Executive Summary

AN EVALUATION OF LEADING VERSUS LAGGING LEFT TURN SIGNAL PHASING

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TO: Harold L. Michael, Director
Joint Highway Research Project

FROM: Kumares C. Sinha, Research Engineer
Joint Highway Research Project

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Project: C-36-17QQ
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Attached is the Final Report on the first part of the HPR Part II Study, "An Evaluation of Leading Versus Lagging Left Turn Signal Phasing and All Red Clearance Intervals." This report presents the research findings on leading vs. lagging left turn signal phasing. A set of guidelines for the use of leading and lagging left turn signal sequences is also included. The research for this report was conducted by Joseph E. Hummer under the direction of me and Prof. Robert E. Montgomery.

This report is forwarded for review, comment and acceptance by the INDOT and FHWA as partial fulfillment of the objectives of the project.

Respectfully submitted,

[Signature]

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Research Engineer

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An Evaluation of Leading Versus Lagging Left Turn Signal Phasing

Executive Summary

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Purdue University
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This research project includes an evaluation of leading vs. lagging left turn signal phasing and all red clearance intervals. This report presents the results of the part of the research involving leading vs. lagging left turn signal sequences. It was found that, in general, lagging sequences at selected types of intersections can provide safety and delay advantages over the (more common in Indiana) leading sequences. Guidelines were developed on the basis of research results for the use of the leading and lagging signal sequences in Indiana.
AN EVALUATION OF LEADING AND LAGGING LEFT TURN SIGNAL PHASING

EXECUTIVE SUMMARY

Introduction

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 most common type of signal scheme accommodating left turns in the United States remains the permissive scheme. 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, by which the green arrow is given to left turning vehicles after the through movements have been serviced,

- protected-permissive, by 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, by which permissive left turns are allowed first in the cycle and protected left turns are accommodated later in the cycle.

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

Research has been conducted on a number of questions about 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 decision on tradition, hearsay, or feeling without any factual evidence. The intent of the present research 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.

There are large potential benefits from an answer to the leading and lagging sequence question. If the guidelines mean one less second of delay per vehicle at 200 typical intersections, about one million hours per year will have been saved. Large fuel and pollution savings would also result from such a reduction in vehicle delay. Additional benefits could accrue to InDOT and to taxpayers if construction projects to add capacity at intersections are delayed or scaled down because of the changes in signal sequence. Also, while the number of accidents involving left turning vehicles per intersection is relatively small, there is the potential for the guidelines to result in accident savings as well.

**Purpose and Scope**

The primary purpose of the research described herein was to produce
guidelines for the use of leading and lagging left turn signal sequences, as discussed above. 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 from this project 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 above. Second, data collection activities were confined to Indiana to avoid geographical bias. Third, with one exception the research was concentrated on intersection types which 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 the interchanges are being signalized.

The major areas of potential concern relative to leading and lagging and other left turn issues which were explored in this research include motorist preferences and understanding, safety, and delay. All of these areas were addressed during the review of relevant past published research findings. Data on motorist preferences and understanding were gathered using 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 these different work elements were used to develop guidelines for the use of leading and lagging left turn signal phasing.

**Literature Review**

The literature on left turn phasing, especially the left turn phase sequence, was reviewed in this project and provided information on delay, safety, and motorist preferences. For delay, no clear trend emerged between leading and lagging at isolated intersections. However, it was clear that a policy which allows the choice of lead or lag at individual approaches in a coordinated system with the aim of maximizing the through band width decreases delay.

Concern for the safety of drivers and passengers in vehicles which become "trapped" in an intersection while waiting to make a left turn has been consistent in the literature. Trapping occurs to a vehicle making a left turn on an approach with a permissive signal where the opposite approach has a permissive-protected signal. When the permissive signal goes to yellow and then to red (in order 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. The apparent danger of trapping virtually mandates that any approach with a permissive-protected signal must be accompanied by a protected left turn phase (or prohibited left turns) on the opposite approach and that if the opposite approach has permissive-protected phasing the protected phases must start simultaneously. If trapping conditions are not present, several reasons why lagging sequences might lead to fewer accidents than leading sequences at certain types of intersections were revealed in the literature. Data to evaluate the relative safety of the signal sequences were sparse, however.

