FINAL REPORT

DEVELOPMENT OF LEFT-TURN LANE GUIDELINES FOR SIGNALIZED AND UNSIGNALIZED INTERSECTIONS

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DISCLAIMER

ABSTRACT

It is generally accepted that the level of service (LOS) at intersections significantly affects the overall LOS of the road system. It is also known that the LOS at an intersection can be adversely affected by frequently allowing left-turning vehicles to block through traffic. In addition, crash rates tend to be higher at intersections than on through sections of a road. The separation of left-turning vehicles from through traffic is therefore an important condition for the safe and effective operation of intersections.

Existing guidelines for installing left-turn lanes have several limitations. They are mainly based on the traffic volumes at the intersection, and they use deterministic models with fixed gap acceptance and/or left-turn maneuver times. In addition, the guidelines for left-turn lanes for unsignalized intersections and signalized intersections must be specific for the type of intersection.

In this study, new left-turn guidelines for both unsignalized and signalized intersections were developed on the basis of well-validated event-based simulation programs. Guidelines for unsignalized intersections were based on the percentage of left turns blocking through vehicles, whereas the guidelines for signalized intersections were developed using a minimum left-turn volume of either 85% left-turn capacity or LOS E delay (55 seconds/vehicle). In addition to the general guidelines, a prioritization tool that can be used to prioritize candidate intersections was developed. The prioritization tool accounts for both operational and safety aspects.

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INTRODUCTION

It is generally accepted that the level of service (LOS) at intersections can significantly affect the overall LOS of a road. It is also known that the LOS at an intersection can be adversely affected by frequently allowing the left-turning vehicles to block the through traffic. Crash rates also tend to be higher at intersections than on through sections of a road. The separation of left-turning vehicles from through traffic can be an important condition for the safe and effective operation of an intersection.

Existing guidelines use the volume of left-turn traffic, the volume of through traffic, and the volume of traffic opposing the left-turn maneuver to determine whether a left-turn lane is needed at an intersection. The most frequently applied guidelines for determining the need for a left-turn lane were developed from analytical equations for specific left-turn percentages for unsignalized intersections and for specific g/C ratios for signalized intersections. The unsignalized guidelines are available as tables in the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on the Geometric Design of Highways and Streets,* commonly called the Green Book (2001). These guidelines are not available for all percentages of left-turning vehicles and do not go below 5% left turns. In the development of these guidelines, the researchers also assumed a fixed value for the critical gap, which represents a simplification of reality. In contrast to unsignalized intersections, there are no widely accepted guidelines for installing left-turn lanes at signalized intersections. For the guidelines that do exist, the researchers did not develop separate guidelines for different percentages of left-turning vehicles.

PURPOSE AND SCOPE

The purpose of this study was to develop left-turn lane guidelines for signalized and unsignalized intersections. Specific objectives were as follows:

- Critically evaluate existing guidelines for providing left-turn lanes at unsignalized and signalized intersections through a literature review.
- Determine how engineers at the Virginia Department of Transportation (VDOT) use existing guidelines.
- Develop, calibrate, and validate event-based simulation models to simulate traffic at unsignalized and simple two-phase signalized intersections.
- Develop new guidelines for left-turn lanes using the event-based simulation models that are applicable for all turning percentages.
- Create a prioritization system for ranking the need for left-turn lane improvements among a number of candidate intersections.

This study was limited to developing guidelines for installing left-turn lanes at signalized and unsignalized intersections. Developing guidelines for left-turn signal phasing was not within the scope of this study. Although each event-based simulation program used for developing guidelines in this project could theoretically simulate any condition seen in the field, the scope of each program was limited to ensure that program coding could be completed in a timely manner. Thus, the scope of the program was defined as follows:

- A maximum of four approaches can be simulated using this program.
- The program can handle all kinds of lane sharing and also accommodate up to four lanes on a given approach.
- Unsignalized intersections on undivided highways are considered for only left-turn lane guidelines. VDOT's *Road Design Manual* (2002) dictates that left-turn lanes are to be provided for traffic on non-access controlled divided highways.
- The signalized intersection program can simulate actuated intersections but assumes simple two-phase signals.
- The model is applicable only for left-turn lane analysis and cannot be used for right-turn lane analysis.
- At signalized intersections, left-turns on the subject link must be permitted.
- The effect of available sight distance and grades on the approaches is not examined explicitly.

- The signalized program is a decision making tool for installing a left-turn lane and should not be used to determine left-turn phasing.

METHODOLOGY

The research approach in this study involved (1) a literature review, (2) a survey on the usage of existing left-turn lane guidelines, (3) field data collection and reduction, (4) development of event-based simulation model, (5) validation of the simulation model, and (6) development of new guidelines.

Literature Review

The current literature and previous research in this area were reviewed as the first task in this study. The Virginia Transportation Research Council (VTRC) library and the University of Virginia libraries were used for this purpose.

Survey on Usage of Existing Left-turn Lane Guidelines

In order to understand how VDOT engineers use current left-turn lane guidelines, an online survey of VDOT resident engineers and district traffic engineers was conducted. A complete questionnaire of the survey is provided in Appendix A.

Field Data Collection and Reduction

Data Collection

Site Selection

Field data had to be collected at existing intersections to gather information that could be used to calibrate and validate the event-based simulation programs. The district traffic engineers were asked to provide sites that were suitable for the study. All sites had to have a shared lane (left and through), and signalized sites had to have permitted phasing for the left-turning vehicles. Sites that had large opposing volumes and large delays for left-turning traffic were preferred. Potential sites had to meet the following criteria:

Unsignalized site requirements:

- shared lane (left + through) on the subject link
- frequent instances of left-turn vehicles blocking through vehicles
- adequate shoulder width on the approaches so that the data collection crew could work safely

Signalized site requirements:

- shared lane (left + through) on the subject link
- frequent instances of left-turn vehicles blocking through vehicles
- adequate shoulder width on the approach to safely park the Smart Travel Van (STV) (Other safety conditions, such as no power cables within 10 feet of the mast, are also required for the safe operation of the STV.)
- permitted left turns on the subject link and the opposing link.

The research team visited 54 sites (11 signalized intersections and 40 unsignalized intersections) suggested by the district traffic engineers and also obtained average annual daily traffic (AADT) counts on available sites. Based on traffic volumes and site characteristics, these sites were classified as "good," "intermediate," or "inappropriate." The good sites were the ones where data collection could be carried out safely, and the inappropriate sites were the sites where data collection was not possible because of safety concerns. For some sites, although the safety criteria were met, sufficient volumes were not observed during the visit. Since there was a possibility of volumes being higher during peak hours, these sites were classified as intermediate.

