60 & 650	Chesterfield	E
2	60 & 755	Chesterfield	E
3	60 & 147/653	Chesterfield	E
4	60 & Airport Rd.	Henrico	E
5	29 & 866	Albemarle	E
6	784 & 1826	Prince Wm.	E
7	1 & 234	Prince Wm.	E
8	29 & 655	Fairfax	E
9	620 & 2864	Fairfax	E
10	620 & 617	Fairfax	E
11	29 & 683	Campbell	E
12	17 & 216/1219	Gloucester	E
13	220 & 661	Roanoke	E
14	17 & 173	York	E
15	24th & Shenandoah	Roanoke City	E
16	50 & 2327	Fairfax	E/P
17	234 & 1566	Prince Wm.	E/P
18	234 & Crestwood	Prince Wm.	E/P
19	234 & 668	Prince Wm.	E/P
20	784 & 640	Prince Wm.	E/P
21	1 & 642/638	Prince Wm.	E/P
22	1 & 123	Prince Wm.	E/P
23	60 & 755	Chesterfield	E/P
24	60 & 754	Chesterfield	E/P
25	620 & 3647	Fairfax	E/P
26	620 & 2864	Fairfax	E/P
27	29 & 678	Campbell	E/P
28	460 & 670	Campbell	E/P
29	17 & 1307	Gloucester	E/P
30	17 & 1304	Gloucester	E/P
31	419 & 220	Roanoke	E/P
32	10 & 638	Chesterfield	E/P
33	10 & 643	Chesterfield	E/P
34	60 & Krouse/Sanborne	Henrico	E/P
35	29 & 243	Fairfax	E/P
36	50 & Allen	Fairfax	P
37	1 & 636/750	Prince Wm.	P
38	220 & Duke of Glouc.	Roanoke City	P
39	10th & Patterson	Roanoke City	P
40	10th & Loudon	Roanoke City	P
41	10th & Orange	Roanoke City	P
42	460 & 131/1012	Appomatox	P
43	460 & 727	Appomatox	P
44	29 & 698	Fairfax	P
45	60 & Lewis Rd.	Henrico	P

Traffic Volumes and Conflicts

Traffic volumes and conflicts were collected at each site with respect to the left-turn approach; that is, the approach with the highest volume. Data were collected during six 45-minute intervals of the off-peak period and continuously during the 2-hour peak period (recorded in 15-min. intervals) of the day defined by the sum of the left-turn and opposing volumes of the study approach. Appendix A displays the position of the observers, Figure A-1, and the data collection forms, Figures A-2 and A-3. The total opposing volume was recorded by a mechanical traffic counter placed as shown in Figure A-1. Opposing through trucks, loosely defined as any trucks larger than a pickup, were counted by observer A. Six types of conflicts were observed.(3) A type 1 conflict is the basic left-turn conflict where the left-turning vehicle crosses in front of an opposing through vehicle whose driver has to brake or weave to avoid the left-turn vehicle. In the type 2 conflict, the second through vehicle following the first through vehicle also has to brake. A truck conflict is one in which a through truck is involved in a type 1 or type 2 conflict.

Type 3 conflicts are violations where vehicles enter the intersection and turn left on red, and a type 4 conflict is a rear-end conflict in the left-turn lane that results when the following vehicle brakes after the lead vehicle begins its left turn and then stops. Incidences of left-turn vehicles overflowing the storage lane and blocking the through lane are type 5 conflicts. Left-turn volumes on the green arrow and green ball were counted. Observer B recorded the type 3 through 5 conflicts and left-turn volumes. Both observers used manual counting boards. The total left-turn conflicts is the sum of types 1 through 5 conflicts.

Left-Turn and Total Intersection Delay

The point-sample-stopped-delay method was used to measure delay.(11,12) Delay is measured in three 15-minute intervals, two off-peak samples, and one peak-period sample, in 2-hour cycles by two observers. "Stopped delay" is the total amount of time vehicles are stopped at an intersection approach. An observer records the number of stopped vehicles on an approach every 15 seconds for 60 point samples of stopped vehicles in 15 minutes. The "stopped delay per vehicle" is the total stopped delay (15 seconds x sum of the number of vehicles in the point sample) multiplied by a modifying factor of 0.92 and divided by the number of vehicles passing through the approach during the study interval. Stopped delay was measured for the left-turn approach being studied plus each approach (or leg) to the intersection. The data collection forms are shown in Figures A-4 through A-6. It is noted that this method did not provide data on the peak-hour delay because of the

2-hour cycle requirement to completely sample the intersection. The 2-hour peak-period sampling was made in the peak hour at some of the sites.

Site Conditions

Site conditions describe the road and intersection environment in which the left-turn signal phasing is operating. The following site conditions were examined:

- signal placement
- number of lanes of opposing through volume
- speed limit
- intersection type and size
- median width
- sight distance and alignment
- adjacent land use
- length of left-turn lane

These factors were investigated to assess their impact on the performance of the left-turn signal phasing. They were displayed in a diagram for each site.

Accidents

Accidents involving left-turning vehicles were analyzed for each site. Accident data were limited since many of the E/P signals were installed within the last 2 years. Accidents were analyzed for the following time periods: (1) recent 2-year period, (2) recent 1-year period, (3) 1-year period before a left-turn signal change, and (4) 6-month transition or adjustment period for E/P signals.

CHAPTER 4

TRAFFIC ENGINEERING ANALYSIS

The traffic engineering analysis examined the study sites relative to existing guidelines for left-turn signal phasing and evaluated the safety and operational aspects of the intersections for the left-turn phasings.

This section is divided into the following areas: (1) guidelines for analysis of the study sites, (2) relationships among the traffic data, (3) before and after analysis of two sites converted from E to E/P phasing, (4) causes of left-turn traffic conflicts and accidents, (5) truck conflict analysis, and (6) user costs versus implementation costs.

Guidelines Used for Examination of the Study Sites

The following guidelines were used for the examination.

a) Volume -- consider a separate left-turn phasing if the product of the peak-hour left-turn and opposing volumes (LTOV) is greater than 45,000, 90,000, and 135,000 for 1-, 2-, and 3-lanes of opposing through traffic, respectively. In other terms, the LTOV divided by the number of lanes of opposing through traffic, NL, should be greater than 45,000. This guideline is commonly used by the Department. Additionally, the peak-hour left-turn volume is at least 50.

b) Delay -- consider an E/P left-turn phasing if the total peak-hour left-turn delay is greater than or equal to 2.0 vehicle-hours and the mean delay is above 35.0 vehicle-seconds/vehicle (veh sec/veh).

c) Conflicts -- consider an exclusive phasing if the total or peak-hour period total left-turn conflicts number and rate exceed the critical conflict number and conflict rate for one approach of a given type of signal phasing.

d) Accidents -- consider an E phasing if both the annual left-turn accidents and accident rate exceed the critical accident number and rate for one left-turn approach of a given type of signal phasing. A left-turn accident is any accident involving a vehicle turning left from the approach being examined.

e) Site conditions -- consider an E phasing if it is determined that site conditions may affect the safety of left-turn signal phasing. These include sight distance, number of lanes of opposing through traffic, speed limit, road geometrics, and access management to adjacent properties (access management examines the influence of vehicles entering and exiting driveways or service roads along the arterial).

The critical number and rate for conflicts and accidents are determined by the following equations based on the rate quality control method.(13)

$$N_c = N_a + K\sqrt{N_a} - 0.5, \tag{4}$$

where,

N_c = critical number for a given type of signal phasing,

N_a = average number for a given type of signal phasing, and

K = constant that determines the level of confidence that rates (or number) are significant and have not resulted by chance. For a 95% level of confidence, K = 1.645.

$$R_c = R_a + K\sqrt{R_a/V} - 0.5/V, \tag{5}$$

where,

R_c = critical rate (number per exposure volume) for a site,

R_a = average rate for a given type of signal phasing, and

V = exposure volume, in vehicles at a site. For conflicts, V = number of left-turn vehicles. For accidents, V = number of left turn plus opposing vehicles.

The critical number should serve as a caution that the accident experience is high, while the combination of the critical number and rate confirms that the accident experience is unusually high.

It is noted that the critical number is the same for all sites of a given type of signal phasing, whereas the critical rate varies for each site because it is dependent upon the exposure volume.

Table 3 displays the critical number and average rates by type of signal phasing for conflicts and accidents.

Table 3

Critical Number and Average Rates

a) Total Conflicts

	Critical Number Peak Hour	Critical Number Total Period	Average Rate (Conflicts per 100 left turns) Peak Hour	Average Rate (Conflicts per 100 left turns) Total Period
E	12	35	3.1	2.8
E/P	15	49	4.5	4.0
P	8	23	8.8	5.6

b) Annual Left-Turn Accidents

	Critical Number	Average Rate (Accidents per 100 million Left-turn & opposing vehicles)
E	2	14.0
E/P	6	55.8
P	2	16.8

The annual left-turn accident rates were calculated using the following equation for the annual exposure volume.

$$V = (\text{12-hour left-turn approach volume} + \text{12-hour opposing volume}) \times 1.41 \frac{\text{day}}{\text{12 hr.}} \times 365 \text{ days/year.} \quad (6)$$

The value of 1.41 reflects the finding that approximately 71% of the intersection volume occurs during the 12-hour count.(14) This was the best approximation since 24-hour volume counts for intersections were not available. It is noted that some of the 12-hour counts were taken more than 3 years ago. However, this information was used because it was the most recent available.

A sensitivity analysis was performed to examine the effect of the highest accident rates for E/P sites on the critical rate. It was found that the changes in the critical accident values were minimal when the extremely high values were omitted in the computation of the critical values as compared to when they were included.

Relationships Among the Traffic Data

Relationships among the traffic data were examined by signal type.

E/P Signals--Volume and Safety

When the E/P sites were ranked in decreasing order of LTOV (Table 4), traffic conflicts and accidents were seen to be prevalent in sites with an LTOV greater than 320,000 (or LTOV/NL greater than 160,000). It is noted that for site 16, the LTOV/NL = 158,000 was rounded to 160,000.

For 5 of the 7 sites with an LTOV/NL greater than 160,000, the peak-hour total conflict number was exceeded. The remaining 2 sites exceeded the total annual intersection accident rate. The total period conflict number was exceeded for 6 of the 7 sites.

Four of the 7 sites exceeded the critical annual number of left-turn accidents. One of these 4 sites exceeded both the critical annual left-turn and total intersection accident rates. A second site with 3 lanes of opposing traffic exceeded the critical annual intersection accident rate. For a third site, there appeared to be a problem with timing of the left-turn signal. The fourth site had the highest LTOV/NL.

Traffic conflicts and accidents tended to be concentrated at sites where the LTOV/NL was greater than 160,000. It is also noted that with the exception of the site with 3 lanes of opposing traffic, the peak-hour left-turn volume was greater than 220 vph.

Because of the higher vehicle exposures for the sites with an LTOV/NL greater than 160,000, there are more opportunities for conflicts or accidents. Consequently, it is beneficial to focus on the rate measures since they take differences in vehicle exposures into account.

The peak-hour conflict rate was not exceeded for any of the sites. Although 4 of the 7 sites exceeded the total period conflict number and rate, site 26, with the second highest LTOV/NL of 299,000, did not.

Four sites had a left-turn accident problem based on both the number and rate of critical accidents occurring annually. Two sites, 19 and 22, had intersection accident problems.

