Guidelines for Use of Leading and Lagging Left-Turn Signal Phasing

JOSEPH E. HUMMER, ROBERT E. MONTGOMERY, AND KUMARES C. SINHA

The use of optimum phase sequences at signalized intersections could save motorists many hours of delay and could result in fewer accidents. However, very little factual information has been available to guide engineers in choosing between the various signal phasing alternatives. To close that gap, leading and lagging signal sequences were evaluated in Indiana using a survey of licensed drivers, an examination of traffic conflicts, an analysis of accident records, and a simulation model of traffic flow. The guidelines developed as a result of these activities generally reflect the advantages documented for lagging sequences over leading sequences in a variety of situations. Lagging sequences are recommended for, among other situations, intersections serving heavy pedestrian volumes, diamond interchanges or one-way pairs, and intersections with fixed-time signals. However, when implementing lagging sequences, caution is recommended to prevent situations in which a vehicle could become "trapped" in an intersection as the green phase elapses.

Left turns at intersections have long been a source of concern for traffic engineers. In recent years, greater traffic volumes at many intersections and fiscal and right-of-way constraints on construction have led traffic engineers to design and implement increasingly sophisticated signal schemes to allow vehicles to turn left safely and efficiently. The permissive scheme is the most common type of signal scheme accommodating left turns in the United States. In this scheme, vehicles may turn left when receiving the green-ball signal and when sufficient gaps appear in the opposing traffic stream, which also has a green-ball signal. In another very common signal scheme, the protected scheme, vehicles may turn left only when receiving a green-arrow signal, which affords them exclusive right-of-way through the intersection. In most applications, the protected signal is given to vehicles turning left from a particular street before the green ball is given to the through movement on the same street (i.e., protected-leading). Most other common signal schemes to accommodate left-turning vehicles involve a variation on or combination of permissive and protected schemes, including:

- Protected-lagging, in which the green arrow is given to left-turning vehicles after the through movements have been serviced;
- Protected-permissive, in which protected left turns are made first in the cycle and a green-ball signal allows permissive left turns later in the cycle; and
- Permissive-protected, in which permissive left turns are allowed first in the cycle and protected left turns are accommodated later in the cycle.

J. E. Hummer, Department of Civil Engineering, University of North Carolina, Charlotte, N.C. 28223. R. E. Montgomery and K. C. Sinha, Purdue University, West Lafayette, Ind. 47907.

Protected-leading and protected-permissive are referred to as "leading" schemes, and protected-lagging and permissive-protected are known as "lagging" schemes.

Research has been conducted on a number of questions involving the common left-turn schemes. However, the question of the effects of leading and lagging schemes has received little attention from researchers. Many localities and practitioners, faced with the choice of lead or lag, base their decisions on tradition, hearsay, or feeling, not factual evidence. The intent of the research reported here was to examine the relative merits of leading and lagging phasing schemes and to develop appropriate guidelines that would assist decisions on lead and lag.

Finding an answer to the leading and lagging sequence question would have many potential benefits. If the guidelines save 1 second of delay per vehicle at 200 typical intersections, about 1 million hours per year would be saved. Such a reduction in vehicle delay would also save fuel and decrease pollution. Additional benefits could accrue to operating agencies and to taxpayers if construction projects to add intersection capacity are delayed or scaled down because of changes in signal sequence. Also, although the number of accidents involving left-turning vehicles per intersection is relatively small, the guidelines would potentially result in accident savings.

PURPOSE AND SCOPE

The primary purpose of the research was to produce guidelines for the use of leading and lagging left-turn signal sequences. A secondary purpose of the research was to advance the body of knowledge regarding left-turn signal schemes in general. General information on left-turn signal schemes would be useful in compiling a comprehensive set of guidelines on left-turn phases.

The scope of the research was limited in a number of ways. First, attention was given primarily to only the five common left-turn schemes described. Second, data collection activities were confined to Indiana. Third, with one exception, the research was concentrated on intersection types that are relatively common in Indiana. Intersections with five or more approaches, dual left-turn lanes, offset approaches, or a great deal of channelization are rare in Indiana, so the limited resources of the project were not expended on them. Although they are not common in Indiana, diamond interchanges where both ramp terminals had signals with left-turn arrows were included for study because an increasing number of those interchanges are being signalized.

The major areas of potential concern relative to leading and lagging and other left-turn issues explored in this research include motorist preferences and understanding, safety, and delay. These areas were addressed during the review of relevant published research findings. Data on motorist preferences and understanding were gathered through a survey at the 1988 Indiana State Fair. Safety was explored using a field study of traffic conflicts and an analysis of accident data at a sample of intersections. A detailed microscopic simulation model of arterial street networks was the primary tool used to study delay. Safety-related variables were also analyzed using a series of simulation runs. The results from all of these different work elements were used to develop guidelines for the use of leading and lagging left-turn signal phasing. A detailed description of the methods, dates, and results of these work elements is provided elsewhere (*1*).

