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16. Abstract

Guidelines for left-turn phase utilization do not generally include recommendations for left-turn signal phase sequence patterns. In this research, the TEXAS Simulation Model is employed to study the effects of various left-turn sequence patterns on traffic operations in order to establish guidelines for utilization of most typical sequence patterns. Recent literature on the effects of left-turn sequence patterns on intersection delay and accidents is reviewed. With vehicular delay as a basis for comparison, protected only and protected/permissive left-turn phasing are studied with pretimed control. Dual leading and dual lagging left-turn phase sequences are also studied when both are supplemented by permissive turning and pretimed control. Furthermore, split, dual, and composite sequences are compared for the pretimed case. The examination of basic phase sequencing schemes under actuated signal control essentially duplicates that for pretimed control. Finally, guidelines for the implementation of phase sequence patterns are presented.

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COMPARATIVE ANALYSIS OF LEFT-TURN PHASE SEQUENCING

by

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Research Report Number 258-2

Warrants for Left-Turn Lanes and Signal Phases (Actuated Controllers)

Research Project 3-18-80-258-2

conducted for

Texas
State Department of Highways and Public Transportation

in cooperation with the
U. S. Department of Transportation
Federal Highway Administration

by the

CENTER FOR TRANSPORTATION RESEARCH
THE UNIVERSITY OF TEXAS AT AUSTIN

November 1983

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

PREFACE

Research results presented in this document represent extensions of work originally done by Dr. Han-Jei Lin and presented within Center for Transportation Research Report 258-1. Dr. Lin's original work was carefully guided by Drs. Clyde Lee and Robert Herman who were co-principal investigators of this research study. Mr. Rick Denney served as the contact representative of the State Department of Highways and Public Transportation throughout the study efforts.

The authors wish to express their thanks to these individuals and attribute to them any positive impacts of these research findings. The workers also wish to thank Mrs. Candace Gloyd for her patient efforts in providing this research report.

SUMMARY

Guidelines for left-turn phase utilization do not generally include recommendations for left-turn signal phase sequence patterns. In this research, the TEXAS Simulation Model is employed to study the effects of various left-turn sequence patterns on traffic operations in order to establish guidelines for utilization of most typical sequence patterns. Recent literature on the effects of left-turn sequence patterns on intersection delay and accidents is reviewed. With vehicular delay as a basis for comparison, protected only and protected/permissive left-turn phasing are studied with pretimed control. Dual leading and dual lagging left-turn phase sequences are also studied when both are supplemented by permissive turning and pretimed control. Furthermore, split, dual, and composite sequences are compared for the pretimed case. The examination of basic phase sequencing schemes under actuated signal control essentially duplicates that for pretimed control. Finally, guidelines for the implementation of phase sequence patterns are presented.

Key Words: Protected/Permissive Phasing, Left-Turn Phasing, Actuated Control
Split Phasing, Leading, Lagging

IMPLEMENTATION STATEMENT

Implementation of protected left-turn signal phases frequently raises a question regarding the sequence in which the multiple-signal phases should be displayed. The extremely wide range of possible phase sequence patterns may have profoundly different effects upon intersection traffic operations.

This document presents background analyses and research findings regarding effects of multi phase signal sequence patterns upon traffic operations at isolated intersections. Findings and recommendations have been summarized and presented in tabular form to facilitate usage.

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CHAPTER 1. INTRODUCTION

Left-turn maneuvers through at-grade intersections are frequently recognized as highly problematic operational elements. When left-turn demands approach or exceed maximum unprotected flow rates at signalized intersections, traffic control schemes are usually modified to provide protected left-turn signal phases. Guidelines for implementation of protected left-turn phases have been presented in several significant papers and recently in Ref 2. These and other guidelines for left-turn phase utilization do not generally provide a specific rationale for choosing among the many possible left-turn signal phase sequence patterns. Although the guidelines may indicate that a separate signal phase should be utilized, they usually do not indicate whether it should, for example, proceed or follow (lead or lag) the main street green or which of the many possible phase sequences would be most appropriate. This study contains a description of the effects of various left-turn sequence patterns upon left-turn as well as total intersection traffic operations. Guidelines for utilization of most typical sequence patterns are presented.

BACKGROUND

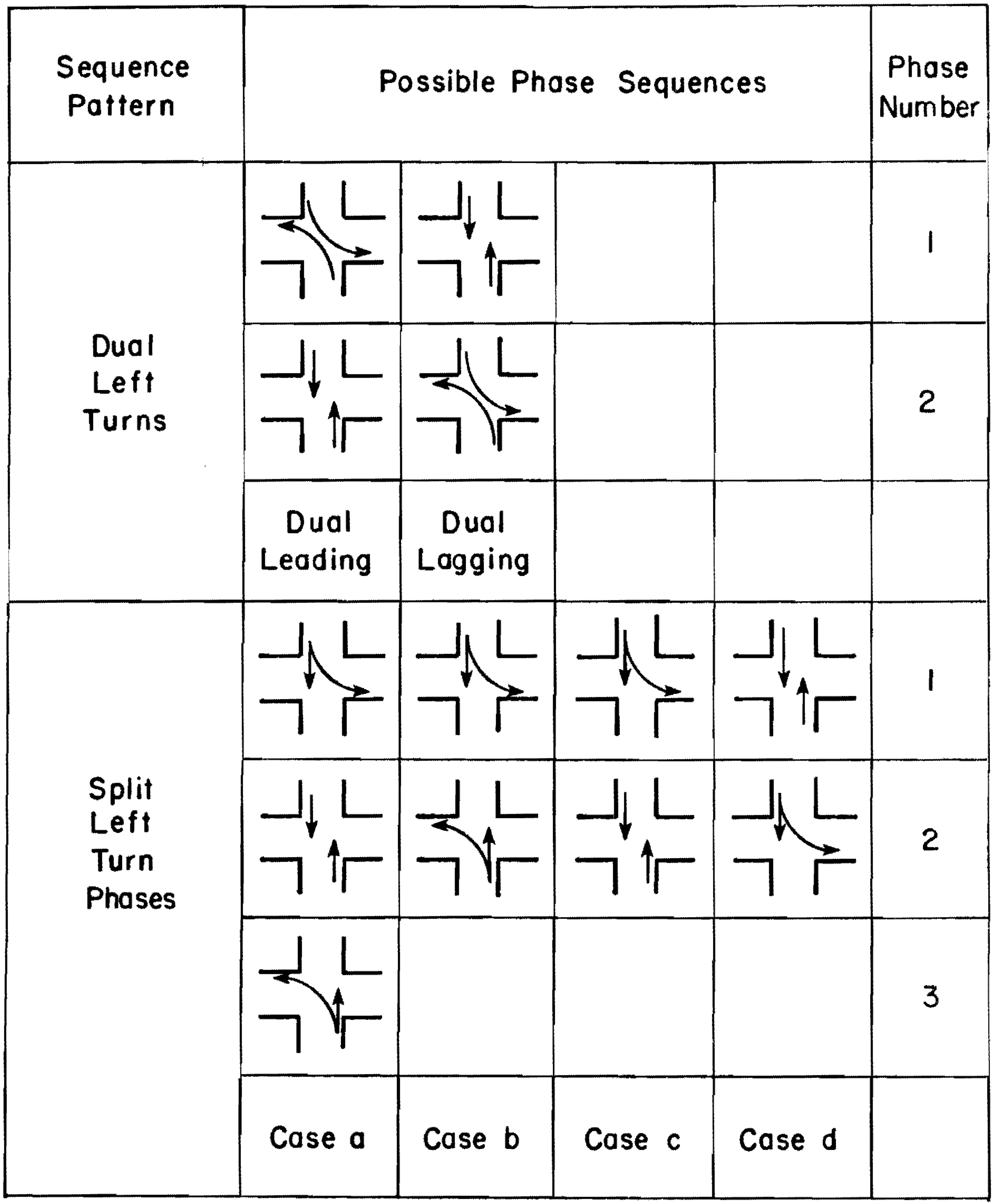
Work previously undertaken as part of this research effort yielded methods for determining left-turn capacity and guidelines for implementation of left-turn phases and bays (Refs 1, 2, and 3). Within the previous work there was little consideration of the possible impacts of alternative sequences of left-turn phasing upon intersection operational efficiency. The discussion which follows is an attempt to complement that of Refs 1, 2, and 3 through provision of guidelines which will assist the engineer in choosing among the many possible sequence patterns.

For purposes of this discussion the following terminology has been adopted for describing left-turn phase sequences. A protected left-turn phase is that portion of the signal cycle in which left-turn maneuvers are permitted and all conflicting maneuvers are prohibited. A permissive left-turn phase is that portion of a cycle in which left-turns are permitted but only through gaps in the opposing traffic stream. A protected left-turn phase which occurs prior to display of the opposing through green is called a leading phase, while one occurring immediately after the opposing through green is said to be lagging. The term "dual left turns" is used to describe protected left-turn phases which occur simultaneously on opposing approaches of the same street. These arrangements are illustrated in Figure 1-1. "Split phasing" is used to describe schemes in which protected left-turn phases on the same street do not occur simultaneously. Such schemes may or may not utilize protected left-turn phases on both approaches, and, where present, the protected lefts may occur before, after, or during through movement green indications. Four basic cases of split phase arrangement are illustrated in Figure 1-1.

Dual and split phase arrangements may be utilized together in an effort to extend the protected green for one approach. This type of arrangement has been termed "composite" left-turn phasing and is also illustrated schematically in Figure 1-1.

STUDY SCOPE

Due to the complexity of the many possible combinations of phase patterns to be evaluated, a stepwise comparative evaluation process was utilized. Initially pretimed signal control was utilized to compare all



(continued)

Figure 1-1. Basic left-turn phase arrangements.