Table 4

Ranking of E/P Phasing Sites by Peak-hour LTOV

Site No.	LTOV (1,000s)	LTOV/NL (1,000s)	No. Left-Turn Veh.	Conflict Problems				Accident Problems		
				Peak hr.		Total Period		Left Turn		Intersections
				NC	RC	NC	RC	NC	RC	RC
17	1,030	515	595	x		x	x	x		
26	598	299	459	x		x		*		
16	474	158	192			x	x	x		x
19	405	203	246					x	x	x
22	384	192	222	x		x	x			
25	369	185	419	x		x	x	x		
35	320	160	303	x		x			NA	
23	293	147	142					x		
31	289	145	203							
20	216	108	141							
18	159	80	84				x			
28	133	67	180					NA	NA	
33	114	114	138							
21	111	56	142			x	x			
27	108	54	76							
34	98	98	145							
29	97	49	145					NA	NA	
30	68	34	104					NA	NA	
24	59	30	143							
32	44	44	71							

NC - the critical number
RC - the critical rate
x - the critical value was exceeded
* - for a 7½-month period, the number and rate of critical accidents were exceeded
NA - not available

E Signals

In comparisons of LTOV and delay (Table 5), 4 of the 7 sites with an LTOV greater than 239,000 (or LTOV/NL greater than 120,000) exceeded both delay criteria.

A traffic conflict problem based on the critical number is noted for all 6 sites with a LT/OV greater than 0.30 and 1 site below this value. Also, the peak-hour left-turn volume was greater than 270 for all 7 sites that experienced a high number of traffic conflicts. At 5 of the 7 sites, turns on red were the predominant conflict, while lane overflows were the primary conflict at the other 2 sites. Two sites had traffic conflict problems based on critical rates.

As expected, left-turn accidents were not a problem at E signal sites.

P Signals

No trends were evident at the P signals, as shown in Table 6. The volume at 1 of the 2 sites that had a high number of traffic conflicts exceeded the volume guideline. This site,37, was changed from E to E/P to P. Site 41 had an intersection angle different from 90° and the approach studied was on a downgrade. Traffic control changes were made at site 41 due to the high intersection accident rate. At site 36 there were service roads on both sides of the major roadway; therefore, access management problems may contribute to the high accident rate at the intersection.

Table 5

Ranking of E Phasing Sites by Peak-hour LTOV

Site No.	LTOV (1,000s)	LTOV/NL (1,000s)	No.Left-turn Vehs	LT/OV	Conflict Problems: Peak Hour NC	Peak Hour RC	Total Period NC	Total Period RC	Total Intersection RC	Delay Problem
9	534	267	413	0.32			x			
1	445	148	303	0.21	x		x	x		x
5	333	167	266	0.21						x
7	308	154	355	0.41	x		x			
10	282	141	264	0.25						x
2	248	124	127	0.06						
3	239	120	294	0.36			x			x
14	213	107	183	0.16						
12	207	104	163	0.13					x	
4	200	100	415	0.86	x		x			
6	200	100	273	0.37	x					
8	179	90	281	0.44	x	x	x	x		
13	55	28	68	0.08						
15	53	27	92	0.16						x
11	30	15	27	0.02						

NC - the critical number
RC - the critical rate
x - the critical value was exceeded
NA - not available

Table 6

Ranking of P Phasing Sites by Peak-hour LTOV

Site No.	LTOV (1,000s)	LTOV/NL (1,000s)	No. Left-turns Vehs.	LT/OV	Conflict Problems: Peak Hour NC	Peak Hour RC	Total Period NC	Total Period RC	Total Intersection RC
37	153	77	180	0.21	x		x	x	
44	75	38	85	0.10					
36	65	65	36	0.02					x
41	32	32	58	0.11	x	x	x		x
40	27	27	103	0.40					
45	27	27	38	0.05					
38	22	22	22	0.02					
39	22	22	87	0.34					
43	15	15	23	0.03					
42	10	10	21	0.04					

NC - the critical number
RC - the critical rate
x - the critical value was exceeded

Before and After Field Study

Data were collected at 2 sites, Rtes. 60 and 755 in Chesterfield County and Rtes. 620 and 2864 in Fairfax County, before and after a left-turn signal phasing change from E to E/P phasing.

Routes 60 and 755 - Chesterfield County

Tables 7 and 8 display the before and after data for the peak-hour and total periods, respectively. For the peak-hour and total periods, the total conflict rate decreased by 40% and increased by 21%, respectively. The 21% increase was due to the increase in types 1 and 2 conflicts. Left-turn vehicle delay in veh sec/veh increased 8% in the peak period and decreased 43% in the total period. The increase in the peak period may have been attributable to a less than optimum signal timing or to the refusal or hesitancy of some drivers to turn left on the green ball phase. Total intersection delay for the peak period and total period decreased 6% and 16%, respectively. The left-turn accident rate was 6.5 times greater with E/P phasing.

Routes 620 and 2864 - Fairfax County

The before and after data for Rtes. 620 and 2864 are shown in Tables 9 and 10. The total conflict rate increased in the peak hour and total period by 54% and 35%, respectively. The increase was due to an increase in types 1, 2, and 4 conflicts. The type 3/100LT conflict rate, denoting left turns on red, decreased 43% in the total period; and the type 4/100LT conflict rate, denoting lane overflows, decreased 53% in the total period. Mean left-turn delay in veh sec/veh decreased 63% and 77% in the peak period and total period, respectively; and total intersection delay for the peak period and total period decreased 15% and 38%, respectively. Accidents increased in the transition period.

Summary

In general, the expected trends were found for the total period for both sites (Tables 8 and 10). The total traffic conflict rate increased (21% and 35%), the left-turn delay in veh sec/veh decreased (43% and 77%), and, mean total intersection delay in veh sec/veh decreased (16% and 38%). Also, from Tables 7 and 9, the number of left-turn accidents increased (200% and 700%).

Table 7

Before and After Data for Routes 60 and 755, Chesterfield County - Peak Hour

	Before(E)	After(E/P)	Percent Change
Conflicts			
Type 1 & 2	0	1	-
Type 1 & 2/per 100LT	0	0.7	-
Type 1 & 2/per 1000LT+OV[a]	0	0	0
Type 3	2	1	-50
Type 3/100LT	1.6	.7	-56
Type 4	3	2	-33
Type 4/100LT	2.4	1.4	-42
Type 5	1	0	-100
Type 5/100LT	.8	0	-100
Total	6	4	-50
Total/100LT	4.7	2.8	-40
Volume			
LT	127	142	12
OV	1954	2061	5
LTOV	248,158	292,662	18
Delay			
Total Left Turn (veh hr)	1.1	1.4	27
Mean Left Turn (veh sec/veh)	32.0	34.5	8
Mean Intersection (veh sec/veh)	18.8	17.6	- 6

Accident (1 yr. period)	No.	Rate	No.	Rate	No.	Rate
Left Turn	1	12.4	8	92.4	700	645
Both Left Turns	1	6.2	10	62.2	900	903
Total	8	46.9	19	111.6	138	138

[a]LT = left turn
OV = opposing volume

Table 8

Before and After Data for Routes 60 and 755, Chesterfield County - Total Period

	Before(E)	After(E/P)	Percent Change
Conflicts			
Type 1 & 2	0	9	-
Type 1 & 2/per 100LT	0	1.2	-
Type 1 & 2/per 1000LT+OV[a]	0	0	-
Type 3	5	6	20
Type 3/100LT	.8	.8	0
Type 4	6	3	-50
Type 4/100LT	.9	.4	-56
Type 5	1	0	-100
Type 5/100LT	.2	0	-100
Total	12	18	50
Total/100LT	1.9	2.3	21
Volume			
LT	643	776	21
OV	8480	9217	8
Percent of LT on green ball	-	43.9	-
Delay			
Total Left Turn (veh hr)	5.3	3.7	-30
Mean Left Turn (veh sec/veh)	29.8	17.0	-43
Mean Intersection (veh sec/veh)	11.5	9.7	-16

[a]LT = left turn
OV = opposing volume

Table 9

Before and After Data for Routes 620 and 2864
Fairfax County - Peak Hour

	Before(E)	After(E/P)	Percent Change
Conflicts			
Type 1 & 2	0	3	-
Type 1 & 2/per 100LT	0	0.7	-
Type 1 & 2/per 1000LT+OV[a]	0	0.1	-
Type 3	1	1	0
Type 3/100LT	.2	.2	0
Type 4	0	5	-
Type 4/100LT	0	1.1	-
Type 5	9	8	-11
Type 5/100LT	2.2	1.7	-23
Total	10	17	70
Total/100LT	2.4	3.7	54
Volume			
LT	413	459	11
OV	1,294	1,302	1
LT+OV	534,422	597,618	12
Delay			
Total Left Turn (veh hr)	3.5	1.4	-60
Mean Left Turn (veh sec/veh)	30.9	11.3	-63
Mean Intersection (veh sec/veh)	17.7	15.0	-15

Accident[b]

	No.	Rate	No.[b]	Rate[b]	No.	Rate
Left Turn	2	32.8	6	157.7[c]	200	381
Both Left Turns	2	16.3	8	65.5	300	302
Total	11	80.6	18	132.2	64	64

[a] LT = left turn
OV = opposing volume

[b] The before accident period was 1 year and the after accident period was 7½ months.

[c] The critical accident rate was exceeded.

Table 10

Before and After Data for Routes 620 and 2864
Fairfax County - Total Period

	Before(E)	After(E/P)	Percent Change
Conflicts			
Type 1 & 2	0	22	-
Type 1 & 2/per 100LT	0	1.2	-
Type 1 & 2/per 1000LT+OV[a]	0	0.2	-
Type 3	13	7	-46
Type 3/100LT	.7	.4	-43
Type 4	0	13	-
Type 4/100LT	0	.7	-
Type 5	23	9	-61
Type 5/100LT	1.3	.5	-53
Total	36	51	42
Total/100LT	2.0	2.7	35
Volume (vehicles)			
LT	1806	1858	3
OV	5325	5476	3
Percent of LT on green ball	-	37.3	-
Delay			
Total Left Turn (veh hr)	17.7	4.2	-76
Mean Left Turn (veh sec/veh)	35.2	8.1	-77
Mean Intersection(veh sec/veh)	15.4	9.6	-38

[a]LT = left turns
OV = opposing volume

Causes of Left-turn Traffic Conflicts and Accidents

Based on the accident reports reviewed, the major factor contributing to accidents involving left-turning vehicles and opposing through vehicles was driver inattention. It is suspected that contributing factors are driver perception errors, impatience, confusion, aggressiveness, and site conditions, and these are discussed below. There are more left-turn accidents at E/P phasing, probably because of the high traffic volumes and the complexity of a combined left-turn signal phasing.

Driver Perception Errors

Drivers may perceive an inadequate gap in the opposing through traffic as being adequate. In other words, a driver may misjudge the amount of time that is available to negotiate a left turn or the time that is required for the turn. A strategy to reduce driver perception errors is to assure that adequate sight distance is available to identify acceptable gaps and to provide a safe stopping sight distance for the opposing volume.

Driver Impatience

Left-turn drivers may accept an inadequate gap because (1) they are in a hurry, (2) they are tired of waiting for a larger gap, or (3) the delay to left-turning vehicles is perceived to be excessive. Impatience leads drivers to intentionally accept an inadequate gap, whereas driver perception errors are not intentional.

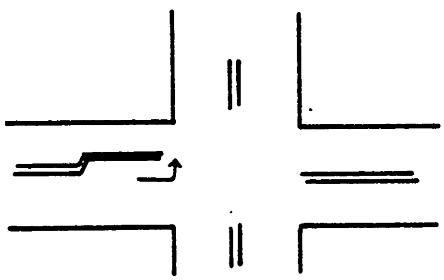
Improved selection of intersections for left-turn signal phasing and improved timing of left-turn signals may help to reduce driver impatience. An example of this is a strategy to improve driver response to the yellow change interval.(15) This problem is evident in that several sites experienced a high number of turn-on-red conflicts. To alleviate the problem, one might first determine if the green phase is reaching its maximum without fully satisfying the left-turn demand. If this is occurring, then the green time could be extended, especially the green arrow time for E/P signals. Secondly, it could be determined if a slow or cautious driver was causing the green phase (the green arrow phase for E/P) to end prematurely. If this is occurring, then the passage time (gap between vehicles that ends the green phase when exceeded) setting could be extended.