LITERATURE REVIEW

The literature on left-turn phasing, especially the left-turn phase sequence, was reviewed and provided information on delay, safety, and motorist preferences. For delay, no clear trend emerged between leading and lagging schemes at isolated intersections. However, it was clear that a policy that allows the choice of lead or lag at individual approaches in a coordinated system with the aim of maximizing the through bandwidth decreases delay (*2–4*).

Concern for the safety of drivers and passengers in vehicles that become "trapped" in an intersection while waiting to make a left turn has been consistent in the literature (*2,5–7*). Trapping may occur to a vehicle making a left turn on an approach with a permissive signal where the opposite approach has a lagging signal. When the permissive signal goes to yellow and then to red (to provide the lagging green-arrow signal for the left-turning traffic in the opposite direction), the signal for opposing through traffic remains green. A vehicle turning left with the permissive signal will not be able to complete its turn at the end of the cycle as at a normal permissive intersection. At best, the vehicle will be able to back up to the stop bar. If other vehicles in the left-turn queue have moved up behind it, the lead vehicle will not be able to back up to the stop bar and will be trapped in the middle of the intersection. At worst, the driver of the left-turning vehicle will not recognize that the opposing traffic still has a green signal and will try to turn, expecting the opposing traffic to stop as usual. Intersections where one approach has a permissive left turn of some kind and the opposing approach has a lagging sequence must be checked for the possibility of trapping. Trapping can be mitigated by eliminating the permissive turn (making it protected-only or prohibiting the turn), by eliminating the lagging sequence, by ensuring that the opposing approaches both have lagging sequences with left-turn phases that begin simultaneously, or by using other phasing measures. The literature revealed several reasons why lagging sequences might lead to fewer accidents than leading sequences at certain types of intersections where trapping conditions are not present (*5*). Data to evaluate the relative safety of the signal sequences were sparse, however.

The only study reviewed that examined motorist preferences for lead or lag showed a great deal of support for the lagging sequence (*8*). The sparse data available on the question of motorist confusion showed few such problems when drivers face a change in signal sequences or a variety of sequences in close proximity (*8–10*).

The plentiful literature on the tradeoffs between permissive, protected, and either protected-permissive or permissive-protected signals was also reviewed. The literature documented the well-known general trend that accidents increase and delay decreases as the level of left-turn protection decreases. Protected signals were recommended in the literature for intersections with high-speed approaches, restricted sight distances, or three or more opposing through-lanes. Warrants for the installation of some type of left-turn protection instead of permissive signals are available. Directional separation left-turn signals, where each intersection approach has the exclusive right-of-way in turn, are another option available to engineers at certain intersections.

MOTORIST SURVEY

A 4-day survey of Indiana drivers was conducted at the 1988 Indiana State Fair. The survey provided many useful results on the relative understanding of various left-turn signal and sign alternatives. The survey also provided data on the preferences of motorists for various left-turn signal alternatives, including the leading and lagging sequence alternative. Survey data were collected during short interviews conducted by transportation graduate students. Respondents received three fair amusement coupons (worth $0.45 each) for completing the interview.

Over 400 valid responses were received. Despite the fact that the survey was conducted in one place over a 4-day span, responses were received from a wide variety of people. The error rate computed for the nine understanding questions, and the lack of association between preferences expressed and particular interviewers or survey days, showed that the survey script, displays, and format were reasonable and that the data were not biased in any substantive way. However, applications of the survey data outside this project must be made carefully, keeping in mind the context of the survey (i.e., the tendencies of Indiana drivers and highways in 1988).

The leading sequence was preferred by 248 respondents, and the lagging sequence was preferred by 59 respondents; 95 respondents expressed no preference for either signal sequence. The difference between leading and lagging was found to be significant using a confidence interval at the 0.05 level, but the relatively high number of respondents with no preference indicates that the overall preference may not have been as strong as the confidence interval would indicate. Table 1, which summarizes the reasons given by respondents for their preferences, shows that more respondents preferred the leading sequence because it was more like normal (i.e., more common). Many other respondents credited the leading sequence with causing less delay and being safer. Table 2 shows the relationships between the preference for leading or lagging sequence and various independent variables from the survey. The preference for leading and lagging sequence was somewhat related to the age of the respondent, although the main contributor to the high chi-square value in this case was the tendency of younger drivers to have no preference more often. The variable for urban or rural county of residence was found to be related to the choice of leading or lagging sequence,

TABLE 1 REASONS FOR PREFERENCES FOR LEADING AND LAGGING SIGNAL SEQUENCES

Reason given \ Signal sequence preferred	Number of respondents*	
	Leading	Lagging
Safer	61	11
Less delay	65	17
Less confusion	27	11
More like normal	73	10
Unsure or other	39	11

* Some respondents provided more than one reason for their preference.

TABLE 2 RELATIONSHIPS BETWEEN PREFERENCES FOR LEADING OR LAGGING SEQUENCES AND VARIOUS INDEPENDENT VARIABLES

Variable	Chi-square value	Reason for significant or nearly significant relationship
Age	.054	Younger drivers had no preference more often
Sex	.126	--
Urban or rural county of residence	.002	Rural residents preferred lagging more often
Annual miles driven	.056	Those driving less preferred lagging more often
Number of errors on nine understanding questions	.526	--

with people from rural counties expressing a preference more often for the lagging sequence. The variable for annual miles driven was also somewhat related to the preference for leading or lagging signals, with people driving the least opting for the lagging sequence more often.