The only study reviewed which examined motorist preferences for lead or lag showed a great deal of support for the lagging sequence. The sparse data available on the question of motorist confusion when facing a change in signal sequences or a variety of sequences in close proximity showed few such problems.

The plentiful literature on the tradeoffs between permissive, protected, and either protected-permissive or permissive-protected signals was also reviewed during the project. The well-known general trend that accidents increase and delay decreases as the level of left turn protection decreases was documented. 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 survey of Indiana drivers was conducted for this project during four days of 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 to the survey. Despite the fact that the survey was conducted in one place over a four-day span, responses were received from a wide variety of different 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 with the context of the survey (i.e., the tendencies of Indiana drivers and highways in 1988, etc.) in mind.

The leading sequence was preferred by 248 respondents, the lagging sequence was preferred by 59 respondents, and 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, with a summary of 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 urban or rural county of residence variable was found to be related to the choice of leading or lagging sequence, with people from rural counties expressing a preference more often for the lagging sequence. The annual miles driven variable 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 which 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") on the basis of motorist understanding. Finally, the protected signal was the most preferred signal because most respondents associated it with less confusion, while the permissive signal was the least preferred signal.
Table 1. Reasons for Preferences for Leading and Lagging Signal Sequences.

<table>
<thead>
<tr>
<th>Preference</th>
<th>Safer</th>
<th>Less Delay</th>
<th>Less Confusion</th>
<th>More Like Normal</th>
<th>Unsure or Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leading vs.</td>
<td>61</td>
<td>65</td>
<td>27</td>
<td>73</td>
<td>39</td>
</tr>
<tr>
<td>Lagging</td>
<td>11</td>
<td>17</td>
<td>11</td>
<td>10</td>
<td>11</td>
</tr>
</tbody>
</table>
Table 2. Relationships Between Preferences for Leading or Lagging Sequences and Various Independent Variables.

<table>
<thead>
<tr>
<th>Variable</th>
<th>Chi-square Value</th>
<th>Reason for Significant or Nearly Significant Relationship</th>
</tr>
</thead>
<tbody>
<tr>
<td>Age</td>
<td>.054</td>
<td>Younger drivers had no preference more often</td>
</tr>
<tr>
<td>Sex</td>
<td>.126</td>
<td>--</td>
</tr>
<tr>
<td>Urban or rural county of</td>
<td>.002</td>
<td>Rural residents preferred lagging more often</td>
</tr>
<tr>
<td>residence</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Annual miles driven</td>
<td>.056</td>
<td>Those driving less preferred lagging more often</td>
</tr>
<tr>
<td>Number of errors</td>
<td>.526</td>
<td>--</td>
</tr>
<tr>
<td>nine understanding questions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
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 for this project. 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, and because traffic conflict data can be collected in a relatively short period of time they are often used as a proxy for accident data.

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 besides 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. A "downtown" pair of intersections with many pedestrians and low vehicle speeds, an "urban" pair of intersections with few pedestrians and 30 to 35 mph speed limits, and a "suburban diamond" (i.e., at a diamond-type freeway interchange) pair with no pedestrians and 40 mph speed limits were studied. Data were gathered manually on all conflicts and unusual maneuvers which were witnessed by observers on two sides of a test intersection.

Table 3 provides the results of the conflict study for the four types of conflicts and unusual maneuvers which were most related to left-turning vehicles, including:
Table 3. Left Turn Conflict Results.