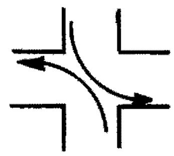
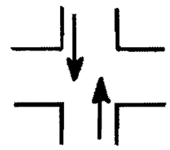
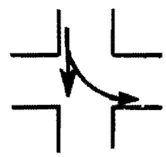
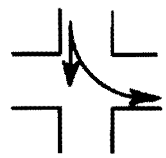
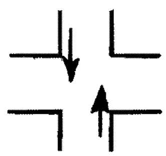
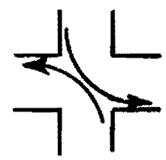
Sequence Pattern	Possible Phase Sequences		Phase Number
Composite Left Turns			1
			2
			3
	Case a Composite	Case b Composite	

Figure 1-1. (Continued).

sequence schemes. Potential improvements in efficiency were examined through repetition of the basic experiment utilizing actuated signal control. Protected left-turn phasing was compared with combinations of protected and permissive with protected left-turn phases programmed as either dual leading or dual lagging. Eight hours of simulated observation time was collected for each of three approach volume combinations while turn percentages were constant. Cycle and phase lengths were held constant throughout the pretimed portion of the experiment in order to simulate field conditions during peak as well as off-peak demand conditions.

Dual leading left-turn phasing was compared to dual lagging with both arrangements being supplemented by permissive turning during through green phases. Twenty traffic volume combinations were examined with each encompassing a different set of left-turn, opposing, and straight critical lane traffic demands. Signal cycle and phase lengths were designed for each respective volume combinations although all cycle lengths were necessarily long. At least one hour of simulated observation time was collected for each case.

Lead and lag left-turn arrangements were also compared for cases in which the phases were split (see Figure 1-1). Operations were compared for a variety of selected phase and cycle lengths, although the comparison was extended to include cases which had optimal cycle lengths. At least thirty minutes of simulated observation time was collected for each of these volume-cycle length cases.

Composite left-turn phasing, Figure 1-1, was compared to dual and split left-turn phasing. Delay was compared for two cycle lengths, with at least one hour of simulated observation time collected for each case.

Appropriate estimation of phase and cycle durations was a critical task for cases in which pretimed control was used. Since many of the demand volumes studied were small enough to enable random traffic flow, a Poisson process was used to estimate numbers of vehicular arrivals. In cases where traffic demands were likely non-random, predicted Poisson arrivals were corrected using an empirical technique. Phase durations were estimated using a four- second start-up time and individual vehicle mean processing times of 2.3 and 3.6 seconds for straight and left-turn movements, respectively. Computation of protected left-turn phase lengths included an allowance for left-turn demands satisfied during permissive green phases. Numbers of left-turn maneuvers completed during permissive greens were estimated using the technique described in Ref 3.

The examination of basic phase sequencing schemes under actuated signal control was essentially a duplicate of that for pretimed control. Presence detection was used uniformly with two second minimum green times and one second extension intervals. Signal controllers were programmed to have full capability to skip any signal phase.

CHAPTER 2. REVIEW OF PREVIOUS RESEARCH FINDINGS

A review of published research findings was developed to provide a background for primary data collection and analyses efforts. A computer file search was obtained utilizing the HRIS system, and this was supplemented through manual search efforts. Several significant references were located and have been summarized within the following sections. Since each of the references discussed the effects of left-turn phase sequencing upon vehicular delay or accidents and conflicts, each of these topics is separately addressed.

DELAY

Five significant references were located which dealt with the question of how left-turn phase sequencing affects vehicular delay (Refs 6, 7 and 9). Each of the studies compared measures of vehicular delay for protected only and protected/permissive left-turn phasing. Particular phase sequence patterns such as dual and split (see Figure 1-1) arrangements were not specifically addressed.

Field studies were conducted in the states of Maryland, California, Florida and Kentucky in which vehicular delay data were collected before and after installation of permissive left-turn regulations. Each study found that intersection delay was reduced when permissive left-turning supplemented the protected phase. The Maryland study found that the average left-turn delay was reduced by 35 percent, and the California study reported 25 to 46 percent reductions in total intersection delay. The Florida study resulted in 40 percent delay reduction to left-turn vehicles and 24 percent to opposing traffic.

In the Kentucky project a 24 percent reduction in total intersection delay and a 50 percent average reduction in left-turn delay were obtained when permissive phasing was installed. Data collected in Kentucky also indicated that 37 percent of all turn movements were made during the permissive portion. During heavy opposing volume conditions, almost no left turns were made during the permissive portion, and the phasing simply operated as protected only phasing.

ACCIDENTS

All of the studies compared the frequency of left-turn accidents before and after permissive phasing was installed. In the Kentucky research project four intersections with protected only phasing were studied. In the one-year period before installation of permissive left-turning 44 accidents occurred, whereas 78 occurred in the year after. Only left-turn accidents due to an error in judging the gap in the opposing traffic or to not understanding permissive signalization increased. Rear-end accidents as well as other types did not increase. Many of the accidents occurred during an initial adjustment period. Approximately 69 percent of the left-turn accidents in the one-year period immediately following installation occurred in the first six months, although one intersection test site experienced over twice as many accidents as any other. The operating speed (55 mph) was higher at this intersection than at any other, and the accidents were more severe. It was recommended that caution be used in installing permissive phasing at intersections with approach speeds of over 45 mph.

The research project in California studied accident data at three intersections with protected only left-turn phasing for one-year periods before and after permissive phasing was installed. Total left-turn accidents increased from one before to 21 after the change. No information was given about an adjustment period.

In the Florida study, 28 intersections where changes were made in the type of left-turn phasing were observed. At 17 intersections permissive phasing was installed at protected left-turn only signals. The remainder of the intersections were changed from protected with permissive phasing to protected left-turn only. Accident data was collected for a one-year period before the change and for a one-year period beginning six months after the change. The first six months after was considered to be an adjustment period for drivers and was not observed.

Most intersections where permissive phasing was installed experienced very little change in left-turn angle accidents. All of these intersections had been judged by traffic engineers to be safe for the change in operation. The intersections that were changed to protected only phasing had been judged to be not suitable for permissive left-turn phasing. The change at these intersections reduced the total number of left-turn accidents from 53 to 7 during the one-year periods.

An FHWA project in California studied seven intersections under protected only and protected with permissive left-turn phasing. It was concluded that left-turn accidents may increase when permissive phasing is installed at a protected left-turn only signal. At intersections where protected left-turn phasing does not exist, however, installation of protected with permissive left-turn phasing may not cause any increase in traffic accidents.

CONFLICTS

The references noted a high positive correlation between accidents and conflicts. The FHWA report (Ref 7) discussed a particular type of conflict called the "trap" condition. A "trap" condition can occur when one intersection approach has a lagging protected left-turn phase and the opposing approach has permissive left turns. A left-turn vehicle waiting for a gap in the opposing traffic stream expects the opposing traffic to stop when a yellow signal is displayed. If the opposing approach has a lagging protected phase, the through traffic may continue with the protected movement. Thus, the vehicle is "trapped" in the intersection awaiting a gap.

This situation can be avoided by using only phase arrangement cases b and c from Fig 1-1 with pretimed control. With actuated control, a cross street green can be forced before a left-turn signal is displayed to avoid the "trap".

SUMMARY

The review of published research findings regarding effects of left-turn phase sequencing may be generally summarized as follows:

(1) Permissive/protected versus protected only sequencing produces significant reductions in vehicular delay.

(2) Abnormally high accident experiences have been historically attributed to permissive/protected left-turn sequencing. Experiences in five states indicate however that permissive phasing does not produce statistically significant changes in accident experience or accident severity at locations with good geometries and approach speeds less than 45 mph.

CHAPTER 3. COMPARATIVE ANALYSES

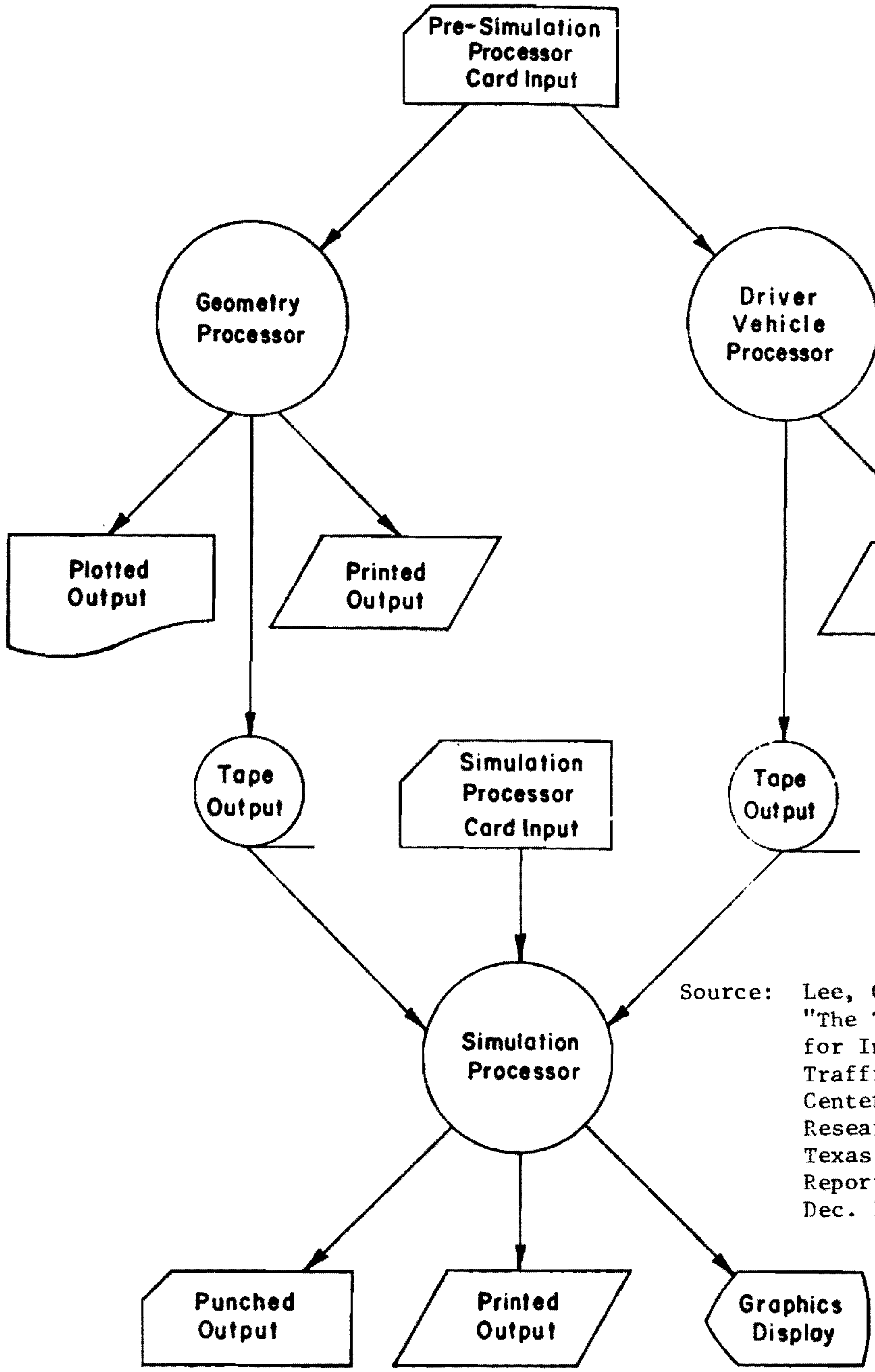
As noted in Chapter 1, left-turn phase sequence patterns were compared under a variety of traffic demands. Both pretimed and actuated signal controllers were tested under optimal as well as non-optimal signal settings.