Several results from the motorist survey that did not pertain to the leading and lagging issue were also notable. The protected signal was far better understood than the permissive signal, which was in turn better understood than the protected-permissive signal. The "left turn yield on green ●" sign proved more confusing than the other protected-permissive sign conditions tested (the no-sign condition and the "left turn on green or arrow" sign). There was little to distinguish the protected sign conditions tested (no sign, "left turn signal" sign, and "left turn on arrow only" sign) on the basis of motorist understanding. Finally, the protected signal was the most preferred signal because most respondents associated it with less confusion, and the permissive signal was the least preferred signal.

TRAFFIC CONFLICTS

The relative safety afforded by leading and lagging signal sequences has not been well documented. To help overcome that gap, a traffic conflict study was conducted at six intersections in Indianapolis. Traffic conflicts are events involving the interaction of two or more road users where one or both users take evasive action such as braking or weaving to avoid a collision. Traffic conflict data have been shown to be correlated with accident data in many traffic situations; because traffic conflict data can be collected in a relatively short period of time, they are often used as a proxy for accident data (*11*).

Three pairs of intersections were identified for the traffic conflict study. Each pair consisted of an intersection with a permissive-protected signal and an intersection with a protected-permissive signal. In most respects except the signal type, the intersections were similar between members of a pair. All six intersections studied were intersections between a two-way street and a one-way street with fixed-time signals in Indianapolis. The intersections included a "downtown" pair with many pedestrians and low vehicle speeds, an "urban" pair with few pedestrians and 30- to 35-mph speed limits, and a "suburban diamond" (i.e., diamond freeway interchange) pair with no pedestrians and 40-mph speed limits. Data were gathered manually on all conflicts and unusual maneuvers that were witnessed by observers on two sides of a test intersection.

Table 3 shows the results of the conflict study for the four types of conflicts and unusual maneuvers that were most related to left-turning vehicles, including

- A left-turning vehicle interacting with an oncoming through vehicle ("left and oncoming");
- A left-turning vehicle interacting with a pedestrian crossing the approach onto which the vehicle is turning ("left and pedestrian");
- A left-turning vehicle hesitating or starting and then stopping suddenly when presented with a green-ball signal and no oncoming traffic or with a green-arrow signal ("indecision left"); and
- A left-turning vehicle crossing the stop bar and entering the intersection on a red-ball signal ("run red left").

Table 3 shows that numbers of conflicts sufficient for analysis were recorded during the periods of observation for almost every conflict type at each intersection. Table 3 also shows that the numbers of left-turning vehicles were very similar between members of the urban and suburban diamond pairs, and were quite different for members of the downtown pair. The conflict rates shown in Table 3 (conflicts per left-turning vehicle) were of reasonable magnitude, ranging from just under 4 percent to just under 0.4 percent.

The largest difference between leading and lagging sequences in Table 3 was for the left and pedestrian conflicts at the downtown pair, where the leading sequence was associated with three times as many conflicts and six times as great a conflict rate as the lagging sequence. In most cases at the leading site, these left and pedestrian conflicts happened when pedestrians stepped off the curb and into the approach to which left-turning vehicles were destined upon seeing a red signal for the cross-street (ignoring the "don't walk" signal). This result agrees with findings from the literature (*5*) and was considered in developing guidelines for left-turn signals.

Table 3 also shows that the lagging sequence intersection of the suburban diamond pair was associated with a significantly lower rate of run red left conflicts (at the 0.05 level) than the leading sequence intersection. Many times at the leading sequence intersection, three vehicles were observed

TABLE 3 LEFT-TURN CONFLICT RESULTS

Conflict type	Inter-section	Number of conflicts	Number of left turns	Proportion of left turns in conflicts	Significant at 0.05?
Left and ped.	Dntn-lag	11	1828	.006	Yes
	Dntn-lead	33	892	.037	
Left and oncoming	Dntn-lag	23	1828	.013	Yes
	Dntn-lead	24	892	.027	
Indeci-sion left	Dntn-lag	30	1828	.016	No
	Dntn-lead	13	892	.015	
Run red left	Dntn-lag	10	1828	.006	No
	Dntn-lead	4	892	.004	
Left and oncoming	Urb-lag	9	1073	.008	Yes
	Urb-lead	22	1022	.022	
Indeci-sion left	Urb-lag	24	1073	.022	No
	Urb-lead	16	1022	.016	
Run red left	Urb-lag	9	1073	.008	No
	Urb-lead	7	1022	.007	
Left and oncoming	Sub-lag	17	1322	.013	No
	Sub-lead	16	1044	.015	
Indeci-sion left	Sub-lag	48	1322	.036	Yes
	Sub-lead	18	1044	.017	
Run red left	Sub-lag	5	1322	.004	Yes
	Sub-lead	15	1044	.014	

making left turns after opposing traffic had begun to stop for the yellow-ball signal (i.e., three "sneakers"), with the third vehicle entering the intersection with the red-ball signal showing. There was generous supply of candidates for this behavior at the leading intersection because many vehicles wanting to make left turns joined the queue during the permissive phase of the cycle and were still in the queue as the permissive phase was ending. By contrast, at the lagging sequence intersection, the available supply of left-turning vehicles was almost always cleared on the green-arrow signal so fewer vehicles were available to run the red signal.