<table>
<thead>
<tr>
<th>Intersections</th>
<th>Conflict Type</th>
<th>Signal Sequence</th>
<th>No. of Conflicts</th>
<th>No. of Left Turns</th>
<th>Proportion or Left Turns in Conflicts</th>
<th>Difference Z Computed</th>
<th>Significant at 0.05?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downtown</td>
<td>Left and pedestrian</td>
<td>Lag</td>
<td>11</td>
<td>1828</td>
<td>.0060</td>
<td>-6.01</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Left and oncoming</td>
<td>Lag</td>
<td>23</td>
<td>1828</td>
<td>.0126</td>
<td>-2.69</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td>Indecision - left</td>
<td>Lag</td>
<td>30</td>
<td>1828</td>
<td>.0164</td>
<td>0.36</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lead</td>
<td>13</td>
<td>892</td>
<td>.0146</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lag</td>
<td>10</td>
<td>1828</td>
<td>.0055</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Run red - left</td>
<td>Lead</td>
<td>4</td>
<td>892</td>
<td>.0045</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lag</td>
<td>9</td>
<td>1073</td>
<td>.0084</td>
<td>-2.49</td>
<td>Yes</td>
</tr>
<tr>
<td>Urban</td>
<td>Left and oncoming</td>
<td>Lead</td>
<td>22</td>
<td>1022</td>
<td>.0215</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Indecision - left</td>
<td>Lag</td>
<td>24</td>
<td>1073</td>
<td>.0224</td>
<td>1.12</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lead</td>
<td>16</td>
<td>1022</td>
<td>.0157</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lag</td>
<td>9</td>
<td>1073</td>
<td>.0084</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Run red - left</td>
<td>Lead</td>
<td>7</td>
<td>1022</td>
<td>.0068</td>
<td>0.40</td>
<td>No</td>
</tr>
<tr>
<td>Suburban</td>
<td>Left and oncoming</td>
<td>Lead</td>
<td>17</td>
<td>1322</td>
<td>.0129</td>
<td>-0.51</td>
<td>No</td>
</tr>
<tr>
<td></td>
<td>Indecision - left</td>
<td>Lag</td>
<td>48</td>
<td>1322</td>
<td>.0363</td>
<td>2.80</td>
<td>Yes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lead</td>
<td>18</td>
<td>1044</td>
<td>.0172</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Run red - left</td>
<td>Lead</td>
<td>5</td>
<td>1322</td>
<td>.0038</td>
<td>-2.79</td>
<td>Yes</td>
</tr>
</tbody>
</table>
A left-turning vehicle interacting with an oncoming through vehicle (e.g., "left and oncoming"),

A left-turning vehicle interacting with a pedestrian crossing the approach onto which the vehicle is turning (e.g., "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 (e.g., "indecision left"), and

A left-turning vehicle crossing the stop bar and entering the intersection on a red ball signal (e.g., "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 suburban diamond pair, and quite different for members of the downtown pair. The conflict rates given in Table 3 (conflicts per left-turning vehicle) were of reasonable magnitude, ranging from just under four percent to just under 0.4 percent.

The largest difference between leading and lagging sequences seen 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 review
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 (at the 0.05 level) lower rate of run red left conflicts than the leading sequence intersection. Many times at the leading sequence intersection three vehicles were observed making left turns after opposing traffic had begun to stop for the yellow ball signal (e.g., three "sneakers"), with the third vehicle entering the intersection with the red ball signal showing. There was a 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 there were fewer vehicles available to run the red signal.

Another important result in Table 3 shows 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 6947 versus 3285 at the leading intersection downtown; 6634 opposing vehicles were recorded at the lagging urban intersection versus 3590 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-minute time 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 the lagging sequence intersection had a significantly lower rate than the leading sequence intersection. For the urban pair 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 caused by indecisive left-turning vehicles and the two effects cancelled each other in the final statistics.

Indecision conflicts accounted for the remaining significant difference between leading and lagging intersections seen 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 and confirm that it was the lagging sequence which 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 which 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 so 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 fifteen approaches with leading
sequences. Almost all the lagging sequence approaches and all 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 (InDOT) 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 shows a summary of the accident data 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 (i.e., all vehicles entering the intersection) vehicle. The difference for the former was not significant at the 0.05 level, while 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 also investigated and was found to differ between the sets. Twenty-five accidents at
Table 4. Lead and Lag Set Accident Data Summary.