Data Collection at Signalized Intersections

The STV was used to collect data on traffic volume, queue length, speed and headways at signalized intersections. The STV is a state-of–the-art van equipped with a computer and two cameras on the mast that can capture the traffic data. The Autoscope program was installed in the computer of the STV. Autoscope is a video detection package, which collects traffic volumes, speeds, time headways, etc. The mast of the STV measures 45 feet when fully raised and gives a bird's-eye view of the intersection. This van was used because it could capture the full view of the intersection including (in some cases) the signal heads. Data were collected for approximately 2 hours at each intersection during either the morning or evening peak hours.

The Autoscope program was used to set up speed and count detectors. The count detector did not have any length in the direction of the traffic flow and counted only the number of vehicles that passed over it. It recorded the time at which the vehicle was activated and deactivated the detector. These times were recorded to within a 1-second accuracy. There was also a global positioning system (GPS) in the STV that recorded the times of each detector activation and de-activation within a 1-millisecond accuracy. This was used to calculate the headways in the opposing flow. The cameras of the STV covered the subject link approach so that the end of the queue was visible (see Figure 1). From these tapes, the queue length (number of cars) at the end of each red phase was calculated in the laboratory. This was used during the validation of the simulation program. The approximate location of a typical count detector is also shown on the subject link and opposing link of Figure 1.

Actuated signalized intersections do not maintain a constant cycle length since the phase lengths change depending on arrival patterns. Furthermore, the camera on the STV did not always capture the signal heads. Therefore a computer program was written to record signal-timing changes. Whenever the user pressed a character in the keyboard, the program recorded the character and time. This program was installed on the laptop that was carried to the field during

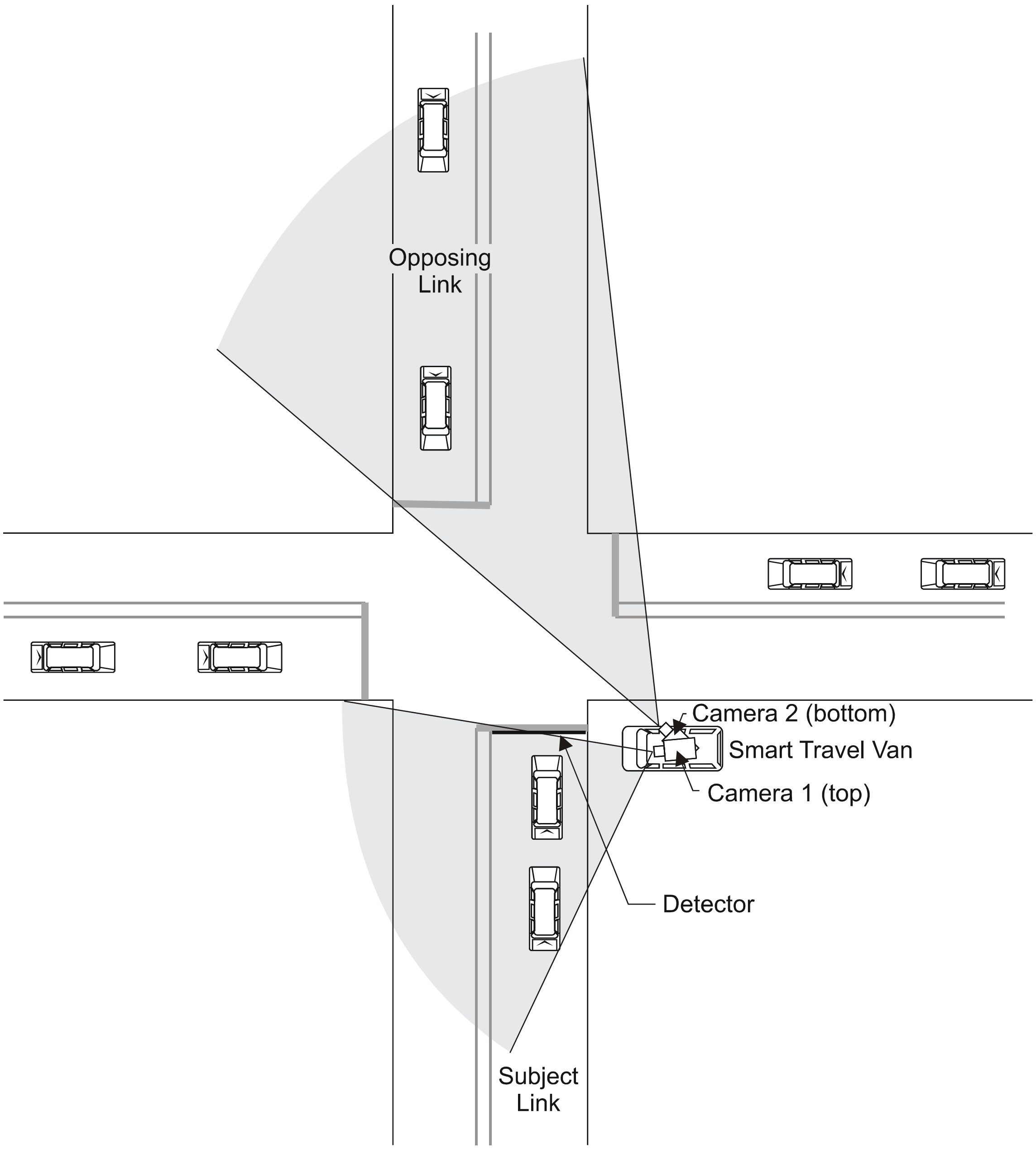

Figure 1. Layout of Data Collection Scheme

the data collection. Whenever a phase change occurred, a key ("r" for red, "g" for green, and "y" for yellow) was pressed. The difference of the times between consecutive values in the text file gives the time for which the signal showed green, yellow, or red. The changes in signal phase times observed in the field were obtained using these procedures. All the signalized sites recommended by the engineers were fully actuated or semi-actuated; hence the cycle lengths as well as the green times were not constant.