Another important result shown in Table 3 is that the lagging sequence was associated with significantly lower rates of left and oncoming conflicts (at the 0.05 level) than the leading sequence at the downtown and urban pairs of intersections. Two alternate explanations for these differences were available based on the data. First, the number of opposing vehicles recorded at the lagging intersection downtown was 6,947 versus 3,285 at the leading intersection downtown; 6,634 opposing vehicles were recorded at the lagging urban intersection versus 3,590 at the leading urban intersection. Thus, vehicles turning left at the lagging intersections may have had fewer opportunities to turn on the green-ball signal and, therefore, fewer opportunities to be involved in left and oncoming conflicts. This possibility was tested by comparing the conflict rates at the leading and lagging sequence intersections for 15-min periods with similar oncoming volumes. The tests showed that the lower oncoming volumes at the leading intersections may account for some but not all of the difference in conflict rates between leading and lagging signals. For the downtown pair during periods of similar oncoming volumes, the lagging sequence intersection had a significantly lower rate than the leading sequence intersection. For the urban pair during periods of similar oncoming volumes, the lagging intersection had a lower rate, but the difference was not significant.

The second explanation for the lower left and oncoming conflict rates at the lagging intersections in the urban and downtown pairs was the tendency at the leading intersections for left-turning vehicles to try to enter the intersection immediately after the yellow-arrow signal had ceased as if they still had the right-of-way. These "time stealers" then interacted with the more forthright of the oncoming vehicles, which had just received the green-ball signal. Examination of the descriptions of particular conflicts revealed that time stealers accounted for most of the difference in conflict rates between the leading and lagging downtown and urban intersections. There were a number of time stealers at the leading suburban diamond intersection as well, but the lagging intersection of that pair had an abundance of left and oncoming conflicts by indecisive left-turning vehicles and the two effects canceled each other in the final statistics.

Indecision conflicts accounted for the remaining significant difference between leading and lagging intersections shown in Table 3. The lagging intersection was associated with a higher rate of indecision conflicts than the leading intersection at all three intersection pairs, and the difference at the suburban diamond pair was significant at the 0.05 level. Examination of the data revealed that virtually all of the indecision conflicts, whether by a left-turning or other vehicle, occurred at the beginning of a signal phase. The number of signal cycles, rather than the number of vehicles observed, may have been the more appropriate available variable with which to compute a conflict rate. Therefore, the indecision conflict rates per signal cycle were computed; they confirm that it was the lagging sequence that was associated with higher indecision conflict rates, including significantly higher rates for the indecision left conflicts at the downtown and suburban diamond pairs.

Two basic reasons emerged to explain the generally higher rates of indecision conflicts at lagging sequence intersections. First, left-turning vehicles that received a lagging green arrow were hesitant to begin a turn until it was absolutely clear that oncoming traffic was going to stop. This was especially true at the suburban diamond location where the speeds of oncoming vehicles were relatively high. These high speeds sometimes led to false starts by left-turn vehicles, rapid decelerations by vehicles behind the left-turn queue leader, horn honking, and other unusual behavior. Second, drivers of left-turning and other vehicles often seemed surprised by a lagging signal sequence, and sometimes committed false or late starts upon receiving the right-of-way. Considering that there are very few lagging sequences in Indiana, some motorist surprise is understandable.

ACCIDENTS

For this project, accident data were used to help evaluate the relative safety of intersections with leading left-turn sequences and similar intersections with lagging signal sequences. Fourteen intersection approaches with lagging sequences (i.e., all Indiana intersections with lagging sequences for which data were available) were compared to 15 approaches with leading sequences. Almost all of the lagging sequence approaches and all of the leading sequence approaches were at intersections where a two-way street met a one-way street. All intersections studied had fixed-time signals, and most were in downtown areas. Indiana Department of Transportation accident records from 1985 through 1988 were used during the study, with traffic volume data from various sources to obtain accident rates for comparison. Only accidents involving a vehicle turning left from an approach with a left-turn signal of interest were analyzed.

Table 4 summarizes the reported accidents for the leading and lagging intersection sets. Accidents were more frequent and occurred at a greater rate at intersections with leading sequences, though the difference between leading and lagging sequences was not large for left-turn accidents per left-turn vehicle or left-turn accidents per total vehicle (i.e., all vehicles entering the intersection). The difference for the former was not significant at the 0.05 level; the difference for the latter was significant at the 0.05 level using the Z-test for proportions. Extreme caution should be used before basing left-turn sequence policy on such a small difference in accident rates between small samples of relatively homogeneous intersections.