<table>
<thead>
<tr>
<th>Signal Seq.</th>
<th>City</th>
<th>Intersection</th>
<th>Left Turn Accs.</th>
<th>Vol., millions</th>
<th>Accs. per mil. vehs.</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Lag</td>
<td>Indianapolis</td>
<td>Meridian @ 12th</td>
<td>1</td>
<td>3.4</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th @ Pennsylvania</td>
<td>1</td>
<td>1.5</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>16th @ Capitol</td>
<td>1</td>
<td>2.7</td>
<td>68</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Washington @ Illinois</td>
<td>2</td>
<td>5.1</td>
<td>86</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Washington @ Capitol</td>
<td>8</td>
<td>4.0</td>
<td>72</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Washington @ Penn.</td>
<td>3</td>
<td>4.3</td>
<td>56</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Washington @ Delaware</td>
<td>4</td>
<td>6.0</td>
<td>92</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lafayette @ I-65 NB Ramp</td>
<td>3</td>
<td>5.2</td>
<td>39</td>
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<tr>
<td></td>
<td></td>
<td>86th @ Keysten SB Ramp</td>
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<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Market @ Delaware</td>
<td>3</td>
<td>3.2</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South @ Delaware</td>
<td>1</td>
<td>3.2</td>
<td>46</td>
</tr>
<tr>
<td></td>
<td></td>
<td>South @ Pennsylvania</td>
<td>2</td>
<td>3.0</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td></td>
<td>86th @ Keysten NB Ramp</td>
<td>4</td>
<td>3.1</td>
<td>no data</td>
</tr>
<tr>
<td></td>
<td></td>
<td>86th @ I-465 SB Ramp</td>
<td>6</td>
<td>13.9</td>
<td>27</td>
</tr>
<tr>
<td></td>
<td></td>
<td>71st @ I-465 SB Ramp</td>
<td>3</td>
<td>12.9</td>
<td>22</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NB Newton @ 6th</td>
<td>8</td>
<td>3.6</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>ER 6th @ Newton</td>
<td>3</td>
<td>5.5</td>
<td>35</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Broadway @ Main</td>
<td>2</td>
<td>2.0</td>
<td>28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NB Main @ State</td>
<td>0</td>
<td>1.5</td>
<td>17</td>
</tr>
<tr>
<td></td>
<td></td>
<td>SB Portage @ Angela</td>
<td>5</td>
<td>6.9</td>
<td>43</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Collsx @ Main</td>
<td>4</td>
<td>6.5</td>
<td>51</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LaSalle @ Main</td>
<td>5*</td>
<td>5.8</td>
<td>71</td>
</tr>
<tr>
<td></td>
<td></td>
<td>LaSalle @ Michigan</td>
<td>12</td>
<td>2.7</td>
<td>58</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sample @ Main</td>
<td>6</td>
<td>4.1</td>
<td>54</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sample @ Michigan</td>
<td>15</td>
<td>1.7</td>
<td>61</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Madison @ Main</td>
<td>0</td>
<td>2.8</td>
<td>41</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Madison @ Jackson</td>
<td>0</td>
<td>1.1</td>
<td>38</td>
</tr>
<tr>
<td></td>
<td></td>
<td>T. Haute @ Cherry</td>
<td>6</td>
<td>7.5</td>
<td>72</td>
</tr>
<tr>
<td>Lead</td>
<td></td>
<td>Mean/Total All Lag Approaches</td>
<td>44</td>
<td>55.6</td>
<td>718</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Mean/Total All Lead Approaches</td>
<td>69</td>
<td>74.3</td>
<td>693</td>
</tr>
</tbody>
</table>

* Accidents were assigned arbitrarily here; they could have happened at LaSalle @ Main.
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 (seven 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 which occurred per intersection per year was relatively low regardless of the signal sequence. One-hundred and thirteen left turn accidents were recorded at 29 intersection approaches over four years, for a rate of just under one accident per approach per year. This conclusion has a much higher likelihood of being generally true than the conclusion discussed earlier regarding the difference between leading and lagging sequences because of a higher sample size and fewer uncontrolled factors. One of the consequences of the relatively low number of 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 occurring before the programs begin 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 NETSIM traffic flow simulation model. NETSIM was chosen for this research because it was stochastic, microscopic, and supported by the Federal
Highway Administration (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, and on intersections with three approaches, on diamond interchanges, measuring the utilization of the various signal phases by left turn vehicles and using 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 which were representative of those at intersections in Indiana. The Signal Operations Analysis Package (SIGOP) 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. 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 modelled.