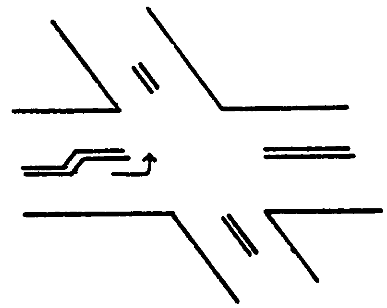
Driver Confusion

Driver confusion is the result of a left-turning driver believing that he has the right-of-way on the green ball when he ought to yield to the opposing through volume. When an E signal is changed to E/P, the driver has been accustomed to turning on the green signal, an arrow, and may continue to do so even though a green ball signal indication has been added. This reaction should be limited to the transition period, and a driver's response to the first E/P signal he encounters. Advance publicity on changes in left-turn signal phasing and driver education appear to offer benefits in reducing driver confusion.

Site Conditions

As noted in Appendix B, three factors -- access management, intersection geometrics, and the number of lanes of opposing through vehicles -- are likely to influence traffic conflicts and accidents. Problems with access management are noted where vehicles using commercial or private entrances and exits or service roads near the intersection interfere with the safe and efficient flow of traffic. Intersection geometrics, especially the angle of the intersection of the two roads, may contribute to the safety problem. Additional time may be required to negotiate a left turn greater than 270° compared to a turn of 270° (Figure 3). When the need for additional time is not perceived, a left-turning driver may accept an inadequate gap and thus create a hazardous situation. Additional time and, therefore, longer gaps are required to traverse 3 lanes as compared to 2 lanes. Only site 16 had an E/P phasing with 3 lanes of opposing traffic. The total period critical conflict rate and number, the critical left-turn accident number, and critical intersection accident rate were exceeded. The left turn critical accident rate was not exceeded (Table 4). These problems were also related to the presence of service roads. It is difficult to identify the major cause of the safety problems for this site because of the many possible contributing factors. At site 1, which has an E phasing with 3 lanes of opposing through traffic, the critical peak hour and total period conflict number and the total period conflict rate were exceeded (Table 5). Although the accident experience indicated no problems, the conflict analysis indicated traffic problems.





Left turn of 270°   Left turn greater than 270°

Figure 3. Comparison of two intersection angles.

Speed limits above 45 miles per hour were not considered to cause a problem based on the two E/P sites, 29 and 30, that have a speed limit of 55 miles per hour.

Aggressive Driver Behavior

Aggressive driving results in driving maneuvers that involve high risks of accidents and is the opposite of cautious, defensive driving. Driver aggressiveness in negotiating left turns is characterized by a willingness to accept small gaps in the opposing through traffic and turning on red. Consequently, driver aggression may be identified by a high number of traffic conflicts. Based on experience, it appears that driver aggression is directly proportional to the traffic volumes and that the more aggressive driver behavior is concentrated in particular areas. While 18 of the 45 sites (40%) are located in Fairfax and Prince William counties, 14 of the 17 sites (82%) that exceeded at least one of the critical traffic conflict values shown in Tables 4 through 6 are in these two counties. Furthermore, for E/P sites, all 8 sites where critical conflict values were exceeded are in these two counties (Table 4). E/P sites with the highest peak LTOV, 6 of which exceeded a critical conflict value, are located in these two counties. This may indicate that (1) driver aggression is directly proportional to volume, and (2) there is a great willingness to use E/P signals, especially at high volume locations, in these two counties.

Although it is difficult to firmly state the extent to which driver aggressiveness influences safety problems, because of the numerous variables involved, it appears that driver aggression does adversely influence the performance of left-turn signal types.

Truck Conflicts Analysis

Conflicts between opposing through trucks and left-turning vehicles (truck conflicts) were included in the data collection because of a concern that accidents resulting from this type of conflict may be very severe and that this conflict may be overrepresented relative to other types of conflicts. The truck conflict ratio, types 1 & 2 conflicts per 100 opposing trucks: types 1 & 2 conflicts per 100 opposing vehicles, was used to determine if the truck conflict rate was greater than the types 1 & 2 conflict rate based on opposing volumes.

Seven sites had a total period truck conflict ratio greater than 1. Of those 7, only 2 had more than 2 truck conflicts. A review of the accident history of those 2 sites revealed that 1 had had a left-turn accident involving a truck. At site 28, Rtes. 460 & 670 in Campbell County, a property damage only accident occurred between a semi-tractor trailer and car during the 6-month transition period of a signal phasing change to E/P. This site, with 6.5% of the opposing volume being through trucks, was the only one with over 4% of the opposing volume consisting of through trucks.

Based on these findings, it was concluded that the through truck volume does not appear more hazardous to left-turning vehicles than the remaining opposing volume.

User Cost Savings for E/P Versus E Phasings

One method for justifying the installation of a left-turn phasing is to demonstrate that the benefits or user cost savings exceed the installation costs. When a separate left-turn phasing is warranted, the alternatives are E or E/P phasing. In general, the user cost savings for E/P are associated with the reduction in delay and the savings for E phasing are associated with the reduction in accidents.

A survey of the Department's district traffic engineers revealed that it costs approximately $500 more to install an E/P than an E signal.

The average delay savings for E/P for the total time period is 20.1 veh sec/veh. Using the mean value of left-turn vehicles for E and E/P of 1,006 for the total period and an adjustment factor of 2.6 to expand the period to 24 hours (from reference 14), the annual total vehicle hours of delay saved can be calculated.

$$\text{Annual delay savings} = 20.1 \text{ veh sec/veh} \times \frac{1 \text{ hr}}{3600 \text{ sec}} \times (1{,}006 \times 2.6) \text{ veh/day} \times 365 \text{ days/year}$$

$$= 5{,}330 \text{ veh hrs.}$$

Using values from reference 11, the following user costs were calculated.

User Cost Savings

Vehicle Operating Cost:	\$312.64/1,000 veh hrs x 5,330 veh hrs =	\$ 1,666
Fuel:	\$1.10/gal x 650 gal/1,000 veh hrs x 5,330 veh =	3,811
Vehicle Travel Time:	\$1 per hour x 5,330 veh hrs =	5,330
TOTAL		\$10,807

It is noted that the reduction in total intersection delay was not included in the savings. After subtracting the \$500 difference in installation cost, the estimated annual cost savings for an E/P signal is \$10,300.

This annual cost savings estimate for E signals is based on a mean accident reduction of 2.5 accidents per year. Unfortunately, no data are available on the mean cost of a left-turn accident. However, to provide a benefit greater than that of an E/P signal, the mean accident cost must be greater than \$10,300/yr divided by 2.5 accidents/yr, or \$4,120.

When applied to a particular intersection, the estimated savings can be improved by using the actual left-turn ADT and delay measures, the mean cost of prior accidents at that intersection, total intersection delay measures, and updated unit costs figure from reference 11. Moreover, reliable methods for predicting differences in delay and accidents would be helpful.

CHAPTER 5

STATISTICAL ANALYSIS

The Statistical Package for the Social Sciences, a collection of computer programs for the application of statistical techniques, was employed to perform Pearson correlation, regression analysis, and analysis of variance.(16) Also, statistical tests to compare mean traffic measures by signal type were conducted manually.

Because of the extensive amount of data collected, the Pearson correlation subprogram was used to screen the data and identify selected variables for regression analysis. The Pearson correlation coefficient, R, is a measure of the association between two variables and an indication of the strength of the linear relationship between them. Variable pairs that have high R values, that is, 0.6 or greater, were selected. The sites were grouped by signal type, then peak hour, average off-peak hour, and total time periods were analyzed.

The multiple regression subprogram was used with the intent of identifying relationships between variables that have the strongest linear correlation in order to explain what variables influence a particular traffic measure.

Analysis of variance is basically a form of multiple regression that determines whether the effect of different classes or categories of a factor or independent variable is significant and that identifies any relations between two or more factors.

The multiple regression analysis of traffic measures by signal type and the analysis of variance of the accident history of E/P sites converted from E phasing are presented in Appendix B.

The findings of the following analyses are presented below: (1) a comparison of mean traffic measures by signal type, (2) left turns on green ball for E/P phasing, and (3) left-turn delay in the off-peak period.

Comparison of Mean Traffic Measures by Signal Type

The purpose of this section is to compare the mean peak-hour traffic measures of the signal types shown in Table 11. Assuming the traffic measures are normally distributed, comparisons of the means of two signal types with unequal variances may be made statistically using the Aspin-Welch Test.(17) A one-sided test was conducted with an 0.05 level of significance. The statistical comparison was limited to the E

Table 11

Mean and Standard Deviation Values for
Peak-hour Traffic Measures by Signal Type

Mean (Standard Deviation)	E	E/P	P
Conflicts			
Type 1+2	0 (0)	4.2 (4.7)	2.2 (3.0)
Type 1+2/100LT	0 (0)	2.0 (1.7)	3.5 (4.8)
Type 1+2/1000LT+OV	0 (0)	0.3 (0.3)	0.3 (0.4)
Type 3	3.5 (3.5)	2.9 (2.2)	2.1 (2.3)
Type 3/100LT	1.5 (1.3)	1.5 (1.2)	4.4 (6.0)
Type 4	1.9 (2.1)	1.0 (1.5)	0.5 (1.1)
Type 4/100LT	0.8 (0.8)	0.6 (0.7)	0.7 (1.7)
Type 5	2.5 (3.1)	1.9 (5.1)	0.3 (0.9)
Type 5/100LT	0.8 (0.9)	0.4 (0.9)	0.2 (0.5)
Total	7.9 (5.8)	10.0 (8.8)	5.1 (4.3)
Total/100LT	3.1 (1.5)	4.5 (2.1)	8.8 (6.6)
Volume (vehs)			
LT	235 (120)	208 (138)	65 (50)
OV	1,034 (389)	1,227 (573)	746 (452)
LTOV	235,248 (137,687)	268,520 (237,989)	44,860 (43,547)
Delay			
Total Left-turn delay (veh hrs)	2.3 (1.0)	0.8 (0.8)	0.2 (0.4)
Mean Left-turn delay (veh sec/veh)	34.8 (16.0)	13.7 (10.3)	10.3 (14.9)
Mean intersection delay (veh sec/veh)	19.1 (15.8)	10.8 (8.1)	7.8 (5.2)
Number of Accidents			
Left Turn	0.7 (0.7)	3.2 (3.7)	0.5 (1.0)
Total	8.8 (4.5)	12.5 (3.5)	6.1 (7.7)
Accident Rates (accidents/100MV)			
Left Turn	15.0 (15.9)	55.8 (48.3)	16.8 (15.9)
Total	81.4 (43.0)	103.9 (70.4)	77.6 (49.7)

and E/P phasings since these sites represented the traffic conditions where a separate left-turn phase was warranted.

A comparison of the total traffic conflict rates showed that the rate for E/P phasing was significantly greater than that for the E phasing. There was no significant difference between the E and E/P LTOV values. The left-turn delay in vehicle hours was significantly greater for the E phasing. There was no significant difference in the mean left-turn or intersection delay per vehicle. Although there was no significant difference in the mean accident rates, the number of left-turn accidents was significantly greater for E/P phasing. For only the E/P sites that were converted from E phasing (with a mean accident rate of 67.1), there was no significant difference in the mean accident rates of E/P sites converted from E phasings.

These findings are consistent with the conclusions documented in the literature on the benefit of E/P phasing in reducing left-turn delay and the benefit of E phasing relative to safety.

Left Turns on the Green Ball for E/P Phasing

The percentage of vehicles that turn left on the green ball influences the left-turn delay at E/P signals. When compared to an E phasing, the reduction in left-turn delay for E/P is directly attributable to the volume or percentage of all left-turn vehicles that turn on the green ball. The relationship between the percentage of left turns on the green ball (LTPCTB) and the opposing volume (OPVOL) is shown in Figure 4 for 1 and 2 lanes of opposing traffic volume, where it can be seen that the LTPCTB decreases as the opposing volume increases. The delay benefits of E/P signals decreased as the opposing volume increased. The E/P signal functions more as an E signal when the higher opposing volume reduces the opportunities for turns on the green ball.