The accident data in Table 4 were analyzed for relationships to several other accident variables. The variation of rates at leading and lagging sequence intersections with left-turn volume, with pavement and light conditions at the time of the accident, and with collision type were all investigated. In all three cases, no significant relationship was found. The severity of accidents in the leading and lagging intersection sets was

TABLE 4 LEAD AND LAG SET ACCIDENT DATA SUMMARY

Statistic	Lagging signals	Leading signals
Number of Indianapolis intersections	9	7
Number of intersections in other cities	5	8
Left turn accidents	44	69
Left turn volume, millions	56	74
Total intersection volume, millions	718	693
Accidents per million left turn vehicles	0.8	0.9
Accidents per million total vehicles	0.06	0.09

also investigated and was found to differ between the sets. Twenty-five accidents at the leading sequence intersections (35 percent) caused one or more reported personal injuries. In contrast, only three of the accidents at the lagging sequence intersections (7 percent) resulted in one or more reported personal injuries. This difference was found to be highly significant at the 0.05 level using a chi-square test.

Another general conclusion that could be drawn from Table 4 is that the number of left-turn accidents reported per intersection per year was relatively low regardless of the signal sequence. Over 4 years, 113 left-turn accidents were recorded at 29 intersection approaches, for a rate of just under one accident per approach per year. Because of a higher sample size and fewer uncontrolled factors, this conclusion has a much higher likelihood of being generally true than the conclusion discussed earlier regarding the difference between leading and lagging sequences. One of the consequences of the relatively low number of reported accidents per approach per year is that a large sample of intersections would be necessary in any future extensive evaluation of leading and lagging sequences or other left-turn alternatives using accidents. In addition, modest changes in the overall traffic safety picture of a region are all that can be expected from even the most widespread left-turn safety treatment programs if the number of accidents reported before the programs begins is low.

SIMULATIONS

The relationship of left-turn signal sequence to delay- and safety-related variables was investigated during this research using a series of experiments with the 1986 version of the NETSIM traffic-flow simulation model. NETSIM was chosen for this research because it is stochastic, microscopic, and supported by FHWA. NETSIM was also desirable because it can model an entire network of streets and intersections.

Five separate experiments were run with NETSIM, including experiments on intersections with four approaches, on intersections with three approaches, and on diamond interchanges. These experiments measured the utilization of the various signal phases by left-turn vehicles and used actual intersection data for inputs. Thirty-minute simulation runs of traffic flow near an intersection with a certain type of left-turn signal and other controlled variables were studied. Many factors were kept constant throughout the experiments to avoid bias. The intent in building models with NETSIM was to provide a fair test of leading and lagging sequences under conditions that were representative of those at intersections in Indiana. The Signal Operations Analysis Package (SOAP) was used to obtain signal-timing parameters throughout the experiments. A left-turn gap-acceptance distribution based on data collected for this project was used in NETSIM throughout the experiments. Comparisons of data collected for this project to NETSIM output, along with the long record of NETSIM in similar research and other recent validation efforts, demonstrated that the model produced reasonable results.

The five experiments were designed and run as factorials. Analysis of variance and Student-Newman-Keuls means tests were used to draw conclusions from the data. The type of left-turn signal was varied in each experiment. The volume of left-turn traffic, the volume of through traffic, and the type of progression on the major street was varied in all experiments except the actual intersection experiment. The desired approach speed and the type of signal equipment (i.e., fixed-time or actuated) were varied in the four-approach experiment, the desired approach speed was varied in the utilization of signal phases experiment, and the type of signal equipment was varied in the diamond interchange experiment. Only fixed-time signals were modeled during the three-approach and the utilization of signal phases experiments. Three different intersections and five different time periods (morning peak, midday, evening peak, overnight, and other hours) were used in the actual intersections experiment. Volume levels used in the experiments were based on peak-hour volume data from random samples of intersections in Indiana with left-turn signals. The volume levels used were generally moderate, causing nearly saturated conditions only when the combination of the highest-volume classes with protected signals was modeled.

Data summarizing the relationships between the delay-related measures of effectiveness and the various left-turn signal types tested for each experiment are shown in Table 5. The largest experiment involved intersections with four approaches; it showed that protected-permissive signals caused slightly more delay, stopped delay, and stops than permissive-protected signals. No significant difference between protected-lagging and protected-leading signals was detected. The experiment on intersections with three approaches was highlighted by the fact that there was little difference between the protected-permissive and permissive-protected signals in delay or stopped delay, but the latter caused significantly fewer stops per vehicle. A variation on this experiment demonstrated the sensitivity of the lead and lag decision to the time in the signal cycle that the progression band arrived at the left-turn signal. The experiment on diamond interchanges documented the superiority of lagging over leading schemes in terms of delay and stops. The results for the delay-related measures of effectiveness for the utilization of signal phases experiment were very similar to the results for the three-approach experiment. The difference between leading and lagging for mean stops per vehicle was significant at the 0.05 level, but there was no significant difference between leading and lagging for the delay-related measures. Finally, the actual intersection experiment confirmed the relative efficiency of the lagging sequence for a limited range of intersections. During the experiments, all other main effects of factors (desired approach speed, signal type, progression class, left-turn volume, through volume, and left-turn signal type) and all interactions between any two of the factors were also investigated. The results are given in detail elsewhere (*1*).