Data summarizing the relationships between the delay-related measures of effectiveness and the various left turn signal types tested for each experiment are given in Table 5. The largest experiment involved intersections with four approaches, and showed that protected-permissive signals caused slightly more delay, stopped delay, and stops then permissive-protected signals. No actual differences 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 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
Table 5. Summary of Relationship Between MOE’s and Left Turn Signal Types in the Five Simulation Experiments.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Left Turn Signal</th>
<th>Mean Delay, sec/veh</th>
<th>Mean Stopped Delay, sec/veh</th>
<th>Mean Stops per Vehicle</th>
</tr>
</thead>
<tbody>
<tr>
<td>Four approaches</td>
<td>Permissive</td>
<td>10.9</td>
<td>5.2</td>
<td>.35</td>
</tr>
<tr>
<td></td>
<td>Permissive-protected</td>
<td>13.5</td>
<td>7.4</td>
<td>.43</td>
</tr>
<tr>
<td></td>
<td>Protected-permissive</td>
<td>14.7</td>
<td>8.5</td>
<td>.46</td>
</tr>
<tr>
<td></td>
<td>Protected-lagging</td>
<td>19.4</td>
<td>12.8</td>
<td>.54</td>
</tr>
<tr>
<td></td>
<td>Protected-leading</td>
<td>19.9</td>
<td>13.3</td>
<td>.56</td>
</tr>
<tr>
<td>Three approaches</td>
<td>Permissive</td>
<td>7.2</td>
<td>4.0</td>
<td>.27</td>
</tr>
<tr>
<td></td>
<td>Permissive-protected</td>
<td>10.4</td>
<td>6.8</td>
<td>.35</td>
</tr>
<tr>
<td></td>
<td>Protected-permissive</td>
<td>10.4</td>
<td>6.8</td>
<td>.36</td>
</tr>
<tr>
<td>Diamond interchange</td>
<td>Permissive</td>
<td>11.9</td>
<td>7.0</td>
<td>.30</td>
</tr>
<tr>
<td></td>
<td>Permissive-protected</td>
<td>13.7</td>
<td>7.7</td>
<td>.38</td>
</tr>
<tr>
<td></td>
<td>Protected-permissive</td>
<td>17.3</td>
<td>10.5</td>
<td>.45</td>
</tr>
<tr>
<td></td>
<td>Protected-lagging</td>
<td>18.4</td>
<td>11.8</td>
<td>.54</td>
</tr>
<tr>
<td></td>
<td>Protected-leading</td>
<td>23.0</td>
<td>15.5</td>
<td>.62</td>
</tr>
<tr>
<td>Utilization of signal phases</td>
<td>Permissive-protected</td>
<td>17.0</td>
<td>10.3</td>
<td>.48</td>
</tr>
<tr>
<td></td>
<td>Protected-permissive</td>
<td>16.9</td>
<td>10.4</td>
<td>.49</td>
</tr>
<tr>
<td>Actual intersections</td>
<td>Permissive-protected</td>
<td>12.4</td>
<td>no data</td>
<td>.44</td>
</tr>
<tr>
<td></td>
<td>Protected-permissive</td>
<td>16.5</td>
<td>no data</td>
<td>.58</td>
</tr>
</tbody>
</table>
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 lagging sequence for a limited range of intersections. During the experi-
ments, 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 investi-
gated.

Table 5 also demonstrates the trend which was seen throughout the simula-
tion 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 dia-
mond 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 provides results for the utilization of signal phases experiment.
The lagging signal had significantly more left turns completed on:
Table 6. Summary of ANOVA Results on Utilization of Signal Phases by Left Turn Vehicles.

<table>
<thead>
<tr>
<th>Interval(s)</th>
<th>Mean Value of Percent of Left Turns on the Interval(s) for Signal Type</th>
<th>Significance Probability for Signal Type</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Permissive-protected</td>
<td>Protected-permissive</td>
</tr>
<tr>
<td>Green Ball</td>
<td>33</td>
<td>23</td>
</tr>
<tr>
<td>Yellow Ball</td>
<td>31</td>
<td>28</td>
</tr>
<tr>
<td>Green Arrow</td>
<td>25</td>
<td>20</td>
</tr>
<tr>
<td>Yellow Arrow</td>
<td>8</td>
<td>15</td>
</tr>
<tr>
<td>Red</td>
<td>3</td>
<td>14</td>
</tr>
<tr>
<td>Green (ball plus arrow)</td>
<td>58</td>
<td>44</td>
</tr>
<tr>
<td>Yellow (ball plus arrow)</td>
<td>39</td>
<td>43</td>
</tr>
<tr>
<td>Ball (green plus yellow)</td>
<td>64</td>
<td>51</td>
</tr>
<tr>
<td>Arrow (green plus yellow)</td>
<td>32</td>
<td>35</td>
</tr>
<tr>
<td>Last yellow before red</td>
<td>8</td>
<td>28</td>
</tr>
<tr>
<td>Last yellow before red plus red</td>
<td>11</td>
<td>42</td>
</tr>
</tbody>
</table>
- 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
- the last yellow indication before the red plus the red indication.