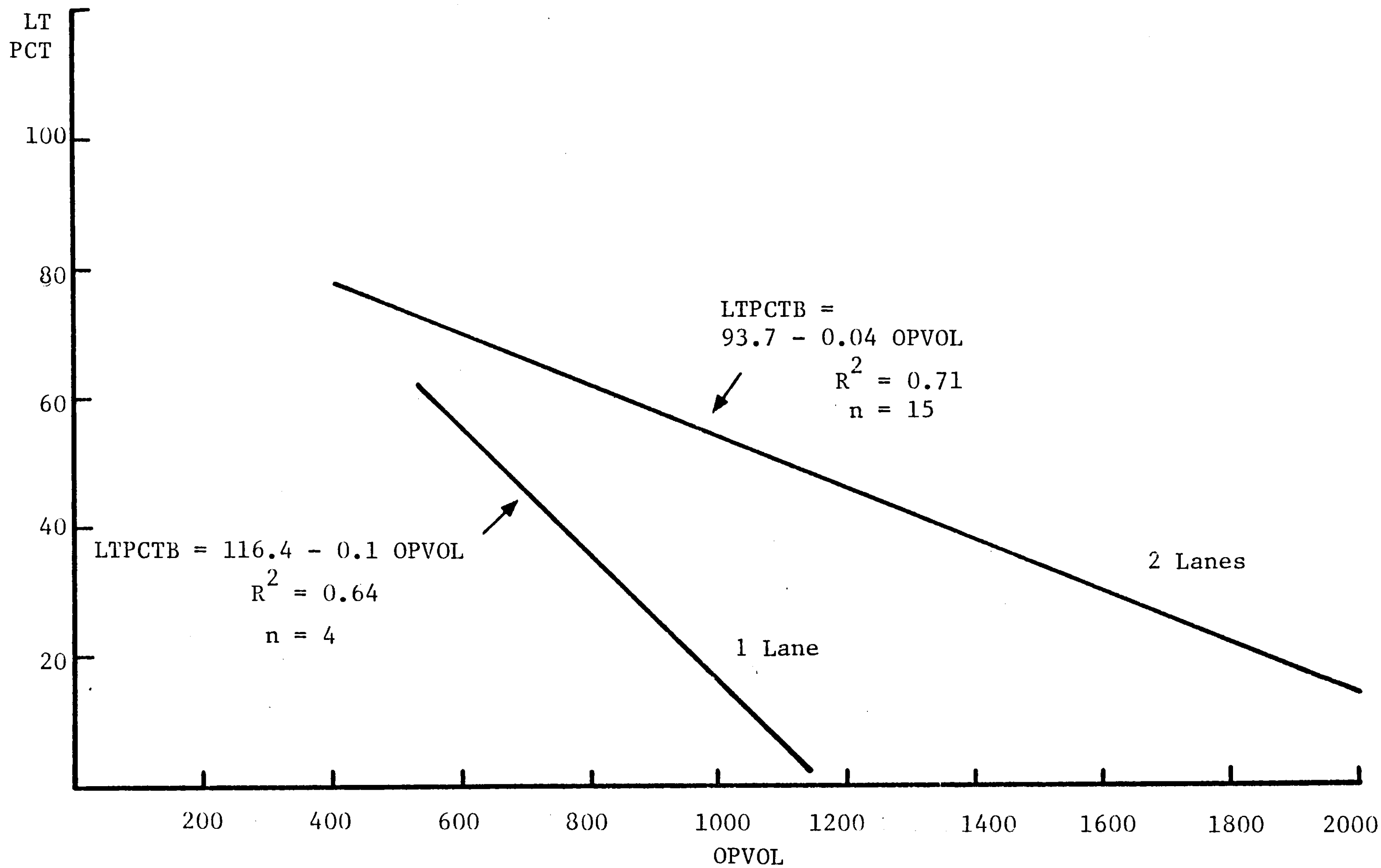


Figure 4. Peak-hour left-turn percentage of vehicles on green ball (LTPCTB) versus opposing volume (OPVOL).

Delay in the Off-Peak Period

The delay benefits of an E/P signal were greater in the off-peak period, which represents the major portion of the day, than in the peak hour. This is evident by the data shown in Table 12, which show that the total left-turn delay was 2.6 times greater for E sites than E/P sites in the peak hour and 4.5 times greater in the off-peak period. Using the Aspin-Welch test to compare the two means, it was concluded that the mean left-turn delay at E sites was significantly greater than the delay at E/P sites in the average off-peak hour. Again, there was no significant difference in the mean left-turn delays for the peak hour. The total left-turn delay was significantly greater for the E signal for both time periods.

Table 12

Mean Traffic Data Measures for the Average Off-Peak Hour

Mean (Standard Deviation)	E	E/P
Left-Turn Delay (veh sec/veh)	27.6 (6.4)	6.8 (3.3)
Total Left-Turn Delay (veh hrs)	1.1 (0.6)	0.2 (0.2)
TOTLT	144 (75.3)	123 (56.5)
OPVOL	716 (298.9)	754 (277)
LTOV	103,247 (66,175)	96,892 (57,924)

Note: Refer to Table 11 for peak hour mean values.

Relationship between Traffic Conflicts and Accidents

Because traffic conflicts and accident data are used for diagnosing safety problems, the regression relationships between them were examined. Measures of the correlation between the annual number of left-turn accidents and either the number or rate of traffic conflicts are given in Table 13. The correlations with the number of accidents were low for both conflict measures for all signal types. Moreover, the correlation with the accident rate was even lower. The correlations between accidents and conflicts were also low for the total time period.

Thus, it was concluded that accidents and conflict measures are not linearly correlated.

Table 13

Relationship between Accidents and Peak-hour Traffic Conflict Experience

A1SN and TOTCONF

Signal	R^2	α	SEE	CV	n
P	.12	.405	1.1	172.2	8
E/P	.11	.82	3.5	117.5	17
E	.13	.18	.7	104.9	15

A1SN and TOTCONFRATE

Signal	R^2	α	SEE	CV	n
P	.32	.143	.94	151.0	8
E/P	.00	.83	3.7	124.5	17
E	.19	.105	.68	101.4	15

A1SN - annual number of left-turn accidents
TOTCONF - total number traffic conflicts in the peak hour
TOTCONFRATE - total traffic conflict rate in the peak hour
R^2 - correlation coefficient
α - level of significance
SEE - standard error of the estimate
CV - coefficient of variance
n - sample size

CHAPTER 6

DEVELOPMENT OF THE GUIDELINES

In this section, the guidelines are developed based on the previous sections and additional analysis. The guidelines are divided into five parts: accident, traffic conflicts, volume, left-turn delay, and site conditions.

Accident Guidelines

Basic Criteria

The annual number of accidents is commonly used to assess the magnitude of an accident problem. However, a comparison of the number of accidents at different locations is inadequate because differences in the traffic volumes at the locations are not considered. The consideration of traffic volumes is significant with wider ranges of traffic volumes and high volumes(13). The number of accidents is included in the guidelines as a warning that when the critical number is exceeded, the left-turn accident experience is high for an intersection. Therefore, the number of accidents should be monitored and possibly evaluated for safety improvements.

The annual left-turn accident rate, left-turn accidents per 100 million left-turn and opposing volume vehicles, is the best available measure for taking vehicle exposure into account when determining if an intersection has an unusually high left-turn accident experience. Since it is possible for the critical rate to be exceeded when the critical number is not exceeded, an unusually high left-turn accident experience is evident when both the critical number and rate are exceeded. When the critical accident rate is exceeded, the following actions, or similar procedures, should be taken: (1) thoroughly investigate the intersection, (2) identify or develop alternatives that would improve the safety of the intersection, (3) evaluate the alternatives, (4) select an alternative for implementation, and (5) implement the alternative. For an E/P signal, the obvious alternative is to convert to an E signal. The investigation may indicate the need to adjust the signal timing with no further changes. Improving signal timing should be strongly considered as an alternative.

Since left-turn accidents are only one part of an intersection accident experience, it is beneficial to examine the annual number of accidents and accident rate. If the annual intersection accident rate exceeds the critical rate, then the same five step action plan used for left-turn accidents is in order.

From Table 3 the critical number of annual left-turn accidents for one approach is 2 for E and P phasing and 6 for E/P phasing. The average annual left-turn accident rate for an approach (i.e. accidents per 100 million LT+OV), is 14.0 for E phasing, 16.8 for P phasing, and 55.8 for E/P phasing. Therefore, it is usual for an E/P phasing to experience more left-turn accidents. Consequently, the primary concern with accidents is focused on E/P phasing.

In the analysis the sites were grouped by left-turn signal type when determining the critical accident number and rate because the objective was to compare traffic performance by left-turn signal type. However, there is a problem in grouping sites by signal type. If the mean accident experience for a signal type is unusually high compared to that of other signal types, then the critical accident values for that signal type will also be unusually high. Consequently, the higher accident experience for a signal type is accepted and tolerated when accident problems are identified based on the higher mean accident experience by signal type. Such is the case with the E/P phasing, where the accident experience is much higher relative to the E and P phasings.

An alternative approach is to use the mean accident experience for all left-turn signal types as the basis for computing the critical values. Compared to the mean accident experience by signal type, this alternative would increase the critical accident values for E and P phasings while decreasing the critical values for E/P phasing. This alternative narrows the range of acceptable left-turn accident experience for all left-turn signal types. Thus, it addresses the problem of an unusually high mean accident experience for a given signal type.

A ranking of E/P sites by peak-hour LTOV and accident data is shown in Table 14. Based on the mean accident number for all signal types, the critical number was 4 and was exceeded by 6 of 18 E/P sites (33% of total) compared to a critical number based on E/P sites of 6, which was exceeded by 4 of 18 E/P sites (22%). The number of E/P sites that exceeded the critical rate increased from 5 (33% of the sites) to 8 (53%) when the rate basis is changed from E/P signals to all types of signals. Similarly, the number of E/P sites with accident problems increased from 5 (33%) to 6 (40%). For sites 20 and 34, the rate was exceeded but not the number. This explains the difference of 2 between the number of sites that exceed the rate and the number of sites with accident problems.

It is concluded that there is only a very small increase in the number of sites that have accident problems when the critical values are based on the mean for all signals.

Table 14

Ranking of E/P Sites by Peak-hour LTOV
With Accident Data

Site No.	LTOV (1000s)	LTOV/NL (1000s)	No. Left-turns veh.	Acc. No.	Rate (accidents/100MV)	Critical Rate[a] (accidents/100MV)	Problem[a]	Critical Rate[b] (accidents/100 MV)	Problem[b]
17	1,030	515	595	7	96.0	60.5	x	94.5	x
26[c]	598	299	459	6	157.7	67.6	x	97.4	x
16	474	158	192	9	95.6	57.9	x	90.6	x
19[e]	405	203	246	13	176.1	60.4	x	94.3	x
22	384	192	222	3	52.3	63.1		98.4	
25	369	185	419	4	64.6	62.3	x	97.1	
35	320	160	303	0	NA	NA		NA	
23[e]	293	147	142	8	92.4	59.5	x	92.9	x
31	289	145	203	3	34.0	58.6		91.5	
20	216	108	141	3	74.0	66.9		104.5	
18	159	80	84	0	0	62.7		97.7	
28	133	67	180	0	NA	NA		NA	
33	114	114	138	0	0	70.4		110.6	
21	111	56	142	1	27.2	68.0		106.4	
27	108	54	76	1	23.0	66.2		103.3	
34	98	98	145	3	76.9	67.3		105.2	
29	97	49	145	3	NA	NA		NA	
30	34	68	104	NA	NA	NA		NA	
24	30	59	143	1	62.0	75.6		121.6	
32	44	44	71	0	0	58.6		110.2	

a - based on a mean rate for all signal types = 32.6 and critical number = 3.5 (rounded to 4)
b - based on mean rate for E/P signals = 55.8 and critical number = 5.6 (rounded to 6)
c - based on data for a 7½-month period, therefore this site is not included in the mean
d - 3 lanes of opposing through volume
e - not included in mean because there was a signal timing problem

Note: A site is considered to have an accident problem when both the critical number and rate are exceeded.