Table 5 also shows the trend seen throughout the simulation experiments that permissive signals were associated with the least delay and the fewest stops, while protected signals were associated with the highest delay and the most stops. Only for the highest-volume levels during the diamond interchange experiment did the permissive signal produce more delay than a competitor signal and did the protected-lagging signal produce less delay than the protected-permissive signal. For all other combinations of volume levels and other variables tested, the rankings between types of left-turn signals on the basis of delay and stops remained unchanged. It should be noted that the measures of effectiveness in Table 5 were computed for all vehicles on the approaches to the intersection being simulated with left-turn signals, not just left-turn vehicles, and that delay and stop data for left-turn vehicles alone may present a different picture.

Table 6 shows results of the utilization of signal phases experiment. The lagging signal had significantly more left turns completed on

- The green-ball indication,
- The yellow-ball indication,
- Green indications, and
- Ball indications.

The leading signal had significantly more left turns on

- The yellow-arrow indication,
- The red indication,
- The last yellow indication before the red, and

TABLE 5 SUMMARY OF RELATIONSHIP BETWEEN MEASURES OF EFFECTIVENESS AND LEFT-TURN SIGNAL TYPES IN FIVE SIMULATION EXPERIMENTS

Experiment	Left turn signal	Mean delay, sec/veh	Mean stopped delay, sec/veh	Mean stops per vehicle
Four Approaches	Permissive	10.9	5.2	0.35
	Permissive-protected	13.5	7.4	0.43
	Protected-permissive	14.7	8.5	0.46
	Protected-lagging	19.4	12.8	0.54
	Protected-leading	19.9	13.3	0.56
Three Approaches	Permissive	7.2	4.0	0.27
	Permissive-protected	10.4	6.8	0.35
	Protected-permissive	10.4	6.8	0.36
Diamond Interchange	Permissive	11.9	7.0	0.30
	Permissive-protected	13.7	7.7	0.38
	Protected-permissive	17.3	10.5	0.45
	Protected-lagging	18.4	11.8	0.54
	Protected-leading	23.0	15.5	0.62
Utilization of signal phases	Permissive-protected	17.0	10.3	0.48
	Protected-permissive	16.9	10.4	0.49
Actual Inter-sections	Permissive-protected	12.4	No data	0.44
	Protected-permissive	16.5	No data	0.58

TABLE 6 SUMMARY OF ANOVA RESULTS ON UTILIZATION OF SIGNAL PHASES BY LEFT-TURN VEHICLES

Interval(s)	Mean value of percent of left turns on the interval(s)		Significance probability for signal type
	Permissive-protected	Protected-permissive	
Green ball	33	23	0.0001
Yellow ball	31	28	0.0150
Green arrow	25	20	0.0755
Yellow arrow	8	15	0.0008
Red	3	14	0.0001
Green (ball plus arrow)	58	44	0.0001
Yellow (ball plus arrow)	39	43	0.0945
Ball (green plus yellow)	64	51	0.0001
Arrow (green plus yellow)	32	35	0.1424
Last yellow before red	8	28	0.0001
Last yellow before red plus red	11	42	0.0001

- The last yellow indication before the red plus the red indication.

The magnitude of the difference noted above ranged from 3 percent to 31 percent in the case of the difference for the last yellow plus the red indications. There was no statistical difference between the signal levels for the percent of left turns on the green-arrow indications, yellow indications, or arrow indications.

The trend that emerged from Table 6 was that, for the conditions tested, lagging meant more turns on the green-ball and yellow-ball indications, while leading meant more turns near the end of the signal cycle. This trend helped explain the advantages lagging signals enjoyed in delay-related measures of effectiveness during various simulation experiments. The implications of this trend for safety are less obvious, however. The only well-established relationship between the utilization of various left-turn phases and safety documented in the literature review held that safety increased as the percent of left turns made on arrow indications increased. Because there was no difference in the percent of left turns made on the green-arrow indication or on arrow indications between leading and lagging, however, neither can be said to be safer based on this relationship.

Regarding the safety implications of the trend in the results noted above, there are two possible reasons that left turns which are made during the green-ball or yellow-ball indications at a lagging signal may be safer than turns at the end of a leading signal cycle. First, the leading turns at the end of the cycle could conflict with oncoming traffic and with cross-street traffic jumping into the intersection early, whereas the lagging turns on a ball indication in midcycle could conflict with cross-street drivers only when those drivers were making highly illegal maneuvers. Second, drivers contemplating left turns at the end of the leading cycle could feel more pressure to turn (or subject themselves and other drivers in the queue to lengthy delays) than drivers contemplating turns on a ball indication in the lagging cycle. More pressure to turn could result in an acceptance of greater risks. There are no data to substantiate these two reasons; therefore, a cautious outlook was assumed in incorporating this trend into the guidelines on leading and lagging sequences.