Data Collection at Unsignalized Intersections

At unsignalized intersections, three cameras mounted on tripods were used for data collection. Two were Sony DV cameras that gave a time stamp in 1/30th of a second. This was necessary since the gap acceptances and rejections required an accuracy of less than 1 second. These two DV cameras (Cameras 1 and 3 in Figure 2) were placed at the ends of the

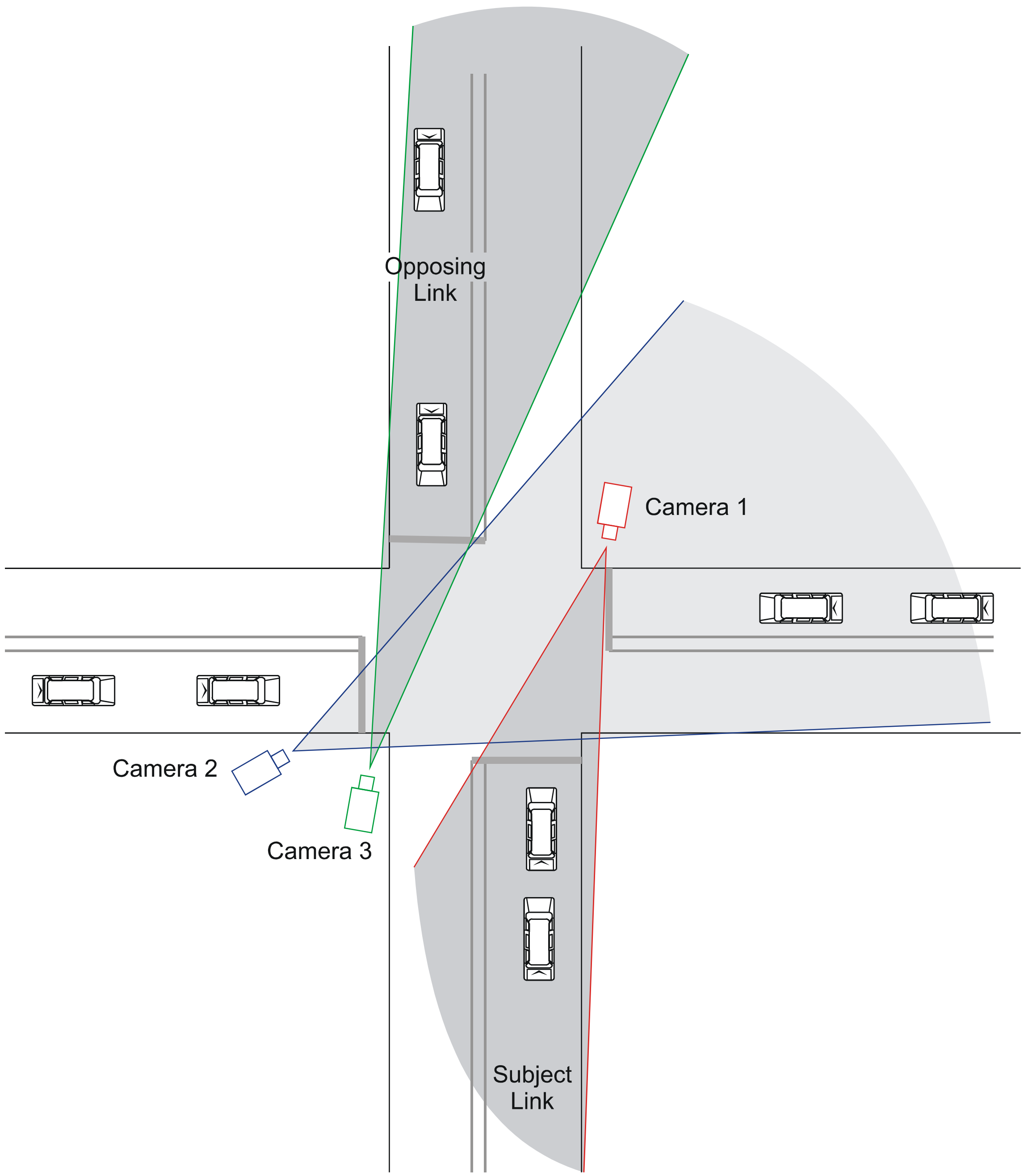

Figure 2. Typical Camera Coverage at Unsignalized Intersection

intersections looking at opposing and subject link flows. The third camera was placed to cover the intersection area as sometimes the queue blocked the view of the other two cameras, thereby preventing the recording of the gaps that were rejected or accepted. The DV cameras collected the traffic volumes while the gap acceptance/rejections were collected from the center camera and/or the DV cameras. Figure 2 shows the typical camera coverage that was followed for the data collection at unsignalized intersections. The subject link and the opposing link are also shown in Figure 2. Data were also collected for approximately 2 hours at each intersection during either the morning or evening peak hours.

Data Reduction

The video data were processed to determine and/or verify information on arrivals, gap acceptances, and traffic counts. Vehicle arrival times on both subject and opposing links were recorded. In addition, vehicle turning movements were also recorded. While a left-turning vehicle on the subject link was waiting for an acceptable gap, time gaps of opposing vehicle and their acceptance or rejection were recorded.

Geometric and Traffic Data

The geometric and traffic characteristics of each intersection were identified and used as input data for the event-based simulation program developed in this project. These data included:

- number of approaches
- number of lanes on each approach
- turn attribute of each lane (left only, right only, etc.)
- volumes on each approach
- percentage of turns on each approach
- operating speed.

Critical Gap Data

The critical gap of the drivers plays an important role in the delays experienced by the left-turning vehicles and therefore will determine whether the shared lane will be blocked or not. This dictates the need for the separate left-turn lane. It was necessary to measure the critical gap of the vehicles in the field to examine left-turn behavior.

As mentioned earlier, for both signalized and unsignalized intersections, the arrival time at the stop line of each left-turning vehicle on the subject link was recorded. The arrival time at the stop line of each opposing vehicle was also recorded. The difference in these times would be the gap that is available for the left-turning vehicle. The left-turning vehicle would accept or reject this available gap; therefore, all these gaps were measured and classified as “R” for rejections and “A” for acceptances. A curve showing the rejections and acceptances was plotted for that particular site. The intersection of the curve for A and R gave the gap above which drivers would accept and below which drivers would reject, which is the critical gap at that particular site. This was done for both signalized and unsignalized intersections. The procedure described here can be found in Garber and Hoel (1999).

Assume that t_1 and t_2 are two times that differ by Δt, $t_2 = t_1 + \Delta t$. Using similar triangles, it could be shown that the critical gap, t_c, is

$$t_c = t_1 + \frac{\Delta t(r-m)}{(n-p)+(r-m)} \qquad [1]$$

where

m = number of accepted gaps less than t_1
r = number of rejected gaps greater than t_1
n = number of accepted gaps less than t_2
p = number of rejected gaps greater than t_2.

This calculation of critical gaps was done for all the sites and was used for the simulation program input. The results of these sites from the program were compared with the field values.