Based on the mean values for all signal types, the four sites with the highest LTOVs had unusually high accident experiences because both the critical number and rate were exceeded. In other words, it appears that unusually high accident experiences occur when the LTOV exceeds 400,000. Of these four sites, only site 16, with 3 lanes of opposing traffic, had an LTOV/NL under 200,000. Two sites, 25 and 23, with an LTOV under 400,000 or an LTOV/NL under 200,000, had unusually high accident experiences. Site 25 appeared to have a timing problem. Site 23 appeared to have a high peak-period delay, 34.5 veh sec/veh, for an E/P signal. It is noted that excluding site 16, peak-hour left-turn volumes above 200 vehicles appeared to result in accident problems.

A second alternative approach, basing the critical values on E and E/P signals, may result in more appropriate critical values since the traffic conditions are similar for E and E/P signals. Use of this approach results in a mean accident rate of 35.4 and a critical number of 3.8. Because the increase in the critical values when using E and E/P signals compared to all 3 signal types is minimal, the use of critical values based on all left-turn signal types is reasonable. In the Manual on Uniform Traffic Control Devices, one part of the accident experience warrant is satisfied when 5 or more reported accidents of types susceptible to correction by traffic signal control have occurred in 1 year.(18) If the critical annual number of 5 or more accidents is used, the results are the same. In order to be uniform and consistent with national standards, a critical number of 5 or more accidents is suggested. The effect of increasing the critical number by 1 is expected to be minimal since only one site, 25, would no longer be labeled as a problem.

Based on experience, some traffic engineers believe that rear end accidents involving left-turn vehicles will increase when an E/P signal is converted to an E signal. However, of the 10 left-turn accidents at the 15 E signal sites, none were of the rear end type. In many rear end accidents the damage may be below the amount required for accident reporting. Based on the available data, E signals do not promote rear end accidents involving left-turn vehicles.

It is noted that the Highway and Traffic Safety Division uses accident rates calculated by the rate quality control method in its hazard elimination program.(19)

Traffic Conflict Guidelines

Since traffic conflict guidelines are also based on critical values, they are also revised in order to be based on the mean traffic conflict experience for all left-turn signal types. The sites with conflict problems are identified in Table 15. The conclusion drawn from

Table 15 is the same as that drawn from Table 4 with critical values based on E/P signals only. Traffic conflict problems are more likely to occur at E/P sites with peak-hour LTOVs equal to or above 320,000 or an LTOV/NL of 160,000. It is noted that these values are lower than the LTOV = 400,000 and LTOV/NL = 200,000 that appear to define the threshold above which accident problems occur. Use of the following mean total traffic conflict rate and critical number of conflicts based on all left-turn signal types is suggested for both the peak hour and total period. The total period includes 4.5 hours during the off-peak period plus the 2-hour peak period. Because the total period is longer and, therefore, provides a larger sample size, the guideline should be based on the total period.

	Critical Number	Mean Traffic Conflict Rate
Peak Hour	12	5.0
Total Period	39	4.0

The use of traffic conflict studies is optional when the left-turn signal phasing type is being selected.

Table 15

Ranking of E/P Sites by Peak-hour LTOV
With Traffic Conflict Data

Site No.	LTOV (1000s)	LTOV/NL (1000s)	No. Left-turn Veh	Total Period Conflict Data					
				No.	Exceed Nc	Rate (no./100LT)	Critical Rate (no./100LT)	Exceed Rc	Problem
17	1,030	515	595	84	x	5.0	4.8	x	x
26	598	299	459	51	x	2.7	4.7		
16	474	158	192	55	x	5.1	5.0	x	x
19	405	203	246	41	x	3.0	4.9		
22	384	192	222	85	x	6.6	4.9	x	x
25	369	185	419	79	x	6.7	4.9	x	x
35	320	160	303	82	x	5.5	4.8	x	x
23	293	147	142	18		2.3	5.1		
31	289	145	203	23		2.5	5.0		
20	216	108	141	30		3.8	5.1		
18	159	80	84	31		6.6	5.4	x	
28	133	67	180	19		2.1	5.0		
33	114	114	138	21		3.6	5.3		
21	111	56	142	46	x	6.3	5.2	x	x
27	108	54	76	7		2.0	5.6		
34	98	98	145	36		3.2	4.9		
29	97	49	145	25		3.3	5.1		
30	68	34	104	12		2.5	5.4		
24	59	30	143	24		3.7	5.2		
32	44	44	71	11		4.1	5.8		

Nc = critical number for all signal types = 38.6
Rc = critical rate for all signal types based on mean rate of 4.0
x = the critical value was exceeded

Volume Guidelines

The minimum left-turn volume should be greater than 2 vehicles per cycle during the peak hour. This is based on the assumption that 2 vehicles will turn left on the clearance interval each cycle when there are no acceptable left-turn gaps in the opposing through traffic. Consequently, the left-turn demand is satisfied for each cycle when the left-turn volume is below the minimum. When above the minimum, an E/P or E left-turn phasing should be considered, provided the following guidelines are satisfied.

The critical peak-hour LTOV above which an E/P or E phasing is needed depends on the left-turn capacity, which, in turn, depends on the left-turn green time or the green time of the left-turn approach, acceptable gaps in the opposing volume, the opposing volume, and the number of vehicles turning left on the clearance interval. It is assumed that the maximum green time and cycle length for the peak hour are experienced. Therefore, the green time in the peak hour equals the product of the maximum green time per cycle and the number of cycles per hour. The critical gap for left-turn vehicles, the length of gap in seconds where the number of vehicles accepting and rejecting the gap are equal, was found to be 3.75 seconds and 4.2 seconds in studies conducted in California and Kentucky, respectively.(3,7) The opposing volume per lane that would limit left turns on the clearance interval only is roughly estimated by dividing the peak hour opposing volume green time, which equals the left-turn green time in seconds, by the critical headway seconds per vehicle, which is equal to the critical gap.(3) The critical gap value of 4.2 seconds was selected in order to be conservative. Table 16 displays the variations in the critical LTOV per lane-based cycle length, C, and the ratio of the green time to the cycle length, G/C. The critical LTOV per lane varies from 34,320 to 72,000. Although this is a rough estimate, it indicates the range that exists for a recommended minimum LTOV per lane, compared to the 45,000 or 50,000 value currently used as a basis for considering a separate phase. While a single critical value for all sites is simpler to use, the procedure for determining a rough estimate should provide a better approximation of the critical LTOV per lane. The accuracy of the rough estimate depends upon the validity of the assumptions used. The median of the range, 53,000, when rounded off is equal to 50,000. When using a single critical value for all sites, 50,000 is used. This value has been verified in the literature.(3,4)

Table 16

Critical LTOV Based on Green Time and Cycle Length

	G/C		
C = 60 sec	0.5	0.6	0.7
Min. left-turn volume, vehs	120	120	120
Opposing volume, vehs	429	514	600
LTOV/Lane	51,480	61,680	72,000
C = 90 sec.			
Min. left-turn volume, vehs	80	80	80
Opposing volume, vehs	429	514	600
LTOV/Lane	34,320	41,120	48,000

C = cycle length, seconds
G/C = ratio of green time to cycle length for the opposing through volume

The upper limit of the peak-hour LTOV is based on safety guidelines such as accidents and traffic conflicts. From the previous discussions, an upper limit of LTOV = 400,000 or an LTOV/NL = 200,000 is suggested.

E/P phasing is suggested for a peak LTOV/NL range of from 50,000 to 200,000.

Left-Turn Delay Guidelines

Since this research effort did not adequately address delay, peak-hour delay guidelines are derived from the literature. An E/P phasing should be considered if, as a minimum, (1) the mean delay per left-turning vehicle exceeds 35 veh sec, (2) the total left-turn delay exceeds 2.0 veh hr, and (3) the 90th percentile left-turn delay is greater than or equal to 73 seconds.(3,6) The mean delay per vehicle was determined based on the 90th percentile minimum. It is noted that higher levels of delay may be acceptable or tolerated at intersections with exceptionally high volumes that exceed the capacity of the intersection.

Site Condition Guidelines

The influence of site conditions on traffic performance was examined in both the traffic engineering and statistical analyses. In the traffic engineering analysis, access management problems, intersection geometrics (especially the angle of the intersection), and the number of lanes of opposing traffic were identified. From the statistical analysis, intersection size appears to influence the safety of traffic performance of P and E/P signals, while intersection type and the number of lanes of opposing volumes influence E sites. Generally speaking, the safety problems increase with increasing intersection size for P and E/P signals. Traffic volumes also tend to increase with increasing intersection size. In general, safety is not a problem at E signals. The number of opposing lanes reflects the intersection size for the route that left-turning traffic is traveling on. The sample sizes for some of the site conditions are small. Therefore, the site conditions to consider are those that resulted from the traffic engineering analysis: access management problems, intersection geometrics, and number of lanes of opposing through traffic (no more than 2 lanes). Also, adequate sight distance is mandatory for P and E/P signals.

Both accident and conflict problems were identified with the one E/P site that had 3 lanes of opposing traffic. This site also had access management problems. Additional E/P sites with 3 lanes of opposing traffic were unavailable because of the prevailing practice of using E/P phasing with no more than 2 lanes of opposing traffic. Based on the data, it is not possible to recommend the use of E/P phasing with 3 lanes of opposing through traffic. It is emphasized that this conclusion is based on a sample size of 1 and current practice.

Left-turn Delay versus Left-turn Accidents

A situation may arise where an E/P phasing should be considered based on delay and an E phasing based on accidents. If the volume and site condition guidelines are satisfied for E/P phasing, then the left-turn phasing selection should consider the trade-off between the annual delay savings of the E/P phasing versus the annual left-turn accident savings based on an E phasing. A subsection in the preceding Traffic Engineering Analysis entitled "User Cost Savings for E/P versus E Phasings" presents an approach for estimating the cost savings for E and E/P phasings. Average values are presented for all E/P and E phasing sites in the study. However, when possible, site specific data should be employed. The use of site specific data should greatly improve the reliability of the estimates. The trade-off should dictate that if the E/P annual delay savings are greater than or equal to the E annual accident savings, then E/P phasing should be considered; otherwise, an E phasing should be considered.

If the volume and site condition guidelines are not satisfied for an E/P phasing, then an E phasing should be considered.

CHAPTER 7

CONCLUSIONS

The following conclusions are drawn from this report.

Traffic Engineering Analysis

1. A peak-hour LTOV above 400,000 or an LTOV/NL above 200,000 results in safety problems at E/P sites. This LTOV value was accompanied by peak-hour left-turn volumes above 200 vehicles.

2. Relative to E phasing, E/P phasing reduces delay and increases traffic conflicts and accidents.

3. Traffic conflicts or accidents involving opposing through trucks were neither overrepresented nor more hazardous than the remaining conflicts and accidents.

4. Using mean data for E and E/P phasings, it appears that an E/P signal is justified if the increased annual left-turn accident costs are less than $10,300, the roughly estimated average annual cost savings for E/P phasings due to reductions in delay.

Statistical Analysis

1. The values for E/P phasing are significantly lower than the E phasing volumes for the following: (a) total left-turn delay for the peak and average off-peak hours, and (b) the mean left-turn delay for the average off-peak hour. The values for an E/P phasing are significantly greater than the E phasing values for the annual number of left-turn accidents and the peak-hour total conflict rate.