DATA COLLECTION

Computer simulation was chosen as the primary data collection tool. Simulation provided a means of systematically examining combinations of geometry and traffic demand which were of specific interest.

The TEXAS Model for intersection traffic was chosen as the most appropriate individual intersection micro-simulation model. This model provides highly detailed traffic operations information by stepping individually characterized driver-vehicle units through the intersection environment and allowing each unit to react to roadway geometry, traffic control features, and other driver-vehicle units.

The model is essentially composed of four component parts normally called processors (see Figure 3-1). The driver-vehicle and geometry processors generate traffic streams and vehicle paths in conformance with user specifications regarding proportions of three driver classes, twelve vehicle classes, and basic intersection geometry. The simulation processor, as its name implies, does the actual work of "moving" the traffic streams through the intersection geometry and allowing each vehicle to react to traffic control features as well as other vehicles and driver desires. The emissions processor uses the time history of each vehicle's speed and



Source: Lee, C.E., et al, "The TEXAS Model for Intersection Traffic-Development," Center for Highway Research, Univ. of Texas, Research Report No. 184-1, Dec. 1977.

Figure 3-1. Flow process of the TEXAS Model.

acceleration to produce estimates of vehicular emissions and fuel consumption (see Refs 4 and 5).

PROTECTED VERSUS PROTECTED/PERMISSIVE PHASING

Many advantages are cited in the literature for left-turn phasing patterns which employ combinations of protected and permissive phases versus protected-only phasing (Refs 6 and 7). Advantages are generally attributed to operational rather than safety related issues. Within the comparative analyses described here, vehicular delay is used as a measure of operational efficiency. Since data were collected through computer simulation, safety issues were not experimentally evaluated.

Within the context of this discussion the order of the terms "permissive/protected" does not imply that permissive turns precede the through movement green. Rather, the terms "lead" and "lag" are used to indicate the time sequence of appearance of the permissive phase.

Effects Upon Phase Lengths

Use of permissive/protected left-turn phasing will frequently allow shorter duration protected left-turn phases and shorter resulting cycle lengths. Shorter cycle durations may lead to a reduction in traffic delay. The magnitude of the potential reduction in protected left phase length due to complementary permissive phasing can be estimated from the following relationship:

$$RPL = -3.2 * K \tag{3-1}$$

where RPL = potential reduction in protected phase length, sec,

3.2 = mean left-turn processing time, sec, and

K = estimated number of left-turn maneuvers completed during and permissive green.

The estimated number of left-turn maneuvers which can be completed during the permissive green can be estimated using the techniques of Ref 3. These procedures have been converted to nomograph form and are presented in Figure 3-2. Unprotected left-turn capacity is presented in the figure in units of vehicles per hour and must be converted to vehicles per cycle before being used in Equation 3-1. This figure particularly addresses the geometric case of left turns being opposed by two traffic lanes, while the less common cases of one or three opposing lanes are described in Ref 3.

Procedures for estimating required durations of protected phase lengths are presented in Ref 8. The procedures involve estimation of the number of left-turn vehicles arriving during one signal cycle. The number of left turn arrivals is reduced by the unprotected left-turn capacity of Figure 3-2. The required protected left-turn phase length can be computed from the following relationship.

$$PPL = 3.6P + 4.0 \qquad (3\text{-}2)$$

where 3.6 = average left-turn processing time in seconds,

P = number of left-turn vehicles to be served during the protected phase, and

4.0 = queue start-up time in seconds.

This relationship clearly indicates that the magnitude of potential phase and cycle duration reductions through permissive phasing can be significant.

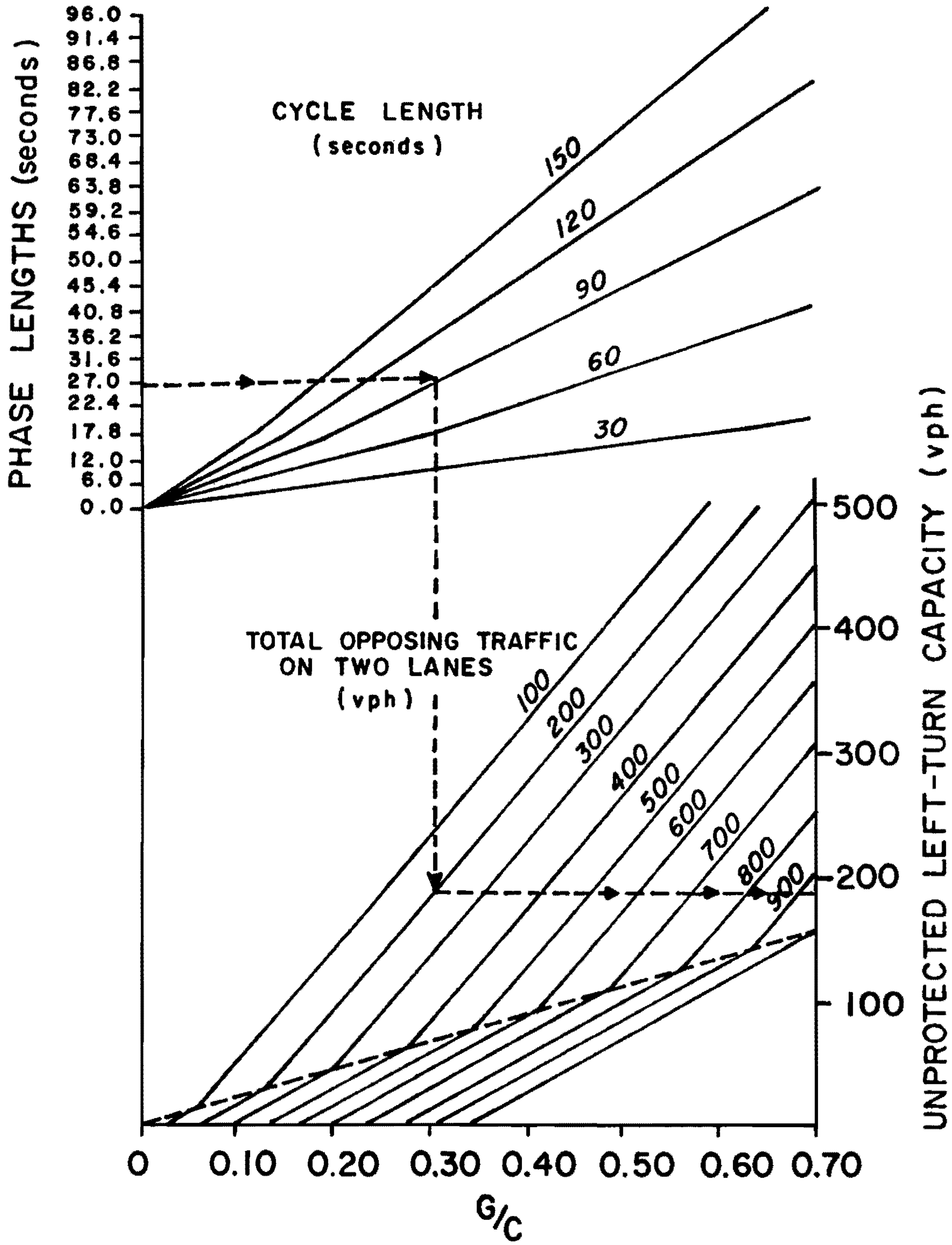


Figure 3-2. Unprotected left-turn capacity.

Effects Upon Vehicular Delay

The experiment conducted as part of this study compared total delay for permissive/protected and protected left-turn phases with fixed cycle and phase durations. The comparisons, therefore, were not affected by different phase or cycle lengths. Test conditions were imposed upon a four-leg intersection in which all approaches were loaded by the same traffic volumes with a left-turn percentage of 20. The timing plan for the intersection is illustrated in Figure 3-3. The application of different traffic demands to one timing plan demonstrates the set of conditions which might exist through the various peak and off-peak hours of a typical day.