Measures of Effectiveness Data

The measures of effectiveness (MOEs) data that were reduced from the tapes of the data collection sites were used to validate the event-based simulation program. The MOEs examined included "number of stopped left-turning vehicles" at unsignalized sites and "green times on the subject link," "average left-turn vehicle stopped delay," and the "maximum queue length on the subject link" at signalized sites. Since the traffic signal controller at these sites was actuated, the green times were not constant for all cycles. The main MOE data that were extracted from the videotapes for signalized and unsignalized intersection are described as follows:

- *MOEs for signalized intersections.* The queues that were present (on the subject link) at the beginning of green times were counted from the videotapes. These were used in validating the simulation program. In other words, the queue length counter was incorporated in the program and the queue lengths generated by the program was compared with the ones seen in the field. In addition to the queue length, left-turn vehicle delay was also reduced from the videotapes. The times of left-turn vehicle arrivals and departures were recorded from the videotapes, and each left-turn vehicle delay was calculated by subtracting arrival time from departure time. An average left-turn vehicle delay from the field was compared with the distribution of average left-turn delays from the simulation output.

- *MOEs for unsignalized intersections.* The MOE used for validation of the unsignalized model was "number of left-turning vehicles that were stopped" on the subject link. These data were reduced at every site by examining the subject link and manually counting the number of left-turning vehicles that had to stop at the intersection.

Development of Event-Based Simulation Model

Event-based simulation programs were developed in this study because existing commercial programs do not directly provide various MOEs needed for developing left-turn lane guidelines. In addition, an event-based simulation tends to be easier to code and execute faster than microscopic simulations, given that the analyst cannot use a commercial package and thus will have to develop the original software.

The event-based simulation programs developed in the project are part of a complete package named the Left Turn Guidelines Analysis Package (LTGAP). In an event-based simulation, the program has a list of events and jumps (in time) from one event to another. For example, the arrival of the vehicles on a particular approach is an event, as are the departures and signal phase changes. The system time moves in steps from one event to another rather than moving in a fixed time steps. The LTGAP is composed of three parts: (1) unsignalized intersection simulation program, (2) signalized intersection simulation program, and (3) user interface for data entry and display of results.

The unsignalized and signalized intersection simulation programs were written in C++, and the interface was developed using Microsoft Visual Studio .Net program.

Validation of Simulation Model

Each event-based simulation model was validated using observed data from the field. As mentioned earlier, the model for the unsignalized intersection was validated based on the number of left-turn vehicle stopped, whereas the model for signalized intersections was validated using maximum queue length and left-turn stopped delay.

Multiple simulation runs were made to account for variability in stochastic simulation program output. A total of 100 runs were made for each test site, and the distribution of the measures of effectiveness was compared with the field data using a histogram.

Development of New Guidelines

The guidelines developed by previous researchers were investigated, and the possibility of developing guidelines based on pure operational savings (such as delay savings) was also investigated by conducting a preliminary cost-benefit analysis. Separate guidelines were developed for signalized and unsignalized intersections using the event-based simulation program developed and validated in this study.

Guidelines for Unsignalized Intersections

The event-based simulation program was run for various combinations of input variables to develop proposed left-turn lane guidelines. The follow levels of input variables were used to generate new guidelines:

- percentage of left-turning vehicles = 3%, 5%, 10%, 20%, 30%
- operating speed = 40 mph, 50 mph, 60 mph
- advancing volume, V_A, = 100 to 800 vehicles per hour (vph) by 50-vph increment
- opposing volume, V_O, = 100 to 800 vph by 50-vph increment.

The maximum advancing and opposing volumes of 800 vph were used because 800 is the practically highest acceptable volume that can be used for determining left-turn lanes at unsignalized intersection. Traffic volumes of more than 800 vph would justify signalization of the intersection. The criterion used for developing the guidelines was the percentage of time through-vehicles were delayed. This was interpolated to find the volumes at their critical values. This was plotted for all combinations of left-turn percentages. The critical percentages of time that through vehicles were delayed were adopted from those used by Harmelink (1967).

Guidelines for Signalized Intersections

Pre-timed Signals

The program was run for all combinations of g/C (0.1 through 0.8 in 0.1 increments), cycle length (60, 80, and 100 seconds), number of lanes (four and six lanes), and percentage of left-turn vehicles (3%, 5%, 10%, 20%, and 30%). The capacity of the advancing volume, V_A, and the left-turn delay were calculated using the event-based simulation model. The proposed guidelines recommended that a left-turn lane be installed when the volume-capacity (v/c) ratio exceeded 0.85 or the delay exceeded 55 seconds/vehicle (LOS E cutoff). The guidelines were developed in the form of tables.

Actuated Signals

The simulation program could be applied (using the LTGAP interface) to any actuated controller settings. In the case of actuated signals, the guidelines were not developed in the form of tables and/or graphs. This is due to the complexity involved in the actuated signal control. Average cycle length and green times are to be estimated through multiple simulation runs and are to be applied to pretimed signalized guidelines.

Length of Left-turn Lane

In case the proposed left-turn lane guidelines recommend the installation of a left-turn lane, the length of the lane needs to be determined. Given that the purpose of installing a left-turn lane is to prevent left-turn overflows, the probability of left-turn lane overflows for varying left-turn bay lengths was investigated using the event-based simulation program.

Recommended left-turn lane length is provided in the form of a graph at a given traffic volume, geometry, and intersection control type. In other words, the probability of left-turn bay overflow is plotted against left-turn bay length. At each left-turn bay length, 100 simulation runs were made to obtain an average left-turn bay overflow probability. Left-turn bay length was evaluated from 0 to 1,200 feet in every 50 feet for signalized intersections and was varied from 0 to 500 feet in every 50 feet for unsignalized intersections.

Prioritization Tool

Traffic engineers are sometimes faced with a problem of allocating limited funds to a set of candidate intersections that are considered for left-turn lane installation. Under these circumstances, a ranking methodology that prioritizes the candidate intersections on the basis of both safety and mobility measures is needed. A unique prioritization tool that considers both operational and safety aspects of installing left-turn lanes was developed in this project. This tool can be used to provide rankings of multiple candidate intersections.

The prioritization methodology tool is applicable for both signalized and unsignalized intersections. The ranking score of individual site is calculated using the following equation.

$$RS_i = W_o \times NO_{ii} + W_s \times NS_i \quad [2]$$

where

RS_i = ranking score of *i*-th intersection
W_o = weight factor for mobility measure (default value = 0.5)
NO_i = normalized operational measure score of *i*-th intersection
W_s = weight factor for safety surrogate measure (default value = 0.5)
NS_i = normalized safety surrogate measure score of *i*-th intersection
$W_o + W_s = 1$.
The normalized operational measure score at intersection *i* is calculated as follows.

$$NO_i = \frac{O_i}{\max(O)} \quad [3]$$

where

O_i = operational measure at intersection *i*
max(O) = maximum operational measure from all candidate intersections.

As noted earlier, unsignalized and signalized intersections are using different operational measures. The percentage of left-turn vehicles blocking through vehicles is used for unsignalized intersection, and the v/c ratio and left-turn delay of left-turn vehicles are used for signalized intersections.