2. There is no linear correlation between left-turn accidents and traffic conflicts.

The guidelines for E/P phasing were developed based on the traffic engineering and statistical analyses.

CHAPTER 8

RECOMMENDATIONS

The results of this study provide support for the following recommendations.

1. It is recommended that the Department adopt the following guidelines for the use of E/P left-turn signal phasing.

   A. Volume. E/P phasing should be considered when the peak-hour product of the left-turn and opposing volumes divided by the number of lanes, LTOV/NL, is between 50,000 and 200,000, provided that the peak-hour left-turn volume exceeds 2 vehicles per cycle during the peak hour. P phasing should be considered for an LTOV/NL under 50,000. E phasing should be considered for an LTOV/NL above 200,000. (These phasing considerations are illustrated in Figure 5.)

   If desired, a rough estimate of the lower limit of LTOV/NL for which an E/P signal should be considered based on capacity may be determined by equations 7, 8, and 9.

   LT = min. left-turn volume = 2 veh/cycle x no. of cycles/hour. (7)

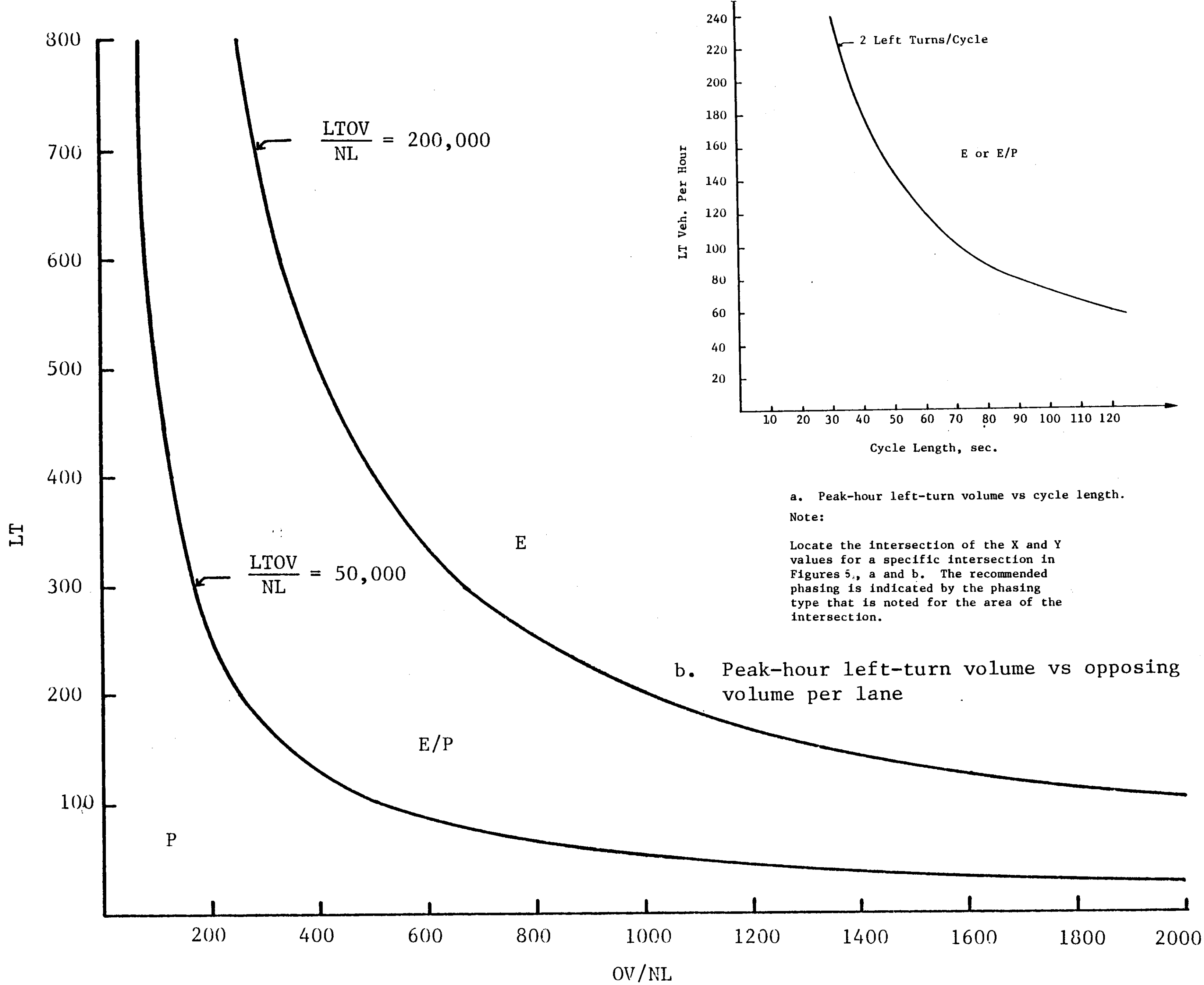
   $\frac{OV}{L}$ = opposing volume per lane = max. green time in the peak hour for the opposing through volume, sec ÷ 4.2 sec/veh (critical headway = critical gap). (8)

$$\frac{LTOV}{NL} = LT \times \frac{OV}{L} . \qquad (9)$$

   If this rough estimate is exceeded by the actual or projected LTOV/NL, then an E/P phasing should be considered. This estimate may be useful when the actual or projected LTOV/NL is between 30,000 and 70,000.

   B. Accidents. An E phasing should be considered when the following critical number and accident rate are exceeded for a left-turn approach at an intersection.

      1. The number of annual left-turn accidents is 5 or more.



a. Peak-hour left-turn volume vs cycle length.

Note:

Locate the intersection of the X and Y values for a specific intersection in Figures 5, a and b. The recommended phasing is indicated by the phasing type that is noted for the area of the intersection.

b. Peak-hour left-turn volume vs opposing volume per lane

Figure 5. Volume guidelines based on peak-hour volume.

2. The average annual left-turn accident rate is greater than the critical accident rate based on a mean accident rate, R_a, of 32.6 accidents per 100 million left-turn plus opposing vehicles. The critical accident rate, R_c, is calculated by using the rate quality control method below.

$$R_c = R_a + 1.645\sqrt{R_a/M} - 0.5/M, \quad (10)$$

where M = annual left-turn plus opposing volume in 100 million vehicles

= 12-hour volume for left turns and opposing volume x 1.41 x 365 ÷ 10^8

If both critical values are exceeded, then a traffic engineering investigation should be conducted to determine the causes of the problem and to recommend an alternative. Therefore, installing an E phasing should be the preferred alternative if less restrictive alternatives such as modifying the signal timing are determined to be inadequate.

C. Traffic Conflicts. If a traffic conflict analysis is performed, a traffic engineering investigation should be considered when the following critical number of total left-turn conflicts and the corresponding critical rate based on the following means are exceeded.

	Critical Number, N_c	Mean Total Traffic Conflict Rate, R_a, in conflicts per 100 left-turns vehicles
Total Period	39	4.0

The critical conflict rate is determined by equation (11).

$$R_c = R_a + 1.645\sqrt{R_a/V} - 0.5/V, \quad (11)$$

where V = left-turn volume in 100 vehicles.

The total period is 6.5 hours long, including a 4.5-hour off-peak and a 2-hour peak period.

D. Left-Turn Delay. An E/P phasing should be considered when the following peak-hour delay measures are exceeded.(3)

1. The mean delay per left-turning vehicle exceeds 35 vehicle seconds/vehicle.

2. The total left-turn delay exceeds 2.0 vehicle hours.

E. Site Conditions. An E phasing should be considered when one or more of the following conditions exist.

   1. There is inadequate sight distance for the left-turning vehicles or the opposing traffic.

   2. There are 3 or more lanes of opposing through traffic. Permissive or E/P signal phasings may be considered with caution at locations with 3 lanes of opposing through volume based on traffic engineering judgement and in accordance with the volume guidelines. It is recommended that the accident experience at these sites be monitored.

   3. The intersection geometrics may promote hazardous conditions such as angles greater than 270° for left-turning vehicles.

   4. There are access management problems (problems caused by vehicles entering and exiting entrances to land uses near the intersection that interface with the left-turn movements).

F. Left-Turn Delay versus Left-Turn Accidents. If an E/P phasing should be considered based on delay, volume, and site conditions and an E phasing should be considered based on accidents, then the phasing selection should consider the trade-off between annual intersection delay cost savings due to the E/P phasing versus the annual left-turn accident cost savings due to the E phasing. If the annual E/P delay savings is greater than or equal to the annual left-turn accident savings, then consider an E/P phasing. Otherwise, consider an E phasing. One approach to estimating the annual savings is discussed in a subsection of Chapter 4, the traffic engineering analysis section entitled "User Cost Savings for E/P versus E phasings." (p. 35)

G. Traffic Engineering Judgement. Traffic engineering judgement should be exercised in conjunction with the guidelines.

H. Application of Guidelines. The parts of the guidelines listed below shall be used for the following four applications.

1.	Existing E/P phasing	--	Accidents Site Conditions
2.	Existing E phasing	--	Volume Site Conditions Delay
3.	Existing P phasing	--	Volume Site Conditions Delay
4.	New signal	--	Volume Site Conditions

The use of other parts of the guidelines is optional.

The guidelines are summarized in Figure 6.

Volume

Use E/P when left-turn volume exceeds 2 vehicles per cycle during the peak hour, and the peak-hour LTOV/NL is between 50,000 and 200,000.

Left-Turn Accidents

If at an E/P site, the number of annual left-turn accidents is greater than 5, and the critical accident rate based on a mean of 32.6 accidents per 100 million left-turn and opposing volume is exceeded, conduct a traffic engineering investigation; otherwise use E/P phasing.

Traffic Conflicts

If at an E/P site, the number of total left-turn conflicts in the total period exceeds 39, and the total left-turn conflict rate is greater than the critical rate based on a mean of 4.0 left-turn conflicts per 100 left turns, conduct a traffic engineering investigation; otherwise, use an E/P phasing.

Left-Turn Delay

An E/P phasing should be considered when the mean peak-hour delay per left-turning vehicle exceeds 35 veh sec/veh and the total peak-hour left-turn delay exceeds 2.0 veh/hr.

Site Conditions

An E/P phasing should be considered if all of the following exist:

- Adequate sight distance for the left-turning vehicles or opposing through traffic (mandatory)
- No more than 2 lanes of opposing through traffic
- Intersection geometrics that do not promote hazardous conditions
- Good access management

Delay-Accident Trade-off

If E/P phasing is suggested for all the guidelines except accidents, then consider E/P if the annual E/P delay savings is greater than or equal to the annual E accident savings; othewise, use an E phasing.

Traffic Engineering Judgement

Traffic engineering judgement should be used in conjunction with the guidelines. This is especially true when one signal phasing is not clearly preferred.

Figure 6. Summary of the guidelines for E/P phasing.

ACKNOWLEDGEMENTS

The author expresses appreciation to S. R. Blackwell, J. D. Shelor, I. N. Blake, E. Paltell, and K. L. Auth for their efforts in collecting field data. Appreciation is due G. R. Allen for preparing the section on selection of sample size, and advising on the statistical analysis. Appreciation is due the Department's district traffic engineers and the traffic signal staff of the Highway and Traffic Safety Division for providing information and reviewing the draft report.

Finally, services provided by the staff of the Virginia Highway and Transportation Research Council are acknowledged. In particular thanks go to Jennifer Ward for assistance in the computer analysis, to H. T. Craft for report editing, to Susan Kane and Jan Kennedy for typing the draft manuscript, to Jean Vanderberry for typing the reproduction masters, and to M. A. Thornton for graphics.

This research was financed from Highway Planning and Research funds administered through the Federal Highway Administration.