Total vehicular delay was compared for the protected only and the permissive/protected phase patterns. The non-parametric Kolmogorov-Smirnov test was utilized to evaluate the statistical significance of the differences in delay statistics. As shown in Table 3-1, the two test conditions were found to be significantly different at all volume levels with permissive/protected phasing producing less delay. Results of the testing along with percentage differences are summarized in Table 3-1. The protected/permissive sequence generally produced an 80 percent reduction in total vehicular delay to left-turn traffic.

The consistency of the delay reduction is particularly significant since opposing traffic volumes ranged from 360 vph (80 percent of 450 vph) to 600 vph (80 percent of 750 vph). Under the low volume condition, the unprotected left-turn capacity exceeded the demand while under the 750 vph demand the unprotected capacity was less than one-third the demand. Therefore, even when a relatively small fraction of the total left-turn demand can be served by a permissive phase, large savings in left-turn delay can be expected.

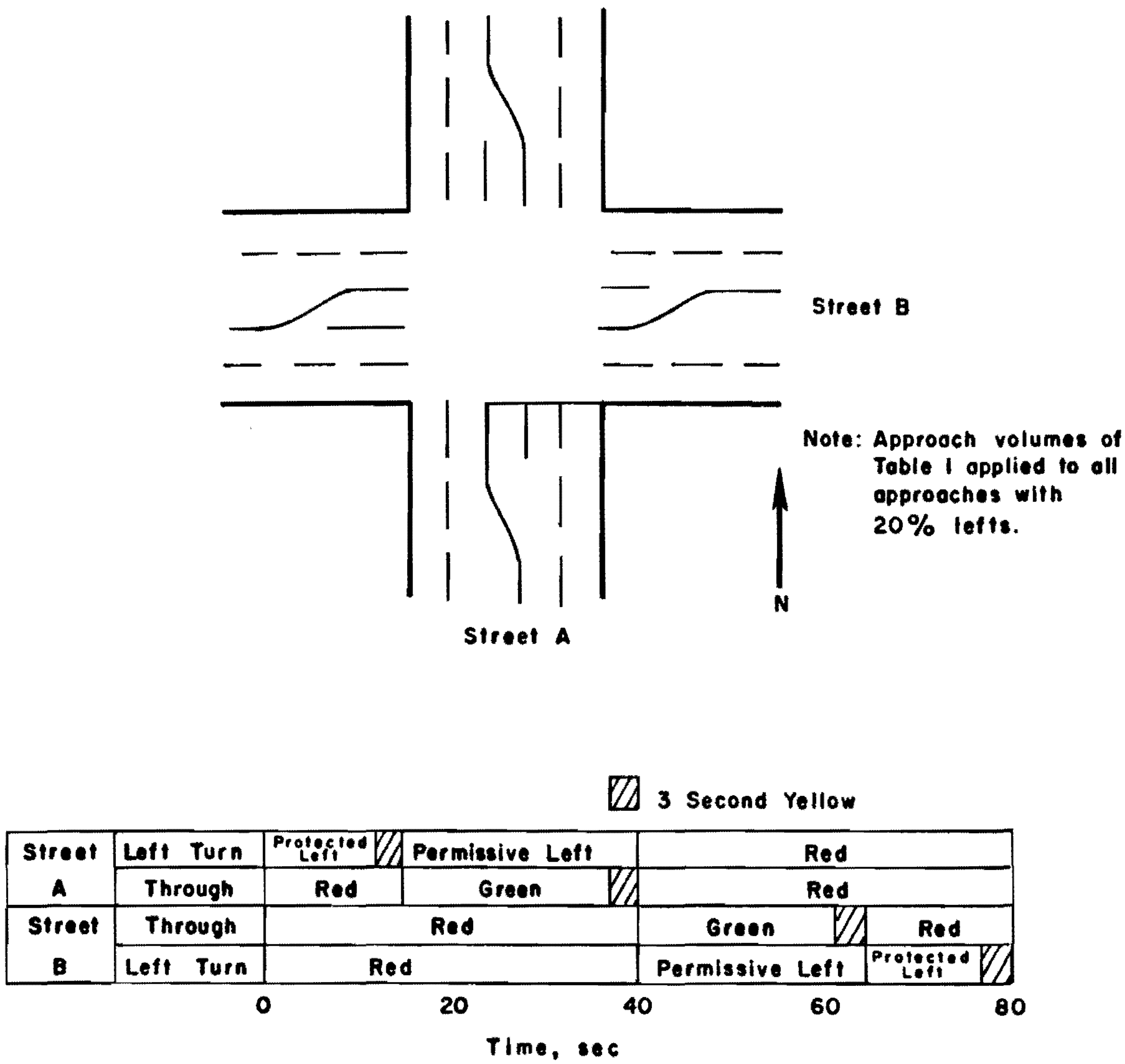


Figure 3-3. Signal timing and geometry for protected versus protected/permissive experiment.

TABLE 3-1. SUMMARY OF RESULTS FOR PROTECTED VERSUS PERMISSIVE/PROTECTED EXPERIMENT

Approach Volume, vph	Simulation Time for Each Condition, hours	Kolmogorov-Smirnov Test Results	Level of Significance	Percentage Increase in Total Delay When Turns Have Protected Only Phasing	
				Left Turns	Approach
450	8	Reject Ho[1]	0.01	82.5	14.4
600	8	Reject Ho[1]	0.01	72.2	14.6
750	8	Reject Ho[1]	0.01	79.2	16.2

[1] Null hypothesis states that total delay statistics for both test conditions came from same population, or that protected and protected/permissive phasing do not produce significantly different vehicular delays.

PHASE SEQUENCES UNDER PRETIMED CONTROL

Within the previous section permissive/protected phasing was shown to be generally effective in reducing vehicular delay relative to protected only phasing. The sequence in which protected phases are provided may also have an effect upon vehicular delay. As illustrated in Figure 1-1 the protected phases may occur simultaneously (dual lefts) or they may be separated in time (split phases). Either of these sequences of protected phasing may be supplemented by permissive turns during the through-green phase. Within this section dual sequencing is evaluated under conditions in which it is not supplemented by permissive turns and when it occurs before (leads) and after (lags) the through green.

Dual-Left-Turn Phasing

Leading and lagging left turns were compared under conditions of protected-only left turning. This experiment utilized the same intersection geometry, signal timing, and traffic demands as the previous experiment (see Figure 3-3). Eight hours of simulated observation time was collected for each test condition. Mean total delay and the range of total delays for each experimental condition are illustrated in Figure 3-4 for delay to left-turn vehicles and in Figure 3-5 for all vehicles utilizing the respective approach. Statistical testing of the differences in total delay between leading and lagging dual phases under protected-only phasing indicates that the two schemes are not significantly different. If all left turns must occur during the protected phase, dual leading and lagging protected phases produce approximately equivalent vehicular delays both to left-turning traffic and to total approach traffic.

Based upon this conclusion, vehicular delay and other operational statistics were compared for leading and lagging dual left-turn phasing when

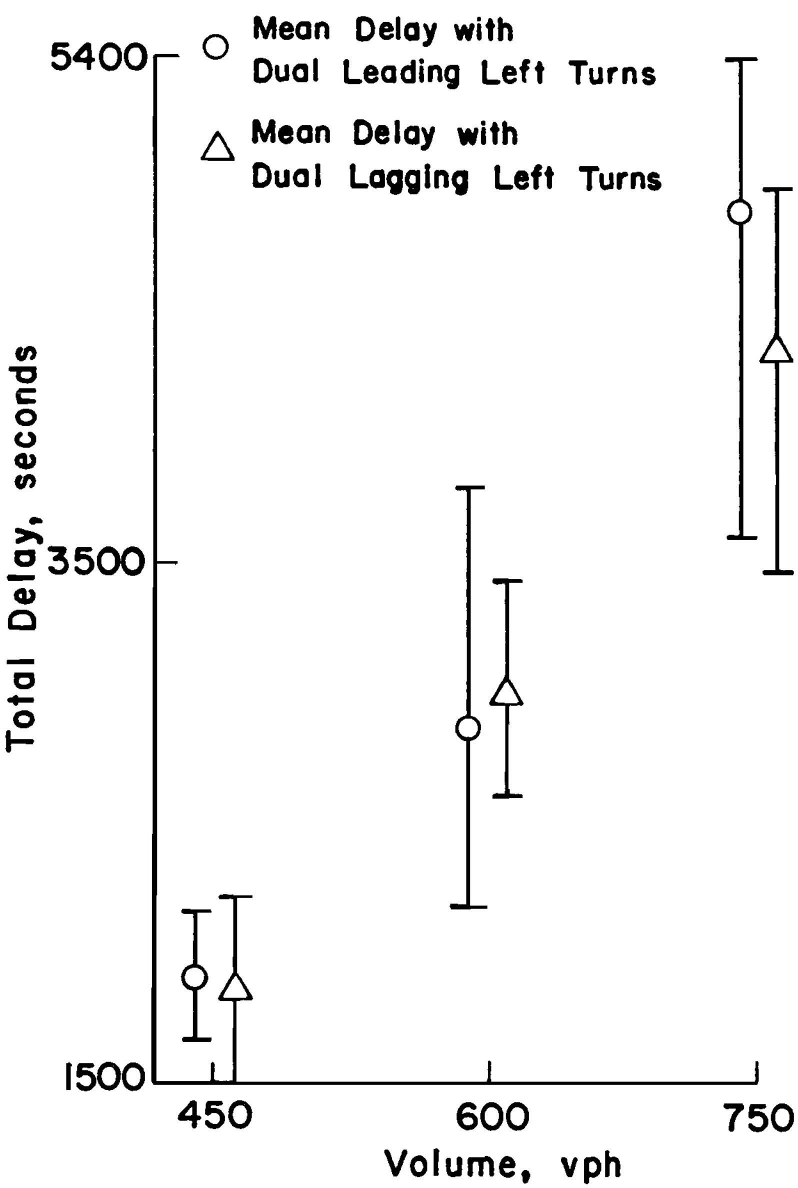


Figure 3-4. Total delay to left-turn vehicles with protected-only left turns.