The normalized safety surrogate score, NS_i, is based on two conflict opportunities: left-turn and rear-end conflict opportunites. The reduction in confict opportunities with added left-turn lane is calculated, and then it is normalized by dividing maximum value among candidate intersections.

$$NS_i = \frac{\Delta CO}{\max(\Delta CO)} \quad [4]$$

where

ΔCO_i = reduction in conflict opportunities with added left-turn lane at intersection *i*
$\max(\Delta CO_i)$ = maximum reduction value from all candidate intersections.

The conflict opportunities calculated in the event-based simulation program are used as a safety surrogate measure. A left-turn conflict opportunity is assumed to occur when a left-turn maneuver is made within 2 seconds of the critical gap period, whereas rear-end conflicts occur whenever a vehicle joins a queue. Both left-turn and rear-end conflict opportunities are treated equally. Detailed procedures on the calculation of conflict opportunities can be found in Ha and Berg (1995).

RESULTS

Literature Review

Guidelines for Unsignalized Intersections

The first guidelines for unsignalized intersections were developed by Harmelink (1967), and these guidelines are still used by traffic engineers in the field. Harmelink calculated the probability of through vehicles being blocked by the left-turning vehicles using analytical equations. He obtained the critical values of these probabilities (for different speeds) from a survey of practicing engineers. He recommended the installation of left-turn lanes at volumes where his analytical equations produced these probabilities. Harmelink probabilities, obtained from the judgment of a panel of traffic engineers, are shown in Table 1. The guidelines obtained by Harmelink are shown in Table 2. These guidelines are also available in the AASHTO Green Book (2001).

Table 1. Probability Values Used in Harmelink Guidelines

Approach Speed (mph)		Probability (ρ)
Design	Operating	
50	40	0.02
60	50	0.015
70	60	0.01

Source: Harmelink (1967).

Table 2. AASHTO Guidelines for Left-turn Lanes on Two-Lane Highways

Opposing Volumes	Advancing Volume			
	5% Left Turns	10% Left Turns	20% Left Turns	30% Left Turns
40-mph operating speed				
800	330	240	180	160
600	410	305	225	200
400	510	380	275	245
200	640	470	350	305
100	720	575	390	340
50-mph operating speed				
800	280	210	165	135
600	350	260	195	170
400	430	320	240	210
200	550	400	300	270
100	615	445	335	295
60-mph operating speed				
800	230	170	125	115
600	290	210	160	140
400	365	270	200	175
200	450	330	250	215
100	505	370	275	240

Source: AASHTO (2001).

One of the shortcomings of Harmelink's guidelines, identified by Kikuchi and Chakroborty (1991), is the use of residual gaps. For example, if there were four consecutive 6-second gaps and the left-turn maneuver time was 4 seconds, the number of left-turn vehicles served in Harmelink's guidelines would be six instead of four. In reality, it should be four. This is because the next vehicle to turn left could not use the residual 2 seconds. Other shortcomings, identified by Kikuchi and Chakroborty (1991), are the definitions of arrival and departure rates. In queuing theory, the unit of arrival and departure should be identical. However, Harmelink used arrival rate on the basis of through vehicles and departure rate on the basis of left-turn vehicles.

Kikuchi and Chakroborty (1991) modified the shortcomings of Harmelink's guidelines and revised the guidelines. The new guidelines are shown in Table 3; the revised guidelines were not incorporated into AASHTO's Green Book (2001). They further developed other guidelines based on other criteria such as LOS and delay using a simulation program. However, their simulation program has assumptions that are not realistic, e.g., the use of a fixed 6-second critical gap for left-turn vehicles, which may be too large for some situations. Kikuchi and Chakroborty (1991) also provided a few new guidelines based on a LOS A/B cut-off for the through vehicles and an arbitrary delay saving value of 14 seconds.

Table 3. Volume Combinations Justifying a Left-turn Lane under Modified Harmelink Guidelines

Opposing Volumes (vph)	Advancing Volume (vph)			
	5% Left Turns	**10% Left Turns**	**20% Left Turns**	**30% Left Turns**
40 mph operating speed				
800	434	300	219	189
600	542	375	272	234
400	682	472	343	293
200	863	600	435	375
100	946	679	493	424
50 mph operating speed				
800	366	257	185	162
600	460	320	234	202
400	577	403	294	255
200	735	513	373	324
100	830	576	424	365
60 mph operating speed				
800	294	207	154	146
600	365	259	187	165
400	461	324	238	206
200	586	414	303	263
100	663	468	344	297

Source: Kikuchi and Chakroborty (1991).

Guidelines for Signalized Intersections

There are no commonly accepted guidelines on when to provide a left-turn lane at a signalized intersection. Oppenlander and Bianchi (1990) proposed one set of left-turn lane guidelines for signalized intersections. They suggested two criteria and recommended lanes whenever intersections met at least one of two criteria. The first was the capacity requirement based on the methodology for signalized intersections in the *Highway Capacity Manual* (HCM) (1985); the second was the storage requirement for storing at least one left-turning vehicle. The storage requirement was modeled using a queuing theory assuming Poisson arrivals and exponential services. The design left-turn volume was used for arrival rate, and a function of permitted left-turn capacity and opposing traffic was used for service rate.

Conflict Opportunities

The safety of an intersection is usually examined by an examination of its crash history. However, crashes are rare events and no crash history is available for new developments. Thus, surrogates for crash history can be used. Conflict analysis is one type of safety surrogate that is often used. Conflicts can be defined as events such as near misses or sudden braking of the vehicles that were about to collide. Unfortunately, conflict data also must be observed in the field, which means that conflict analysis cannot be used for intersections that have not been constructed.

Ha and Berg (1995) defined another type of safety surrogate as conflict opportunities. A conflict opportunity occurs when there is a potential for a collision between two vehicles. There are two main types of conflict opportunities: left-turning conflicts and rear-end conflicts. If an opposing vehicle is too close to the left-turning vehicle as the vehicle makes the turn, the event could be treated as a left-turn conflict opportunity. Similarly, there is an opportunity for a rear-end collision to occur whenever every single vehicle joins the queue. Therefore every vehicle joining the queue could be treated as a rear-end conflict opportunity. An advantage of conflict opportunities is that they can be generated theoretically based on volumes, traffic control, and intersection geometry. This means that, unlike conflicts, conflict opportunities can be estimated for intersections that have not yet been constructed.

Survey Results

Fifty-two of 60 (85%) engineers responded to the survey. As seen in Figure 3, there appears to be some confusion about the application of the Harmelink guidelines to signalized intersections. Harmelink guidelines developed for unsignalized intersections are not supposed to be applied for signalized intersections. Measures such as left-turn charts, accident experience, LOS based on the HCM (2000), etc., were combined in the "others" shown in the Figure 3. The total responses do not add up to 52 because some engineers did not respond to this question.