The magnitudes of all the differences summarized were documented and may be useful to engineers making traffic signal decisions. The results from the simulations should be used within the context in which they were produced. The limitations of the NETSIM model should be factored into any decision based on these results. Other important limitations of the experiments were biases against protected-permissive signals in the four-approach intersection experiment (no phase overlap at actuated signals) and in the diamond interchange experiment (no "four-phase" operation).

GUIDELINES

Based on these results, guidelines were developed on the use of leading and lagging phase sequences in Indiana. The guidelines are generally applicable at intersections similar to those which were tested during the research. The major features that analysts should check before applying the guidelines include

- Three- or four-leg intersections on four-lane arterials;
- Intersection angles of approximately 90 degrees;
- Narrow or nonexistent medians;
- Single left-turn lanes;
- Adequate left-turn lane lengths (spillback is rare);
- Relatively unaggressive driver population (gap-acceptance distribution about 0.5 to 1.0 sec more relaxed than drivers in Washington, D.C., no left-turn "jumpers," a maximum of two left-turn "sneakers");
- Light to medium-heavy (but still unsaturated) volumes;
- Balanced flow between the directions on the street with the left-turn signals; and
- Simple two- or three-phase signal control at diamond interchanges.

If conditions at an intersection where a leading versus lagging decision is pending differ greatly from the above conditions, the guidelines should not be directly applied (although the research methods and results may still be of some use). Details on the limitations of the data collected are provided elsewhere (*1*).

The guidelines for choice of leading or lagging left-turn phase sequence when some form of left-turn phasing is warranted are as follows:

1. In coordinated signal systems, use should be made of any phasing sequence on a particular approach that will maximize the through bandwidth.
2. Lagging instead of leading phase sequences should be used at isolated signals serving heavy pedestrian traffic.
3. Lagging instead of leading phase sequences should be used at isolated diamond interchanges or one-way pairs.
4. Permissive-protected signals should be used instead of protected-permissive signals where there is a history of or a potential for left-turn and oncoming vehicle accidents but where protected-leading or protected-lagging signals are not feasible alternatives.
5. Permissive-protected signals should be used instead of protected-permissive signals at isolated intersections with four approaches if the signals are fixed-time or incapable of overlapping phases.
6. Intersections where one approach has permissive left turns and the opposing approach has a lagging sequence must be checked for the possibility of trapping. If trapping is possible the phasing should be changed to eliminate that possibility by eliminating the permissive turn (making it protected-only or prohibiting the turn), by eliminating the lagging sequence, by ensuring that the opposing approaches both have lagging sequences with left-turn phases that begin simultaneously, or by using some other phasing measure.
7. At intersections where the above guidelines do not fully answer the question of lead or lag, the existing phase sequence should not be changed or, if the signal or left-turn protected phase is new, the phase sequence which is most common at similar sites in the area should be used.

Figure 1 is a flow chart based on the guidelines to aid in making phase sequence decisions at individual intersections.

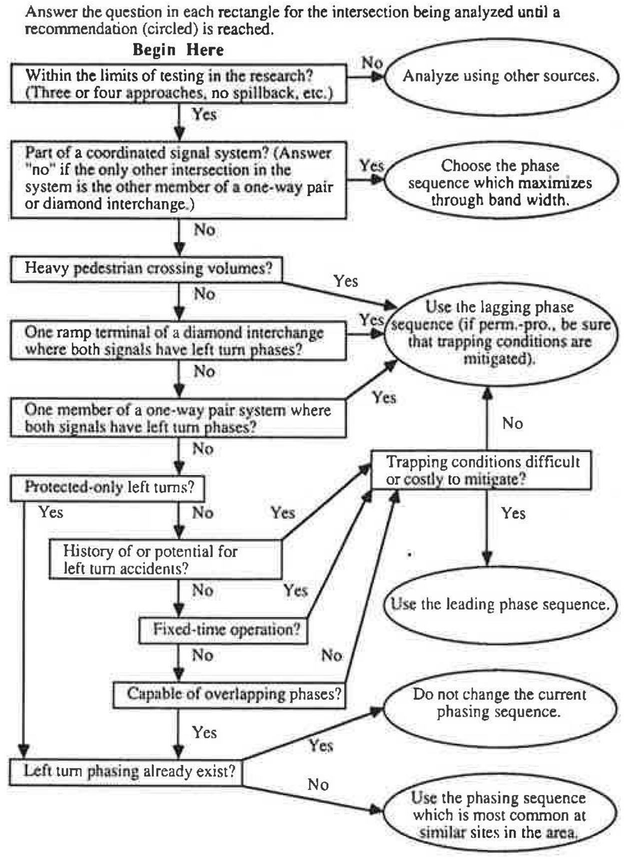

FIGURE 1 Flowchart for decisions on phasing sequence of individual intersections.