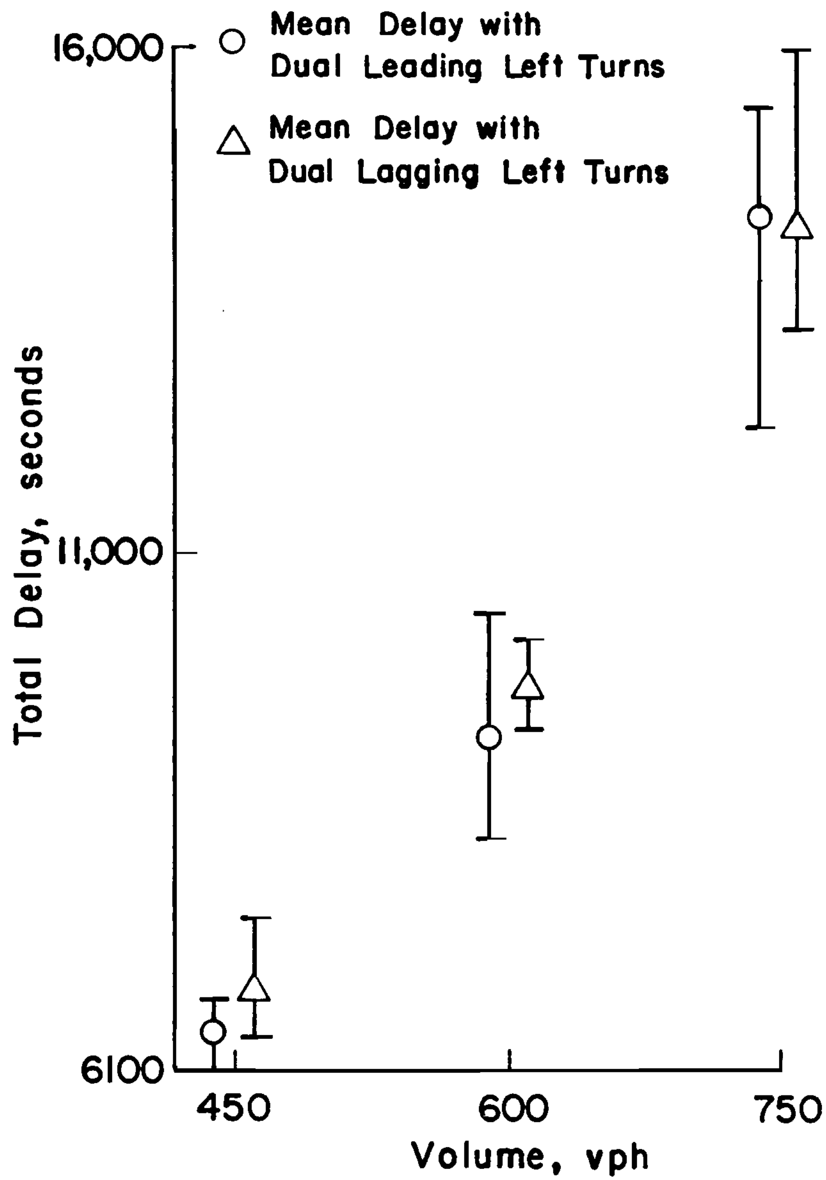


Figure 3-5. Total delay to approach vehicles with protected-only left turns.

both were supplemented by permissive turning. The test conditions were expanded to encompass a wide range of traffic demands as shown in Table 3-2. For each case, signal phase and cycle lengths were arranged to be nearly optimal for the stated demand. For each experimental condition at least one hour of simulated observation time was collected.

A summary of non-parametric statistical testing for cases one through twenty (see Table 3-2) is presented in Table 3-3. The testing indicates that dual leading left-turn phases produce less delay to left-turn vehicles than dual lagging if the opposing traffic demand on two inbound lanes is less than approximately 600 vph. When opposing volumes are relatively small, significant numbers of vehicles can execute left-turn maneuvers during the permissive portion of the signal cycle. As opposing traffic volumes increase, the numbers of left-turns made during permissive phases decrease until the only opportunities may occur during clearance intervals. As indicated previously, dual leading and dual lagging sequences tend to produce equivalent left-turn delays when very few turning opportunities are available during permissive green intervals. Therefore, dual leading phasing apparently provides for more efficient utilization of unprotected left-turn phases.

A further comparative illustration of the potential effects of dual lead versus dual lag is provided in Figures 3-6 and 3-7. These figures present a comparison of the two dual sequencing schemes for the same test conditions used to compare protected and permissive/protected phasing. Signal timing was fixed (see Figure 3-3) through all volume levels, so test conditions for data of Figures 3-6 and 3-7 are identical to Figures 3-4 and 3-5, except permissive left turns were allowed. Total approach volumes in these figures were composed of 20 percent left turns so the volume of opposing left turns

TABLE 3-2. TRAFFIC VOLUME CASES

Case	Approach Volume (vph)	Left Turns (%)	Left-Turn Volume (vph)	Critical Straight Lane Volume (vph)	Total Opposing Volume on Two Lanes
* 1	250	20	50	100	200
* 2	300	33	100	100	200
* 3	300	33	100	200	400
4	400	50	200	200	400
* 5	500	20	100	200	200
6	500	40	200	150	400
7	600	33	200	200	200
8	700	14	100	400	800
9	700	43	300	200	200
10	800	25	200	400	800
11	900	11	100	400	600
12	900	33	300	400	800
13	1000	20	200	400	600
14	1100	9	100	600	1200
15	1100	27	300	400	600
16	1200	17	200	600	1200
17	1300	8	100	600	1000
18	1300	23	300	600	1200
19	1400	14	200	600	1000
20	1500	20	300	600	1000
21	750	20	150	400	800
22	1000	20	200	400	600
23	800	12	100	350	400
24	500	20	100	350	700

*At least 2 hours of simulation time

TABLE 3-3. RESULTS FROM PRETIMED PERMISSIVE DUAL LEFT-TURN EXPERIMENT

Description of Population Tested	Kolmogorov-Smirnov Result	Level of Significance
Total delay to left turn for all experimental conditions	Reject Ho Less delay with dual lead phases	0.01
Total delay to left turn vehicles with opposing volumes ≥ 600 vph (on two inbound lanes)	Cannot reject Ho Leading and lagging are not different	
Total delay to left turn vehicles with opposing volumes < 600 vph (on two inbound lanes)	Reject Ho Less delay with dual lead phases	0.01
Average queue lengths for straight through vehicles	Cannot reject Ho Leading and lagging do not effect through movements	
Average queue lengths for left-turn vehicles	Reject Ho Shorter queues with dual lead	0.01

Ho - Null hypothesis that the two samples are from the same population

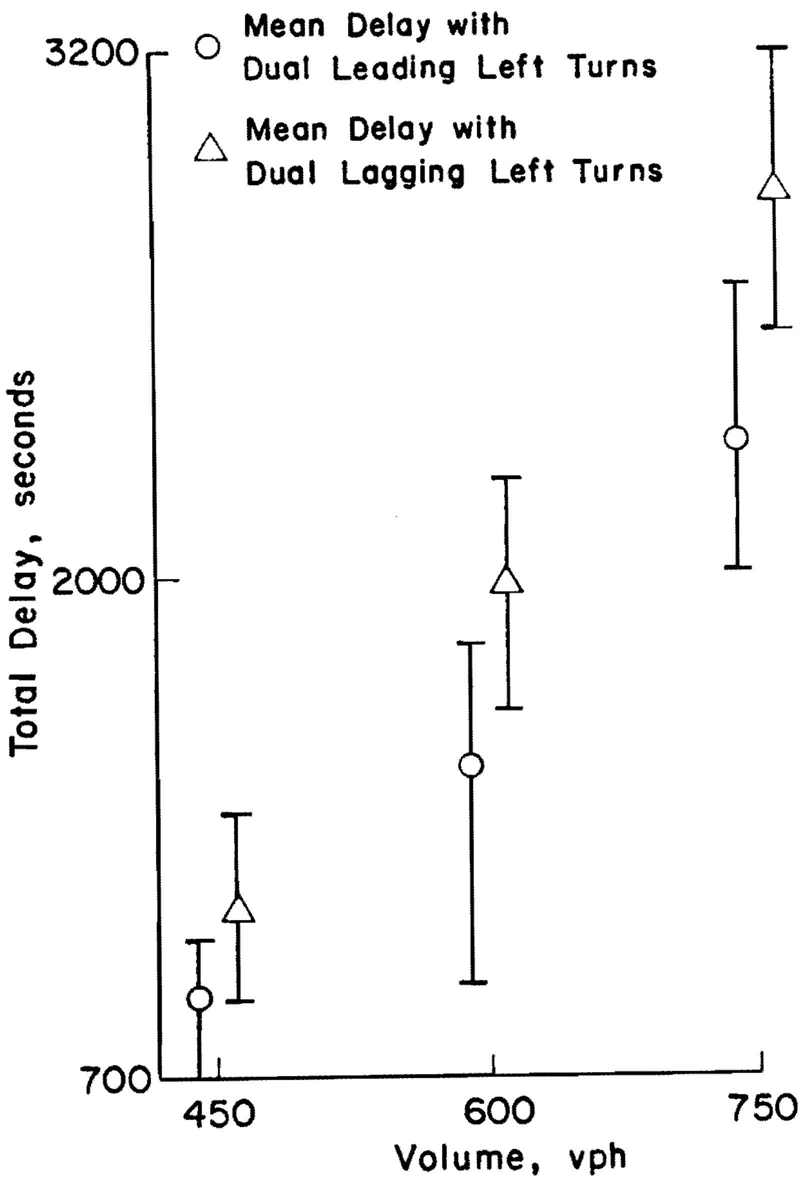


Figure 3-6. Total delay to left-turn vehicles with permissive turning.