The respondents were also generally happy with the performance of the guidelines they used, as indicated in Figure 4. It is interesting to note that none of the engineers thought the current guidelines called for lanes when they were not needed.

The usage of the different methods/guidelines for unsignalized intersections is shown in Figure 5. Again, many respondents said they are using Harmelink guidelines for installing left-turn lanes at unsignalized intersections.

The majority of the engineers seemed to be happy with the current unsignalized guidelines. Figure 6 describes their responses.

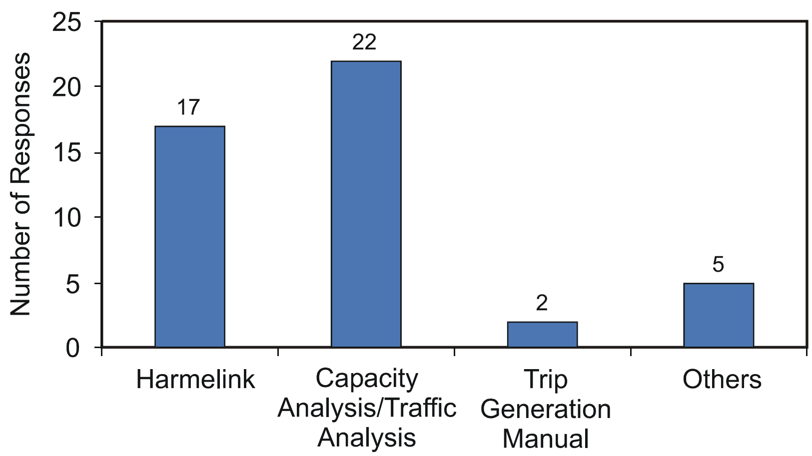

Figure 3. Comments Regarding Use of Current Guidelines for Signalized Intersections

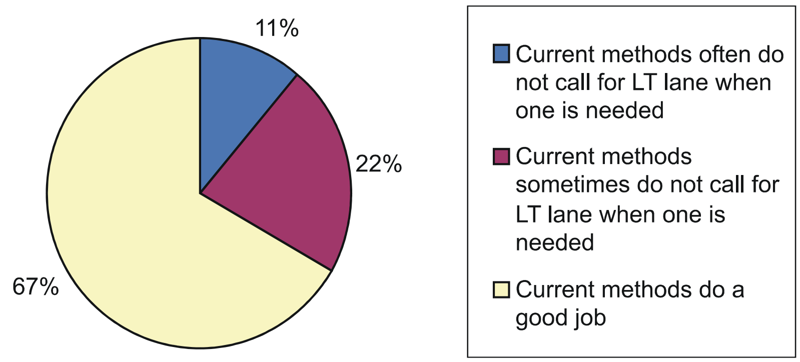

Figure 4. Comments Regarding Guidelines Currently Used for Signalized Intersections

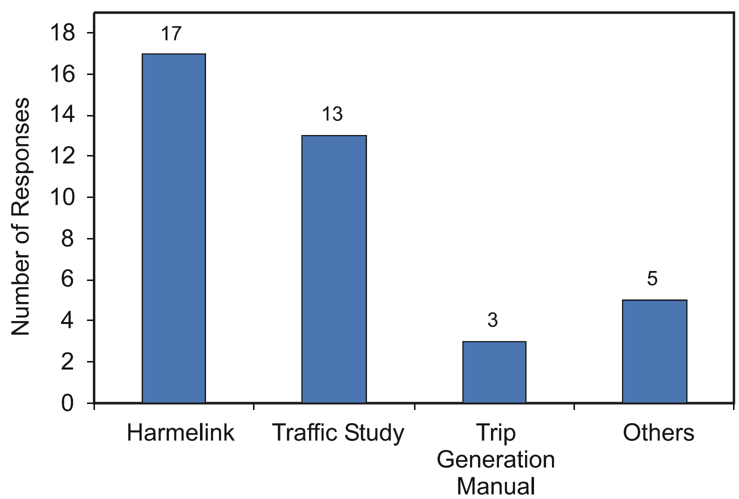

Figure 5. Comments Regarding Usage of Particular Guidelines for Unsignalized Intersections

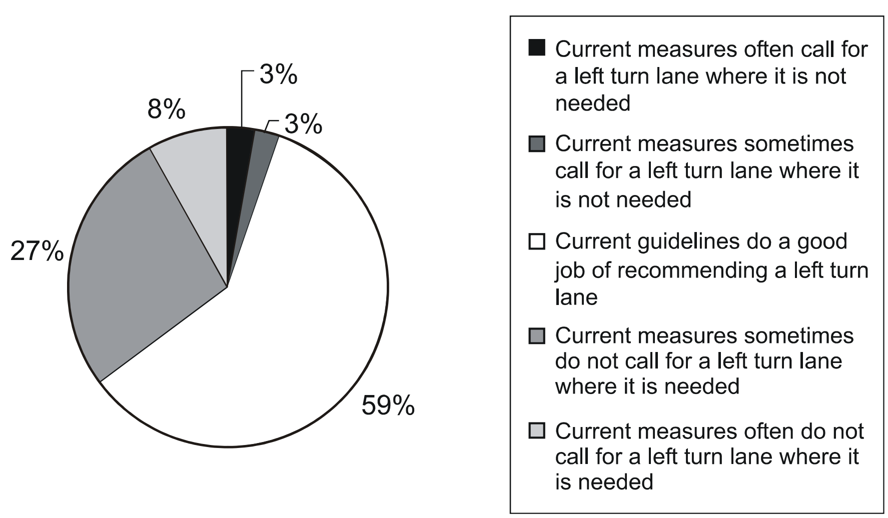

Figure 6. Comments on Satisfaction With Current Guidelines for Unsignalized Intersections

Data Collection and Reduction

After the 51 intersections recommended by VDOT engineers were visited, 6 signalized and 5 unsignalized intersection sites were selected for data collection. Finding sites that were appropriate for this study proved to be extremely difficult. In general, if traffic volumes were large enough to create left-turn delays, a left-turn lane was already installed at the site. As a result, the number of sites where data were collected was limited. Table 4 and Figure 7 show the signalized intersections and their locations, and Table 5 and Figure 8 show the unsignalized intersections. In Tables 4 and 5, the number of subject link lanes is expressed by direction. The summary results of traffic counts during the peak hours for both unsignalized and signalized intersections are shown in Tables 6 and 7.