Two points must be kept in mind regarding the above guidelines and Figure 1. First, although the guidelines suggest that the signal sequence at a particular intersection in a coordinated system should be chosen to maximize the bandwidth (Point 1), uniformity of signal sequence along an arterial or in a given area may be desirable. When more data are available that show that a variety of signal sequences along an arterial or in a given area does not pose a hazard, policies that encourage more flexible signal sequence decisions may be warranted. Second, the guideline that encourages permissive-protected over protected-permissive signals when left and oncoming accidents have occurred or could occur (Point 4) is based on conflict, simulation, and other data pertaining to the end of the signal cycle (i.e., during and immediately after the yellow-ball indication for the protected-permissive signal). If there is a history of or potential for left and oncoming accidents during other parts of the signal cycle, this guideline does not apply, and other sources should be used to make decisions on the signal sequence in that case.

The guidelines have been developed with caution, and changes in phase sequence are called for only in situations where another phase sequence has been proven clearly superior. This cautious approach is appropriate because of the litigious climate surrounding traffic control decisions and the likelihood that accidents may increase immediately after a change in traffic control, such as from lead to lag. If future testing shows that the immediate negative impacts of changes in signal sequence are small, a more active role in changing intersections with the leading phase sequence to the lagging phase sequence should be assumed.

FUTURE WORK

Several other aspects of the leading and lagging issue deserve attention. Foremost on the agenda of future work should be a before-and-after field test of the guidelines developed during this research using both safety- and delay-related measures of effectiveness. A continuous effort over a period of several years is needed to conduct a proper evaluation.

Another area deserving future effort is the simulation of the use of the various signal phases. This portion of the research yielded interesting results, but the cumbersome data collection method limited the amount of data that could be collected. In addition, the question of whether it is better policy to encourage left turns on the green-ball signal or at the end of the signal cycle should be explored. A comprehensive examination of the utilization of signal phases—including alterations to NETSIM or some other traffic simulation model, a thorough validation of the improved model, an experiment comparing phasing alternatives, and a field or accident data collection effort sufficient to convert the simulation results into an estimate of accident reductions—would be a step forward for the traffic community.

Another useful extension of this study would be a series of similar simulation experiments with more varied volume levels. Modeling volumes typical of saturated conditions, unbalanced flows, or the middle of the night may yield some interesting data which could easily extend the scope of the guidelines for leading and lagging left-turn signal phasing.

ACKNOWLEDGMENTS

The research presented in this paper was performed as part of a project titled "Evaluation of Leading Versus Lagging Left-Turn Signal Phasing and All-Red Clearance Intervals" by the School of Civil Engineering of Purdue University for FHWA and the Indiana Department of Transportation. Carl Tuttle was the project advisor from the Indiana Department of Transportation and Ed Ratulowski was the project advisor from FHWA.

REFERENCES

1. J. E. Hummer. *An Evaluation of Leading Versus Lagging Left Turn Signal Phasing*. Ph.D. thesis. Purdue University, West Lafayette, Ind., Aug. 1989.
2. B. W. McKay. Lead and Lag Left Turn Signals. *Traffic Engineering*, April 1966, pp. 50–57.
3. *Guidelines for Signalized Left Turn Treatments*. Report FHWA-IP-81-4, FHWA, U.S. Department of Transportation, 1981.
4. S. L. Cohen and J. R. Mekemson. Optimization of Left-Turn Phase Sequence on Signalized Arterials. In *Transportation Research Record 1021*, TRB, National Research Council, Washington, D.C., 1985, pp. 53–58.
5. H. E. Hawkins. A Comparison of Leading and Lagging Greens in Traffic Signal Sequence. *Proc., 33rd Annual Meeting of ITE*, Toronto, Ontario, Canada, 1963, pp. 238–242.
6. P. Basha and D. Anderson. Authorize Six Month Trial Period of Lagging Left Turn. Report to Mayor and City Council, City of Scottsdale, Ariz., Feb. 29, 1988.
7. Florida Section, ITE. Left Turn Phase Design in Florida. *ITE Journal*, Sept. 1982, pp. 28–35.
8. P. Basha. Lagging Left Turn Arrow Test Results. Memo to Thomas J. Wilson, Acting City Manager, City of Scottsdale, Ariz., Aug. 25, 1988.
9. C. J. Messer, R. H. Whitson, C. L. Dudek, and E. J. Romano. A Variable Sequence Multiphase Progression Optimization Program. In *Highway Research Record 445*, HRB, National Research Council, Washington, D.C., 1973.
10. Tucson's Lag Left Summary. Traffic Engineering Division, City of Tucson, Ariz., Undated.
11. M. Parker and C. V. Zegeer. *Traffic Conflict Techniques for Safety and Operations, Engineer's Guide*. Report FHWA-IP-88-026. FHWA, U.S. Department of Transportation, 1988.

The views expressed in this paper are those of the authors and do not necessarily reflect the views of Purdue University, the Indiana Department of Transportation, or FHWA. The authors assume sole responsibility for the accuracy of the data and conclusions presented in this paper.

Publication of this paper sponsored by Committee on Traffic Control Devices.