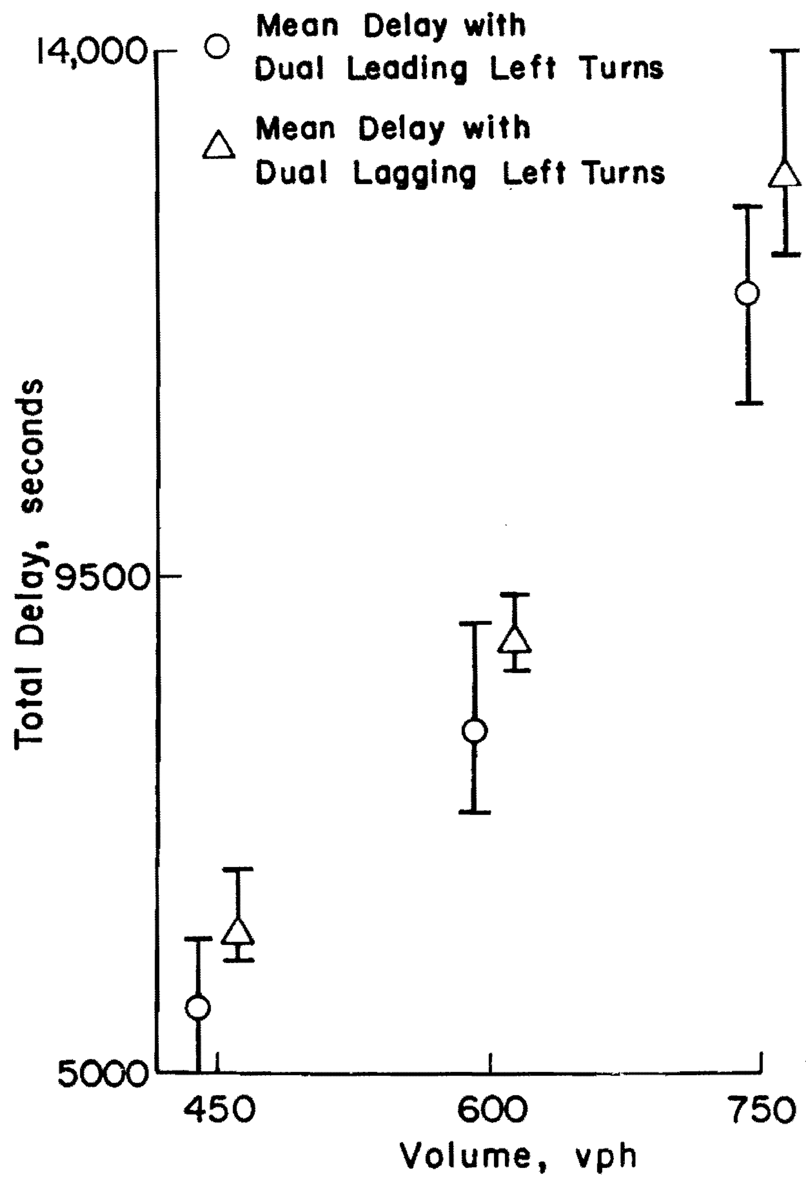


Figure 3-7. Total delay to approach vehicles with permissive turning.

is 80 percent of the indicated demands or a maximum two-lane volume of 600 vph. Comparison of delays for leading and lagging sequences of Figures 3-6 and 3-7 indicates a clear reduction in vehicular delay under dual leading with permissive turning allowed. Comparison of Figures 3-6 and 3-7 with Figures 3-4 and 3-5 indicates another significant reduction when permissive turning is allowed.

Dual Versus Split Phasing

Split left-turn phasing schemes were earlier identified as any of a family of phase sequencing arrangements in which protected left-turn phases on two approaches of the same street do not occur simultaneously. One variation of the split phase arrangement is the lead-lag with overlap in which the left-turn phases on opposite approaches of the same street overlap for some part of this duration. This type of operation approaches the dual left management as a limiting case. The lead lag with overlap is not specifically investigated since it is a special case of the more generic sequences. Split phasing is used most effectively on a street where the maximum left-turn and through movement demands occur on the same approach. Thus, both the left-turn and through movement volumes on the opposite approach would be non-critical if both approaches were serviced by a common signal phase. This situation would be particularly appropriate for split phase sequencing with no permissive turning. Ideally, if permissive turns are to be allowed the left-turn demand on one approach should require more processing time than the through movement while on the opposing approach more green time would be required to process the through movement. For example, in Figure 3-8, Street B would be served more efficiently with dual left-turn phasing because the maximum left-turn volume (400 vph) is not on the same approach as the maximum through movement volume (200 vph). Split phasing

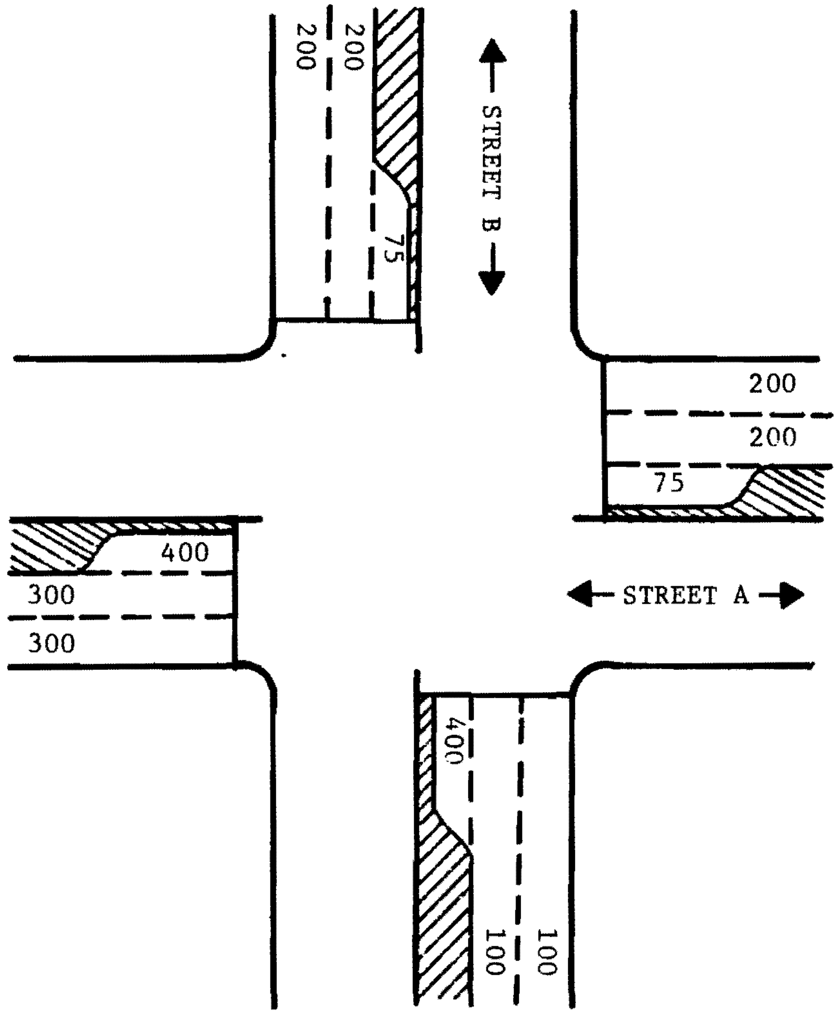


Figure 3-8. Example traffic volumes.

with permissive turning during a common through movement phase would, however, be more efficient on Street A because the maximum volumes are both on the north bound approach. Also, the north bound approach requires more green time for left-turn maneuvers, whereas the main street vehicles require more processing time on the southbound approach.

In order to compare vehicular delay resulting from dual and split phasing a series of specially designed experiments was conducted. Approach traffic volumes earlier referenced as cases 21 through 24 of Table 3-2 were loaded onto a four by four intersection as shown in Figure 3-9. Two nearly optimal signal timing schemes were developed for this intersection-traffic demand condition. In one scheme dual leading left-turn phases were imposed while in the other split left-turn phasing was utilized, and in both permissive left turns were allowed. Nearly optimal signal timing was defined as the timing, subject to the above constraints, which produces the smallest quantity of total intersection delay. A trial and error adjustment process was used to derive optimal conditions. Resulting phase and cycle lengths are shown in Figure 3-9. Due to the fact that only Street A required a protected left-turn phase, the number of signal phases was identical for the dual and split arrangements. Despite the equal number of phases, the dual left-turn arrangement produced a significantly shorter cycle length than the split phase arrangement. Required green time on Street B is smaller under the dual arrangement because during the shorter duration red, fewer vehicles will accumulate.

As expected, the dual left phasing produced significantly less left-turn and total intersection delay. This effect can be attributed largely to the shorter phase and cycle lengths possible with dual sequencing.