Table 4. Signalized Intersections Used for Data Collection

Site No.	Intersection	Speed Limit	Number of Approaches	Number of Subject Link Lanes	County	District
1	US 340, US 522, and SR 277 (Double tollgate intersection)	40	4	2	Clarke	Staunton
2	US 250 and US 15	55	4	1	Louisa	Culpeper
3	US 33 and New Bridge Rd	40	3	2	Henrico	Richmond
4	US 1 and Lakeside Avenue	45	4	3	Henrico	Richmond
5	US 250 and SR 616	45	4	1	Albemarle	Culpeper
6	SR 28 and SR 652	35	4	1	Fauquier	NOVA

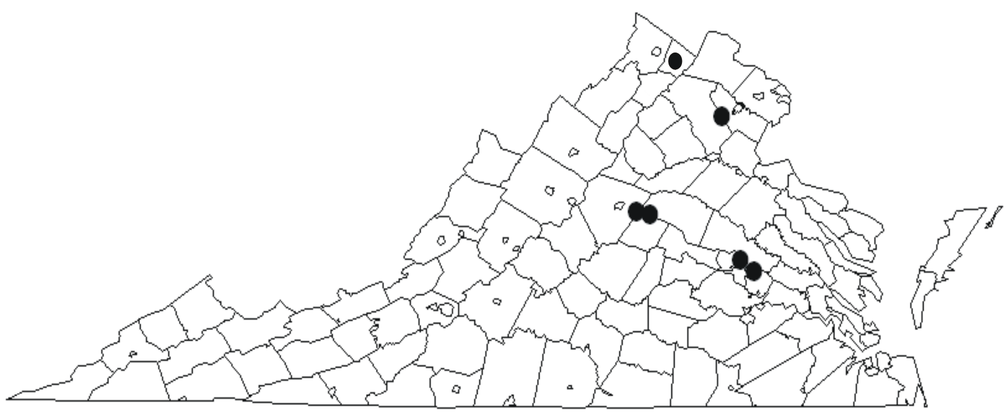

Figure 7. Data Collection Sites for Signalized Intersections

Table 5. Unsignalized Sites Used for Data Collection

Site No.	Intersection	Speed Limit	Number of Approaches	Number of Subject Link Lanes	County	District
1	SR 20 and SR 6	25	3	1	Albemarle	Culpepper
2	US 15 and SR 636	55	4	1	Buckingham	Lynchburg
3	US 15 and SR 650	55	4	1	Buckingham	Lynchburg
4	SR 22 and SR 731	45	3	1	Albemarle	Culpepper
5	SR 151 and SR 6	55	4	1	Nelson	Lynchburg

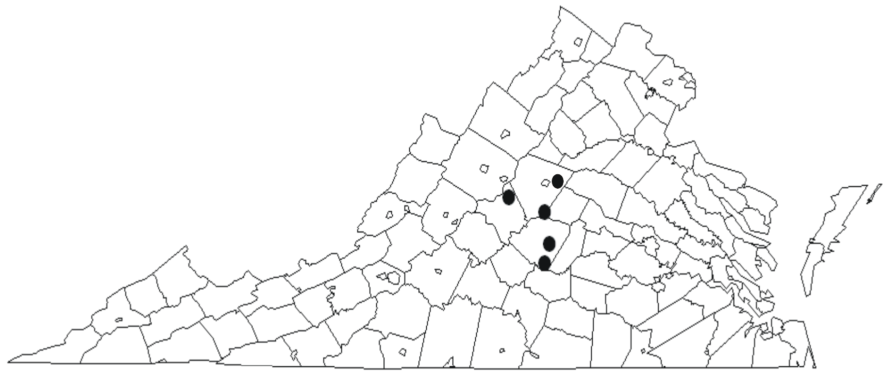

Figure 8. Data Collection Sites for Unsignalized Intersections

Table 6. Measured Volumes at Unsignalized Intersections

Site Name	Turning Movement	Traffic Counts (vph)			
		Subject Link	Opposing Link	Cross St 1	Cross St 2
SR 20* and SR 6	Left	101	–	8	–
	Through	113	303	–	–
	Right	–	7	108	–
US 15* and SR 636	Left	40	5	10	10
	Through	140	115	10	10
	Right	2	25	10	10
US 15* and SR 650	Left	14	–	45	–
	Through	200	180	–	–
	Right	–	90	45	–
SR 22* and SR 731	Left	8	–	11	–
	Through	195	347	–	–
	Right	–	20	17	–
SR 151* and SR 6	Left	108	–	36	–
	Through	168	150	–	–
	Right	–	50	88	–

* Subject road.

Table 7. Measured Volumes at Signalized Intersections

Site Name	Turning Movement	Traffic Counts in vph			
		Subject Link	Opposing Link	Cross St 1	Cross St 2
US 340/US 522 and SR 277*	Left	156	60	152	36
	Through	171	85	400	330
	Right	80	100	80	80
US 15* and US 250	Left	201	30	96	58
	Through	282	135	100	62
	Right	89	25	96	140
US 33* and New Bridge Rd.	Left	45	–	172	–
	Through	436	316	–	–
	Right	–	96	48	–
US 1* and Lake Site Ave.	Left	22	4	16	220
	Through	542	556	0	8
	Right	32	276	12	80
US 250 and SR 616*	Left	178	25	20	10
	Through	210	80	150	150
	Right	19	7	20	20
SR 28 and SR 652*	Left	100	12	20	40
	Through	84	104	520	272
	Right	40	32	80	40

*Subject road.

Critical Gap Reduction

Tables 8 and 9 show the critical gap values calculated for the left turns on the subject link at unsignalized and signalized intersections.

Table 8. Field Measured Critical Gap of Left Turns at Unsignalized Intersections

Site ID	Intersection	Critical Gap (sec)
1	SR 20 and SR 6	5.8
2	US 15 and SR 636	5.9
3	US 15 and SR 650	6.5
4	SR 22 and SR 731	3.7*
5	SR 151 and SR 6	4.4

*Critical gap estimated on basis of 8 left-turn vehicles.

Table 9. Field Measured Critical Gap of Left-turns at Signalized Intersections

Site ID	Intersection	Critical Gap (sec)
1	US 340, US 522, and SR 277	3.75
2	US 250 and US 15	4.4
3	US 33 and New Bridge Rd	6.9
4	US 1 and Lakeside	6.2
5	US 250 and SR 616	4.0
6	SR 28 and SR 652	4.5

Headway Distributions

The headways at the signalized sites were important as the gaps in traffic flow dictate the cycle length (since all the signalized sites had fully actuated controllers) and other MOEs. The inter-arrival (gap) distribution was tested at the signalized sites and was following negative exponential distributions. All sites passed the Kolmogorov-Smirnov test for $\alpha = 0.05$. The results of these tests are summarized in Table 10. Based on these results, the program was coded such that it produced vehicles according to a negative exponential distribution.