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APPENDIX A

DATA COLLECTION PROCEDURES AND FORMS

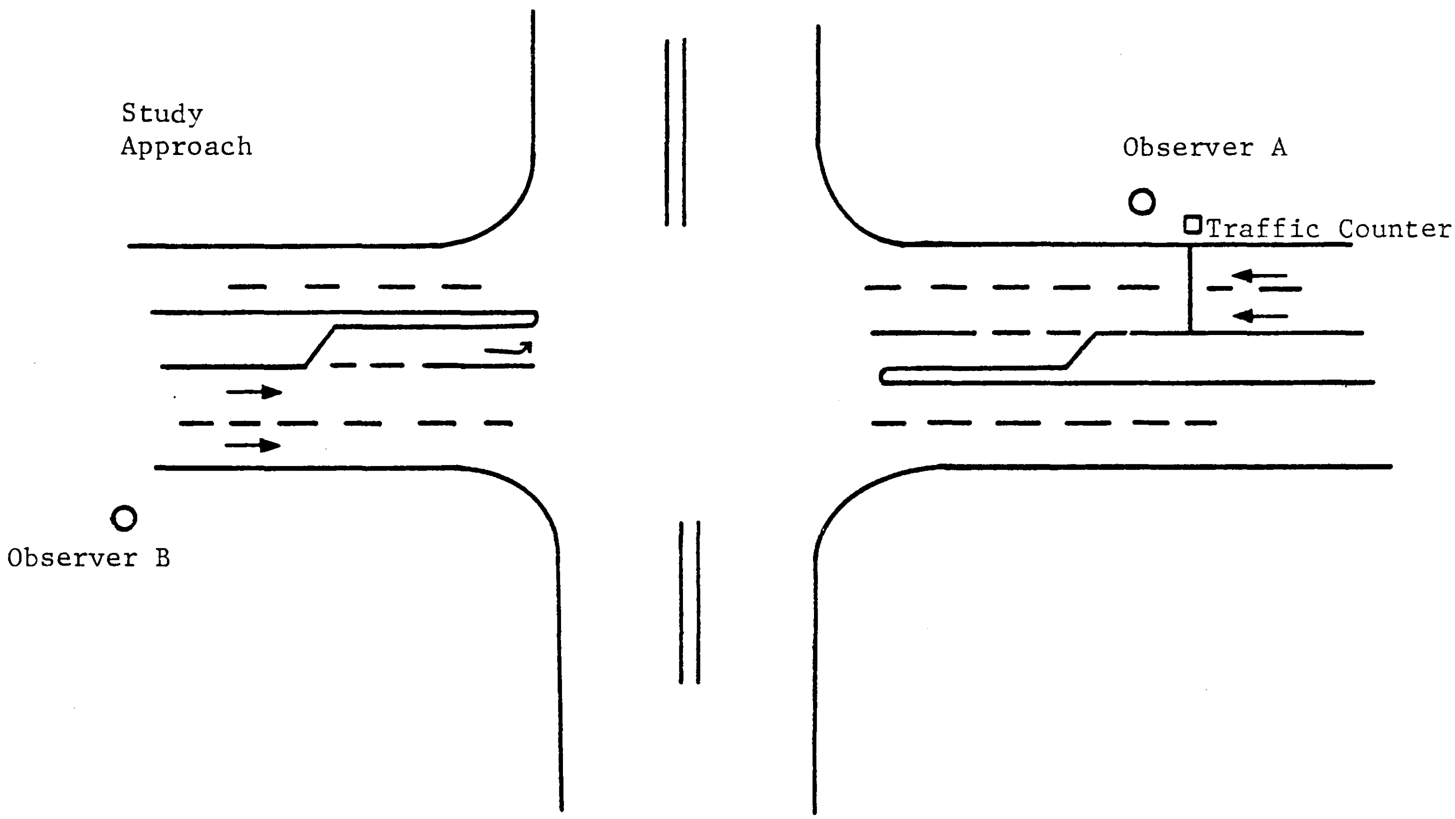

Figure A-1. Typical location of observers and the traffic counter.

LOCATION ____________________

DATE __/__/__ SIGNING Overhead/Post Both/Other

SETTING CBD/IND/STRIP/RURAL/OTHER

SIGNAL PLACEMENT Overhead/Post/Comb. OBSERVERS 1

SIGNAL TYPE Exclusive/Permissive/E/P

SPEED LIMIT:

OBSERVED CONFLICTS TURNS *

TIME PERIOD (Peak Period Omitted)	OPPOSING VOLUME		Type #1 Left Turn Opposing Conflict	Type 2 Left Turn 2nd Opp. Conflict	Type #3* Left Turn on Red	Type #4* Left Turn Following Conflict	Type #5* Lane Overflow Blocks Traffic	Volume on Green ←	Volume on Green ●
	Total	Thru Trucks	Truck Conflicts						
7:15 a.m. - 8:00 a.m.									
8:15 a.m. - 9:00 a.m.									
9:15 a.m. - 10:00 a.m.									
10:15 a.m. - 11:00 a.m.									
11:15 a.m. - 12:00 NOON									
1:15 p.m. - 2:00 p.m.									
2:15 p.m. - 3:00 p.m.									
3:15 p.m. - 4:00 p.m.									
4:15 p.m. - 5:00 p.m.									
5:15 p.m. - 6:00 p.m.									
TOTAL									

G G Y Y R					SEVERE CONFLICTS:
*SIGNAL TIMING: (done between observations intervals)					
					OBSERVER COMMENTS

*Completed by observer B

Figure A-2. Data form for observer B.

LOCATION ____

DATE ____________________ SPEED LIMIT ____________________

OBSERVER ____________________

Time Period (Peak Period Omitted)	Thru Truck Volume	Truck Conflicts	Type #1 Left Turn Opposing Conflict	Type #2 Left Turn 2nd Opposing
7:15 a.m. - 8:00 a.m.				
8:15 a.m. - 9:00 a.m.				
9:15 a.m. - 10:00 a.m.				
10:15 a.m. - 11:00 a.m.				
11:15 a.m. - 12:00 Noon				
1:15 p.m. - 2:00 p.m.				
2:15 p.m. - 3:00 p.m.				
3:15 p.m. - 4:00 p.m.				
4:15 p.m. - 5:00 p.m.				
5:15 p.m. - 6:00 p.m.				
TOTAL				
SEVERE CONFLICTS				
OBSERVER COMMENTS:				

Figure A-3. Data form for observer A.

INTERSECTION DELAY STUDY
POINT SAMPLE, STOPPED DELAY METHOD

Intersection ____________ **Study Traffic On** ____________

City and State ____________ **Agency** ____________

Day, Date ____________ **Study Period** ____________ **Observer** ____________

Traffic Approaching From ____________ **Weather** ____________
N,S,E,W

If more than one person is studying same approach, explain division of responsibilities. ____________

INTERVAL BETWEEN SAMPLES = 15 SECS.

RECORD THE NO. OF VEHICLES AT EACH 15-SECOND POINT SAMPLE

1 START

									30	
									60	TOTAL

2 START

									30	
									60	TOTAL

3 START

									30	
									60	TOTAL

Comments: ____________

(over)

Figure A-4. Form for intersection delay study. (From reference 12.)

PERCENT STOPPING STUDY

Intersection ____________ Study Traffic On ____________

City and State ____________ Agency ____________

Day, Date ________ Study Period ________ Observer ________

Traffic Approaching From ______ (N,E,S,W) Weather ____________

If more than one person is studying same approach, explain division of responsibilities. ____________

STOPPING *	NOT STOPPING *
1 START TIME	1
2 START TIME	2
3 START TIME	3
4 START TIME	4
5 START TIME	5

TOTAL STOPPING ____ TOTAL NOT STOPPING ____

PEAK PD. TOTAL STOPPING ____ PEAK PD TOTAL NOT STOPPING ____

COMMENTS: ____________

Figure A-5. Form for percent stopping study. (From reference 12.)

DATA REDUCTION FORM

INTERSECTION DELAY AND PERCENT STOPPING STUDIES

Intersection ______________________ City & State ______________________

Study Approach On ______________________ Traffic From ______________________ N, S, E, W

Day, Date, Time ______________________

PERCENT STOPPING STUDY

		Off Peak	Peak	Total
(i)	Total no. of vehicles "stopping"			vehs.
(ii)	Total no. of vehicles "not stopping"			vehs.
(iii)	Total volume = (i) + (ii)			vehs.
(iv)	Observed Percent Stopping = [(i) ÷ (iii)] x 100			
(v)	Actual Percent of Vehicles Stopping = (iv) x 0.96			

CORRECTION PROCEDURE FOR MISSED SAMPLES IN DELAY STUDY

		Corr. * No. 1	Corr. * No. 2
(a)	Total no. of point samples taken in field during 30-sample period	___	___
(b)	30 - (a)	___	___
(c)	Sum of point sample values for 30-sample period on field data sheet	___	___
(d)	Value of each missing sample = (c) ÷ (a), round to nearest whole number	___	___
(e)	Total value for all missing samples in 30-sample period = (b) x (d)	___	___

(f) Total value for all missing samples in study period = sum of (e) for all corrections . . . . . ___

* Use one correction factor for each 30-sample period in which the field data sheet has one or more missing values.

INTERSECTION DELAY STUDY

		Off Peak.	Peak	Total
(1)	Total no. of point samples taken in field			
(2)	Total no. of point samples missed, from (b) above			
(3)	Total no. of point samples used in calculations = (1) + (2)			
(4)	Interval between samples			secs
(5)	Sum of observed point sample values			vehs.
(6)	Sum of calculated "corrected" point sample values, from (f), above			vehs.
(7)	Sum of all point sample values = (5) + (6)			vehs.
(8)	Total Stopped Time = (4) x (7)			veh.-secs.
(9)	Stopped Delay = (8) x 0.92			veh.-secs.
(10)	Approach Delay = (9) x 1.3			veh.-secs.
(11)	Total Volume = (iii)			vehs.
(12)	Stopped Delay Per Vehicle = (9) ÷ (11)			veh.-secs./veh.
(13)	Approach Delay Per Vehicle = (10) ÷ (11)			veh.-secs./veh.

Figure A-6. Data reduction form for intersection delay and percent stopping study. (From reference 12.)

APPENDIX B

MULTIPLE REGRESSION ANALYSIS AND ANALYSIS OF VARIANCE

Regression Analysis by Signal Type

Causative regression relationships that explain the variation in a traffic performance measure as the dependent variable were identified for the following traffic performance measures: total number of traffic conflicts, the annual number of left-turn accidents, the annual left-turn accident rate, and total and mean left-turn delays. The following criteria were used in the selection of regression equations: (1) the correlation coefficient, R^2, for the equation should be greater than or equal to 0.50; (2) the level of significance, α, should be greater than or equal to 0.5; and (3) the R^2 of any two independent variables in an equation should be less than 0.50. The standard error of the estimate, SEE, that is, the standard deviation of the actual dependent variable, Y_N, from the predicted value of Y, and the coefficient of variation, CV, that is, the percent of error relative to the mean, ((SEE/Mean) x 100%), measure the accuracy of the linear equation in predicting the Y value. Because of the high CV values, these regressions are used only to explain the variation in the dependent variable, and not for predicting the dependent variable.

Total Number of Traffic Conflicts

The equations for the total number of traffic conflicts, TOTCONF, for the peak hour for each signal type are shown in Table B-1.