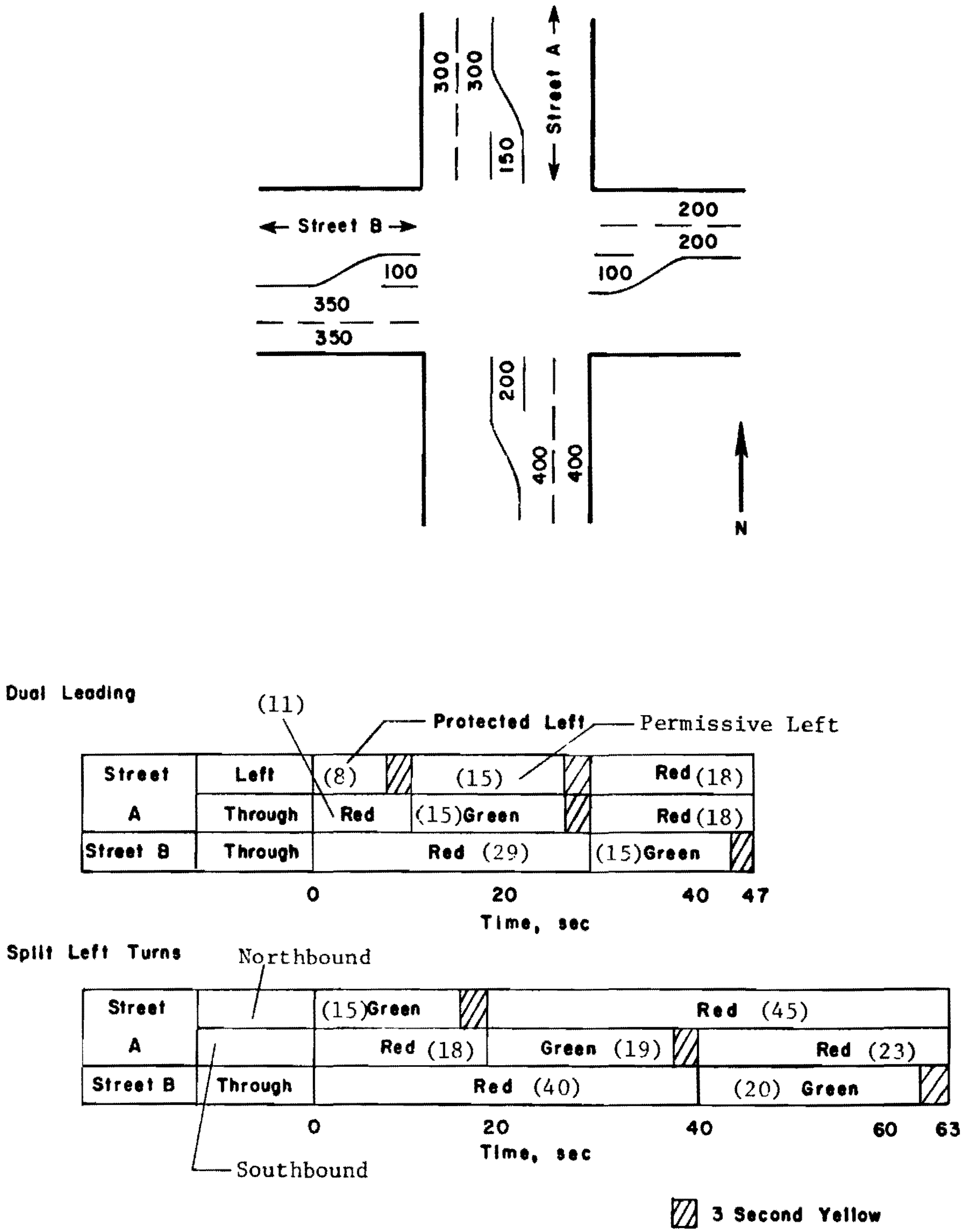


Figure 3-9. Optimum signal timing for dual versus split left turns experiment.

In order to extend the comparison and examine the effects of cycle length, another series of experiments was conducted. In these cases, the traffic demands of Figure 3-9 were utilized again but signal cycle lengths of 60, 80, and 150 seconds were used for both the dual and split sequences. The number of phases required for the 60-second cycle was the same as in the optimum cycle experiment, and the results were the same.

For the 150-second cycle, the much larger red times produced larger queues and requirements for protected left-turn phases on all four approaches. Here again, dual left-turn phasing should be better than split phasing because on both streets each approach required more time to process the main street traffic than the left-turn vehicles. The experimental results confirm this conclusion.

The 80-second cycle, on the other hand, produced requirements for protected left-turn phases on both approaches of Street A, but only one approach of Street B. In this case, split phasing resulted in less total approach delay on Street B, while dual phasing performed more efficiently on Street A.

The experiments comparing dual and split phases under pretimed control indicate that split phase sequencing should be considered as a candidate sequencing scheme where:

(1) The critical left-turn and through movement demands occur on the same approach and left-turn demands on both, or neither approach, require more processing time than through movements. In this case protected only phasing should probably be considered.

(2) The critical left-turn and through movement demands occur on the same approach and on only one approach the required left-turn processing time exceeds that for the through movement. In this case split phasing would be highly desirable with either protected or protected/permissive phasing, although permissive turns would provide significant efficiency advantages.

Composite Left-Turn Phasing

A phasing scheme which is a combination of the dual and split schemes was compared to dual and split phasing using the traffic volumes of Figure 3-9 and two different signal cycle lengths.

This scheme which has been termed "composite" phasing (see Figure 1-1) caused less total delay than dual phasing when an 80-second cycle length was used, but more delay than dual phasing when a 150-second cycle was used. These results indicate that composite phasing is preferable to dual phasing under the same conditions in which split is better than dual.

However, when the composite scheme was tested against split phasing, the split sequence consistently resulted in more total delay. Composite phasing permits more permissive left turns during the through movement green. Thus, with more efficient utilization of the intersection, composite phasing results in less delay.

Usually, however, composite phasing is not practical when the protected left-turn phase is supplemented by permissive turning. Under such conditions left-turn vehicles on one approach face a red signal during phase two (Figure 1-1) while left-turners on the other approach may continue. The red signal between the protected left-turn signal and the main street green signal is likely to cause driver confusion and may create safety problems. Therefore, even though composite type phasing schemes may offer significant operational efficiency, they are not generally desirable if permissive left turns are allowed.

PHASE SEQUENCES UNDER ACTUATED CONTROL

A testing program for left-turn phase sequencing under actuated signal control was designed to parallel that for pretimed control. A number of questions regarding detector patterns and controller timing were also studied in order to provide results comparable to those of the previous experiment.

Detector Configuration and Phase Timing

Sensitivity analyses of Ref 9 along with supplemental studies of detector configurations were utilized to develop plans for detector configuration and phase timing. These studies in conjunction with consideration of the traffic demands to be studied yielded initial specifications consisting of 90 foot long presence detectors in the left-turn bays and across both through traffic lanes (Figure 3-10). The detectors were set back 10 feet from the stop lines.

One-second initial intervals and one-second vehicle extension intervals were used with two-second minimum greens. In all experiments permissive left turns supplemented protected left turns. The signal durations developed for the pretimed dual phase experiments were examined, and the longest duration for each phase was selected as the maximum extension for the actuated controller. The resulting signal timing plan was used to test all 24 traffic demand combinations, although combinations that included more than 200 vph turning left against an opposing traffic flow of more than 500 vph per lane were given two-second vehicle interval times to prevent early gap-out. At least one hour of simulated observation time was collected for each case.

Lead and lag left-turn phase arrangements were also compared for cases in which the phases were split, as in the pretimed control experiments. The first 20 of the traffic demand combinations were used in this experiment. The longest duration phases used in the pretimed split left-turn phase experiments were used as the maximum extension times with the actuated controller. Although the experiments were conducted with fully skippable phases, the three phases of Case (a) - Figure 1-1 (split phase sequencing) occurred consistently on both streets. In the tests detector one (Figure 3-10) determined the length of phase one while any additional traffic on detector three or traffic on detector four triggered phase two. Finally, detector two allowed the remaining left-turn traffic to process in phase three. At least 30 minutes (and up to 90 minutes) of simulated observation time was collected for these traffic volume cases.

Dual Left-Turn Phasing

Operational efficiency, with vehicular delay as the principal measure of effectiveness, was compared for leading and lagging dual protected left-turn phasing when both were supplemented by permissive left turns and timed by an actuated controller. All traffic demands in Table 3-2 were included.

Non-parametric statistical tests of the experimental results are summarized in Table 3-4. The testing indicates that dual lagging left-turn phasing creates shorter signal cycle lengths which produce smaller delays to the dominant through movements. This is principally due to the fact that the lagging sequence causes the left-turn queue to be waiting at the beginning of the through movement green and with permissive turns will allow some of the left-turn demand to be satisfied during the through movement. A leading left-turn phase, on the other hand, may process the entire left-turn queue before the main street green. Therefore, the main street green is utilized to process only those left-turn vehicles that arrive while it is in progress. The main street green is utilized much more effectively with lagging left-turn phases because vehicles in the left-turn queue can process during gaps in the main street traffic. If the gaps in approaching traffic allow at least as many left-turn movements as there are left-turn arrivals during the through movement green phase, the protected left-turn phase will be shorter than when a leading phase is used. As a result, the cycle length for the