The magnitude of the differences noted above ranged from three 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 indication, yellow indications, or arrow indications.

The trend which emerged from Table 6 was that, for the conditions tested, lagging meant more turns on the green 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 MOE's 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 which were made on arrow indications increased. Since 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 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 mid-cycle 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 the above 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 above were documented and may be useful to engineers making traffic signal decisions. The results from the simulations should be used with the context in which they were produced in mind. 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).
Based on the results summarized above the following guidelines were developed on the use of leading and lagging phase sequences in Indiana when some form of left turn phasing is warranted:

1. In coordinated signal systems, use should be made of any phasing sequence on a particular approach that will maximize the through band width.

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 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. Permissive-protected signals should not be used at an approach unless left turns from the opposite approach are prohibited, protected with protected-lagging or protected-leading signals, or made with a permissive-protected signal with the protected intervals starting for the opposing sides simultaneously.
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 contains a flow chart based on the guidelines to aid in making phase sequence decisions at individual intersections.

Several points must be kept in mind regarding the above guidelines and Figure 1. First, the guidelines should not be applied beyond the limits of testing in this research. Some of the more important limits include intersections with three or four approaches, left turn lanes on the streets with the left turn signals, two through lanes in the directions opposing that with the left turn signals, non-saturated traffic flow conditions, balanced flow between the directions on the streets with the left turn signals, negligible median widths on the streets with the left turn signals, negligible curves and grades on the streets with the left turn signals, and near 90-degree intersections. Second, 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 above), uniformity of signal sequence along an arterial or in a given area may be desirable. When more data are available which show that a variety of signal sequences along an arterial or in a given area does not pose a hazard, policies which encourage more flexible signal sequence decisions may be warranted. Finally, the guideline which encourages permissive-protected over protected-permissive signals when left and oncoming accidents have or could occur (point 4 above) is based on conflict, simulation, and other data from the end of the signal cycle (i.e., during and
Answer the question in each rectangle for the intersection being analyzed until a recommendation (circled) is reached.

**Begin Here**

1. **Within the limits of testing in the research?**
   - Yes: Analyze using other sources.
   - No: Part of a coordinated signal system? (Answer "no" if the only other intersection in the system is the other member of a one-way pair or diamond interchange.)

2. **Part of a coordinated signal system?**
   - Yes: Choose the phase sequence which maximizes through band width.
   - No: Heavy pedestrian crossing volumes?

3. **Heavy pedestrian crossing volumes?**
   - Yes: Use the lagging phase sequence (if perm.-pro., be sure that trapping conditions are mitigated).
   - No: One ramp terminal of a diamond interchange where both signals have left turn phases?

4. **One ramp terminal of a diamond interchange where both signals have left turn phases?**
   - Yes: Trapping conditions difficult or costly to mitigate?
   - No: One member of a one-way pair system where both signals have left turn phases?

5. **One member of a one-way pair system where both signals have left turn phases?**
   - Yes: Use the leading phase sequence.
   - No: Protected-only left turns?

6. **Protected-only left turns?**
   - Yes: Fixed-time operation?
   - No: History of or potential for left turn accidents?

7. **History of or potential for left turn accidents?**
   - Yes: Capable of overlapping phases?
   - No: Left turn phasing already exist?

8. **Capable of overlapping phases?**
   - Yes: Use the phasing sequence which is most common at similar sites in the area.
   - No: Left turn phasing already exist?

9. **Left turn phasing already exist?**
   - Yes: Use the phasing sequence which is most common at similar sites in the area.
   - No: Fixed-time operation?

10. **Fixed-time operation?**
    - Yes: Do not change the current phasing sequence.
    - No: Do not change the current phasing sequence.

---

Figure 1. Flowchart for Decisions on the Phasing Sequence of Individual Intersections.
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**

There remain several aspects of the leading and lagging issue that 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 utilization of the various signal phases. This portion of the research yielded interesting results, but the data collection method was cumbersome limiting the amount of data which 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 which included alterations to NETSIM or some other traffic simulation model, a thorough validation of the improved model, an experiment comparing phasing alternatives, and a field and/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 experiments similar to those conducted in Chapter 6 with more varied volume levels. Modelling volumes typical of saturated conditions or typical of the middle of the night may yield some interesting data which could be used to extend the scope of the guidelines for leading and lagging left turn signal phasing.