Table B-1

Regression Equations for the Peak-hour Total Number of Traffic Conflicts, TOTCONF

Signal Type	Equation
P	$TOTCONF=0.818x10^{-4}LTOV+6.13DINTSZ^{2}-1.10DINTS21+1.26$
	R^2=.94 α=.000 SEE=1.29 CV=25.3% n=10
E/P	TOTCONF=0.056TOTLT+0.36DINTSZ6+3.67DINTSZ1+3.45DINTSZ4-3.15
	R^2=.85 α=.000 SEE=3.88 CV=39.0% n-20
E	TOTCONF=0.039TOTLT-3.67DINTTYP3+1.2DINTYP2+0.33
	R^2=.85 α=.000 WEE=2.48 CV=31.5% n=15

n = sample size
TOTCONF = total number of traffic conflicts
LTOV = product of the peak-hour left-turn and opposing traffic volumes
TOTLT = total peak hour left-turn volume
DINTSZ1 = 1 for an intersection with left turns froma 2-lane road onto a 2-lane road
DINTSZ2 = 1 for an intersection with left turns from a 2-lane road to a 4-lane road
DINTSZ4 = 1 for an intersection with left turns from a 4-lane road to a 4-lane road
DINTSZ6 = 1 for an intersection with left turns from a 6-lane road to a 4-lane road
DINTTYP3 = 1 for a cross or 4-legged intersection
DINTTYP2 = 1 for a T or 3-legged intersection

For P signals, TOTCONF increases linearly with the LTOV. The TOTCONF is higher for intersections of 2- and 4-lane roads while it is slightly lower for intersections of two 2-lane roads. The TOTCONF increases linearly with the TOTLT, left-turn volume, for E and E/P signals. There are increases in the TOTCONF for E/P signals at intersections of two 2-lane roads and 6- and 4-lane roads. The TOTCONF for E signals decreases for cross intersections and slightly increases for T intersections. The exceptionally high R^2 values for all three equations indicate very strong causative relationships.

Total Traffic Conflict Rate

Relationships between the peak-hour total traffic conflict rate, number of conflicts per 100 left-turn vehicles, TOTCONFRATE, and TOTLT, are graphed in Figure B-1. Although the R^2 value for P signals is slightly less than 0.5, it is displayed for comparison. The equations for both E/P and E signals increase asymptotically to values of 6 for E/P and 4 for E signals. These equations were obtained by dividing a regression equation of TOTCONF as a function of TOTLT by TOTLT.

Annual Number of Left-Turn Accidents

In Table B-2, equations for the annual number of left-turn accidents on the studied approach, A1SN, are displayed for both the peak hour and total period. For P signals, the A1SN increases linearly with the OPVOL, opposing volume, for both the time periods and with identical R^2 values of 0.72. The A1SN for E/P and E signals increases linearly with LTOV for the peak-hour data. Additionally, the A1SN is increased by 3.5 for intersections of 6- and 4-lane roads, by 1.8 for intersections of two 4-lane roads, and decreased by 1.7 for intersections of two 2-lane roads based on peak-hour data. The A1SN for E signals decreases by 0.8 for roads with 2 lanes of opposing through traffic. It is noted that 14 of the 15 sites have 2 lanes of opposing traffic while one site has 3 lanes. For the total time period, the A1SN for E/P signals increases linearly for both TOTLT and OPVOL.

Annual Left-turn Accident Rate

The only regression equation that satisfied the selection criteria for the annual left-turn accident rate, A1SR, was for E/P signals based on the total time period data. The equation is

$$A1SR = 0.089\ TOTLT - 23.1 \qquad n = 14$$
$$R^2 = 0.58 \qquad \alpha = 0.002 \qquad SEE = 32.58 \qquad CV = 58.4\%$$

The A1SR increases linearly with the TOTLT.

Left-turn Delay in the Peak Hour

The total left-turn delay, in vehicle hours (VEHHRS) and the mean left-turn delay, in vehicle seconds/vehicle (VEHSEC), are shown in Table B-3. For E and E/P phasings, the total left-turn delay linearly increases with LTOV. For E/P signals, the total left-turn delay is higher by about 1 veh hr for sites with 3 lanes of opposing traffic. The total left-turn delay is lower by about 1 veh hr for E signals at 4-legged intersections with 1 leg as a private entrance. The mean left-turn delay at E/P signals increases linearly with the LTOV and is higher for larger intersections.

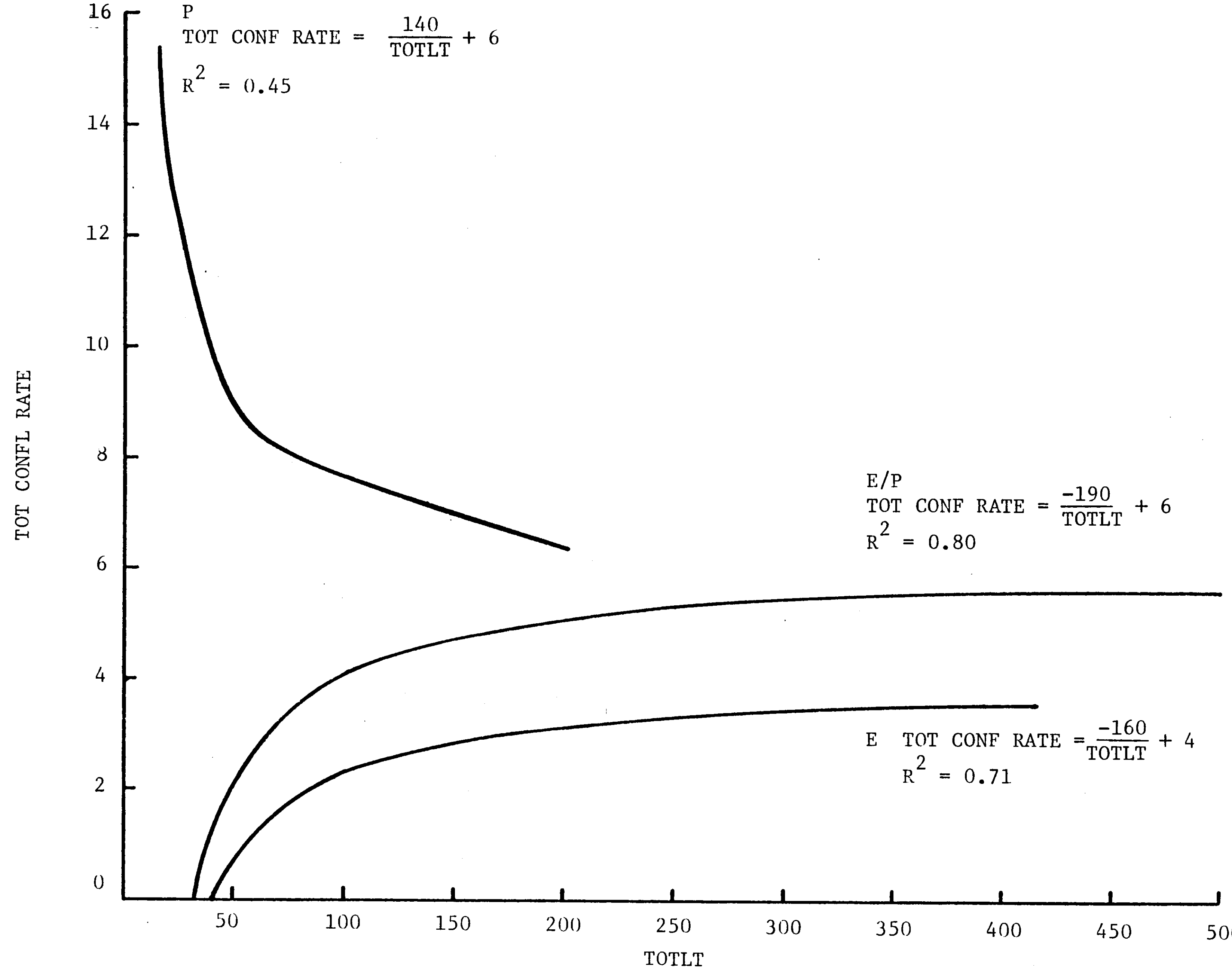

Figure B-1. Peak-hour total conflict rate versus left-turn volume.

Table B-2

Regression Equations for the Annual Number of Left-Turn Accidents, A1SN

Signal Type	Equation
	a) A1SN based on peak-hour data
E	$A1SN=0.00215OPVOL-1.24$
	$R^2=0.72$ $\alpha=.007$ SEE=0.60 CV=96.5% n=8
E/P	$A1SN=0.917x10^{-5}LTOV+3.5DINTSZ6-1.7DINTSZ1+1.8DINTSZ4+1.1$
	$R^2=0.51$ $\alpha=0.055$ SEE=2.9 CV=97.5% n=17
E	$A1SN=0.282x10^{-5}LTOV-0.8DLANES2+0.7$
	$R^2=0.50$ $\alpha=0.016$ SEE=.56 CV=83.3% n=15
	b) A1SN based on total period data
P	$A1SN=0.354x10^{-3}OPVOL-0.95$
	$R^2=0.72$ $\alpha=0.008$ SEE=0.61 CV=97.8% n=8
E/P	$A1SN=0.718x10^{-3}OPVOL+0.376x10^{-2}TOTLT-4.38$
	$R^2=0.52$ $\alpha=.006$ SEE=2.69 CV=89.6% n=17

OPVOL = opposing volume
LTOV = product of left-turn and opposing volume
DINTSZ6 = 1 for an intersection with left turns from a 6-lane to a 4-lane road
DINTSZ1 = 1 for an intersection with left turns from a 2-lane to a 2-lane road
DINTSZ4 = 1 for an intersection with left turns from a 4-lane to a 4-lane road
DLANES2 = for 2 lanes of opposing volume

Table B-3

Regression Equations for the Peak-Hour Left-Turn Delay

Signal Type	Equation
	a) Total left-turn delay in vehicle hours
E/P	$VEHHRS=0.279x10^{-5}LTOV-.01DLANES2+.95DLANES3+.03$
	$R^2=.94$ $\alpha\dot{=}0.000$ SEE=.21 CV=25.1% n=20
E	$VEHHRS=0.437x10^{-5}LTOV-.001DINTTYP2-1.1DINTTYP1+1.4$
	$R^2=.67$ $\alpha=0.005$ SEE=.68 CV=31.3% n=15
	b) mean left-turn delay in vehicle-seconds/vehicle
E/P	$VEHSEC=0.486x10^{-5}LTOV+31.1DINTSZ6-2.27DINTSZ2+7.29DINTSZ4+9.8$
	$R^2=0.61$ $\alpha=0.005$ SEE=7.22 CV=52.9% n=20

LTOV = product of left turn and opposing volumes
DLANES2 = 1 for 2 lanes of opposing through traffic
DLANES3 = 1 for 3 lanes of opposing through traffic
DINTTYP2 = 1 for a T intersection
DINTTYP1 = 1 for a cross intersection with 1 approach as a private entrance
DINTSZ6 = 1 for an intersection with left turns from a 6-lane to a 4-lane road
DINTSZ2 = 1 for an intersection with left turns from a 2-lane to a 4-lane road
DINTSZ4 = 1 for an intersection with left turns from a 4-lane to a 4-lane road

Analysis of Variance for E/P Sites Converted from E

Experience and the data revealed that the numbers of accidents at E/P sites that were previously E phasing were higher than those at E/P sites that had had no E phasing. An analysis of variance was used to test for statistically significant differences in the mean accident rate for groupings of sites based on accident rates for a given time period. In other words, the relationships between the accident rates in different time periods were examined. The three time periods were one year before with E phasing, BS, a 6-month transition period for the E/P phasing, T, and one year of E/P phasing after the transition period, AIS. The groupings shown in Table B-4 were used.

Table B-4

Groups by Accident Rate Ranges and Number of Sites

	BS (accidents/100mv)	TS (accidents/100mv)
Trial A	1. 0 n = 4	1. 0 n = 3
	2. 1-34 n = 3	2. 1-100 n = 3
	3. > 200 n = 2	3. > 100 n = 3
Trial B	BS	TS
	1. 0 n = 4	1. 0-33 n = 4
	2. 1-248 n = 5	2. 33-297 n = 5

The TS group in trial A had a statistically significant effect on AIS based on an $R^2 = 0.57$ and a level of significance of 0.081. The mean AIS rate for TS groups 1-3 were 38.1, 38.3, and 115.3, respectively. Accident rates that are above 100 in the transition period tend to remain high in the one-year period after the transition. This was the only test of the two trials that resulted in a statistically significant difference.