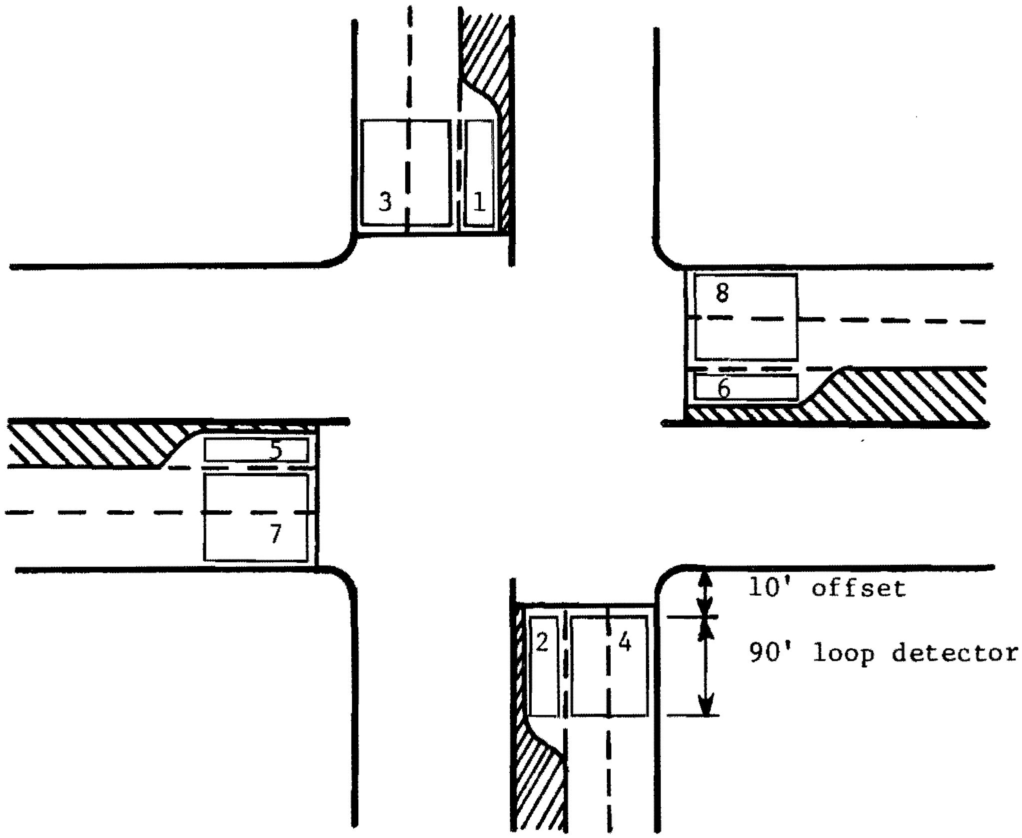


Figure 3-10. Basic detector configuration for actuated control.

TABLE 3-4. RESULTS FROM ACTUATED DUAL LEFT-TURN EXPERIMENT

Description of Population Tested	Median Test Result	Level of Significance
Average Signal Cycle Lengths	Reject Ho Cycle lengths shorter with dual lag	0.02
Total Delay to Straight Through Vehicles	Reject Ho Through total delay less with dual lag	0.02
Total Delay to Left-Turn Vehicles	Cannot Reject Ho Left-turn delay not affected by lead vs. lag	
Total Delay to All Vehicles on Approach	Cannot Reject Ho Total delay to all vehicles not affected	

Ho - Null hypothesis that the two samples are from the same population.

intersection is reduced. In situations where the maximum phase extension is reached during the protected left-turn phase, with dual lag phasing the cycle length will be equal to or shorter than with dual lead phasing.

As the statistical tests also verify, the reduction in cycle duration due to lagging phases causes a significant reduction in delay to straight through vehicles. Left-turn vehicles benefit from this delay reduction, but at the same time experience a delay increase from the slower queue dissipation. Thus, left-turn vehicles may or may not benefit from either phase arrangement, depending on the left-turning traffic demand and the opposing traffic demand.

For some experimental traffic arrangements lagging phases produce significantly less delay to all traffic on an approach (total approach delay of Table 3-4). But when all experimental traffic demand cases were tested together, the difference was not significant. Approach delay under actuated control is dependent on the interactive performance of all maneuvers utilizing an approach and the relative efficiency and relative magnitude of each maneuver. These interactive effects have, therefore, masked the differences of the two phasing schemes regarding their total approach delay statistics.

Dual leading left-turn phasing was compared to dual lagging for the same twenty traffic demand combinations that were examined in the corresponding pretimed experiment with four additional special cases. Since dual lag phasing generally produced shorter cycle lengths and less delay than dual lead phasing, a supplementary experiment was designed in an attempt to produce shorter cycle durations with dual lead phasing. The left-turn lane loop detectors were incrementally shortened in three tests along with a shorter vehicle extension interval for left-turn traffic.

The test results are summarized in Table 3-5. Although forcing the left-turn traffic to use the permissive portion of the green signal by causing early gap-out of the protected left-turn phase caused the cycle duration to be reduced, it was never as short as with dual lag phasing. Vehicular delay was consistently less for dual lagging sequencing schemes. The dual lagging sequence was, therefore, judged to be more efficient than dual leading.

Dual Versus Split Phasing

As noted earlier, split phase timing patterns were developed for the twenty traffic demand situations. Vehicular delay for through and left-turn movements was compared to the corresponding statistics gathered under dual left-turn sequencing. Results of the comparisons were virtually identical to those produced under pretimed control.

Therefore, the conditions determining whether split or dual phasing should be used do not change when actuated instead of pretimed control is used. The previous discussion of split versus dual phasing for pretimed control also applies to cases with actuated control.

Split Phasing, Lead Versus Lag

In cases where split left-turn sequences are selected under actuated control, the question of which left-turn movement should lead a through movement green may arise. To determine whether the leading left-turn movement performs differently than the lagging movement in a split left-turn phase arrangement, the first 20 traffic demand combinations in Table 3-2 were compared for each of the two situations.

The results indicate that there is no significant difference in delay to left-turn or to straight through vehicles when a lagging phase is used

TABLE 3-5. SUMMARY OF RESULTS FOR DUAL LEAD AND LAG UNDER ACTUATED CONTROL

Arrangement	Left-Turn Detector Loop Length (feet)	Vehicle Interval on Left-Turn Lane (sec)	Average Cycle Length (sec)	Total Delay Per Vehicle Intersection
Dual Lead	90	1.0	92.6	30.28
Dual Lead	60	1.0	84.8	28.10
Dual Lead	30	1.0	82.7	28.08
Dual Lead	30	0.5	80.0	26.73
Dual Lag	90	1.0	70.6	24.0

instead of a leading phase, even though the required phase lengths are very different. This is because the left-turn queue discharges more efficiently with a leading phase minimizing delay to individual vehicles, but it requires a longer phase to do so, causing a longer cycle duration and more delay to the intersection. On the other hand, since the lagging phase is shorter, the main street green signal must be longer to process the straight vehicles that would process with the left-turn vehicles with a leading phase. Thus, there is no significant difference between the lead and lag phases with split left-turns and actuated control.

SUMMARY

The experiments described in the previous sections have compared a wide variety of left-turn phase sequencing patterns. The comparisons have included pretimed as well as actuated signal control and a significant sampling of different traffic demands. The analyses are based upon "single" intersection performance and the requirements of an interconnected system may override those of a "single" location. Several of the conclusions are summarized as follows.

(1) Permissive left-turning as a supplement to protected left-turn signal phases offers significant improvements in operational efficiency regardless of the basic type of phase sequence pattern.

(2) If permissive left-turning is allowed with pretimed control and dual sequencing, dual leading sequences will create less vehicular delay than dual lagging.

(3) Under actuated signal control and permissive turning, dual lagging sequence patterns create less vehicular delay than dual leading.

(4) The choice of dual versus split phase sequence patterns is not generally affected by the type of signal controller. Split phasing will be the more efficient sequence pattern where the critical left-turn and through movement traffic demands occur on the same approach and the left-turn processing time of only one approach is less than the respective through processing time.

CHAPTER 4. FINDINGS AND RECOMMENDATIONS

The preceding discussion has included a comparative examination of left-turn phase sequence patterns. Computer simulation was utilized as the primary data collection tool. Random variability of generated traffic data has been considered as an important aspect of the study and has been treated through multiple replication of experimental units. Comparative analyses have been developed around traffic operational data with vehicular delay as the primary measure of effectiveness. Safety related issues have been included through a review of published safety data. The analyses have been developed for "single" intersections and the requirements of interconnected systems may override that of a single location.

FINDINGS

Based upon these analyses the following findings have been developed:

(1) From a traffic operations perspective, provision of permissive left turns during the through green will always be beneficial regardless of the type signal control or left-turn sequence pattern. Only in situations where safety concerns are an overwhelming influence should permissive left turns be prohibited. Data published in Ref 6 indicate that safety problems associated with permissive lefts are frequently not severe. Intersection approach speeds in excess of 45 mph are frequently cited as a reason for prohibiting permissive left turns.

(2) There is no operational difference between dual leading and dual lagging sequences when permissive left turns are prohibited. When permissive turning is allowed, dual leading sequences produce less vehicular delay than dual lagging sequences if pretimed signal control is used. Under actuated control, dual lagging sequence patterns tend to produce less vehicular delay.

(3) Split left-turn sequence patterns tend to produce less vehicular delay where critical left-turn and through movements occur on the same approach, and the left-turn movement processing time for only one approach is greater than the through movement processing time.

RECOMMENDATIONS

Research findings have been summarized in tabular form and are presented as Table 4-1. This decision chart might provide a convenient resource for choosing among possible left-turn sequence patterns. Permissive left-turning is an excellent means of improving operational efficiency under many conditions. Use of permissive turns is suggested unless safety concerns prohibit such use.

TABLE 4-1. PHASE SEQUENCE DECISION CHART

Traffic Arrangement	With Permissive Left Turns		Protected Only
	Actuated Control	Pretimed Control	
The critical left-turn and through movement demands are on the same approach. On only one approach, the left-turn demand requires more processing time than the through movement	Dual Lag[1]	Dual Lead[1]	Split[1]
The critical left-turn and through movement demands are on the same approach of the street. On both approaches or on neither approach, the left-turn demand requires more processing time than the through movement	Split[1]	Split[1]	Split[1]
All other cases	Dual Lag[1]	Dual Lead[1]	Dual Lead[1] or Dual Lag[1]

[1] See Figure 1-1 for illustrations of phase sequences

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