Table 10. Kolmogorov-Smirnov (K-S) Test Results at Signalized Intersections

Site ID	Intersection	Calculated K-S Test Statistics	Theoretical K-S Test Statistic (from table)	Negative Exponential K-S Test ($\alpha = 0.05$) Result
1	US 340, US 522, and SR 277	0.075	0.090	Accepted
2	US 15 and US 250	0.037	0.059	Accepted
3	US 33 and New Bridge Road	0.041	0.058	Accepted
4	US 1 and Lakeside Avenue	0.028	0.059	Accepted
5	US 250 and SR 616	0.010	0.068	Accepted
6	SR 28 and SR 652	0.027	0.101	Accepted

Event-Based Simulation Program

The event-based simulation programs developed in the project are part of a complete package named the Left Turn Guidelines Analysis Package (LTGAP). The LTGAP is composed of three parts as shown in Figure 9:

1. unsignalized intersection simulation program
2. signalized intersection simulation program
3. user interface for data entry and display of results.

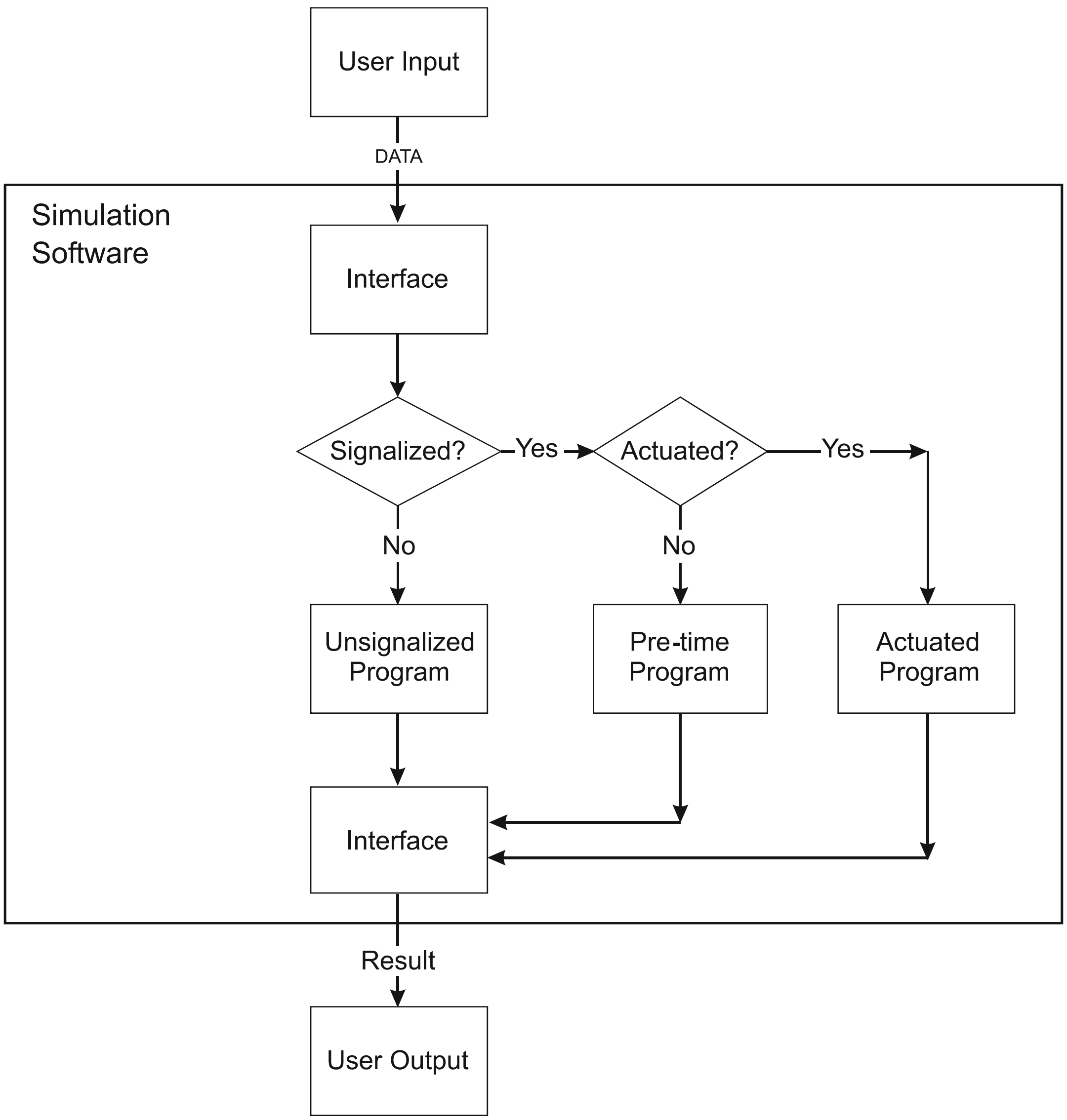

Figure 9. Basic Structure of LTGAP

Simulation Parameters

LTGAP has a configuration file (config.txt) that contains all the variables entered by the user. All the parameters that define the intersection were identified and incorporated into this configuration file. The key input parameters used in the config.txt file are:

1. number of lanes on each approach
2. lane attributes (like the lane length, and lane usage)
3. volumes and turning percentages (both left and right)
4. number of simulation runs
5. operating speed at the intersection
6. duration of runs
7. signal timing parameters (for signalized intersections only)
   - minimum green and maximum green for each phase
   - maximum value of the initial green
   - time increment of minimum green (seconds/vehicle)
   - gap out times
   - yellow and all red clearance times
   - Boolean variable indicating phase skip feature, enabled or disabled.

Interface

The interface transfers from user inputs to the program, runs the program, and presents the results to the user in a graphical format. The interface makes sure that the user enters all the parameters required for the simulation by providing error messages for inadequate data entry. The interface has text boxes where the user must input the values for volumes and signal timings and check boxes for guidelines, etc. This makes the proposed interface user-friendly. All these parameters are taken from the user and put in a text file by the interface. The text file serves as the input for the event-based simulation programs. In other words, the interface creates the configuration (config.txt) file used by the event-based programs. Each program then outputs MOEs into a text file. The interface reads this text file and presents the results to the user.

Figure 10 is a snapshot of data entry for a signalized intersection. The user can add up to four lanes on a maximum of four approaches. Each lane has an associated length, turn intention, and phase group.

The unsignalized interface output has a base graph of the guideline curve and the result of meeting left-turn lane guidelines at a given user input. For signalized intersections, the left-turn capacity on the approach is calculated. The minimum vehicular volume of 85% of the capacity and the delay of 55 seconds per vehicle are the critical values where left-turn lanes are recommended. The interface displays this result to the user.

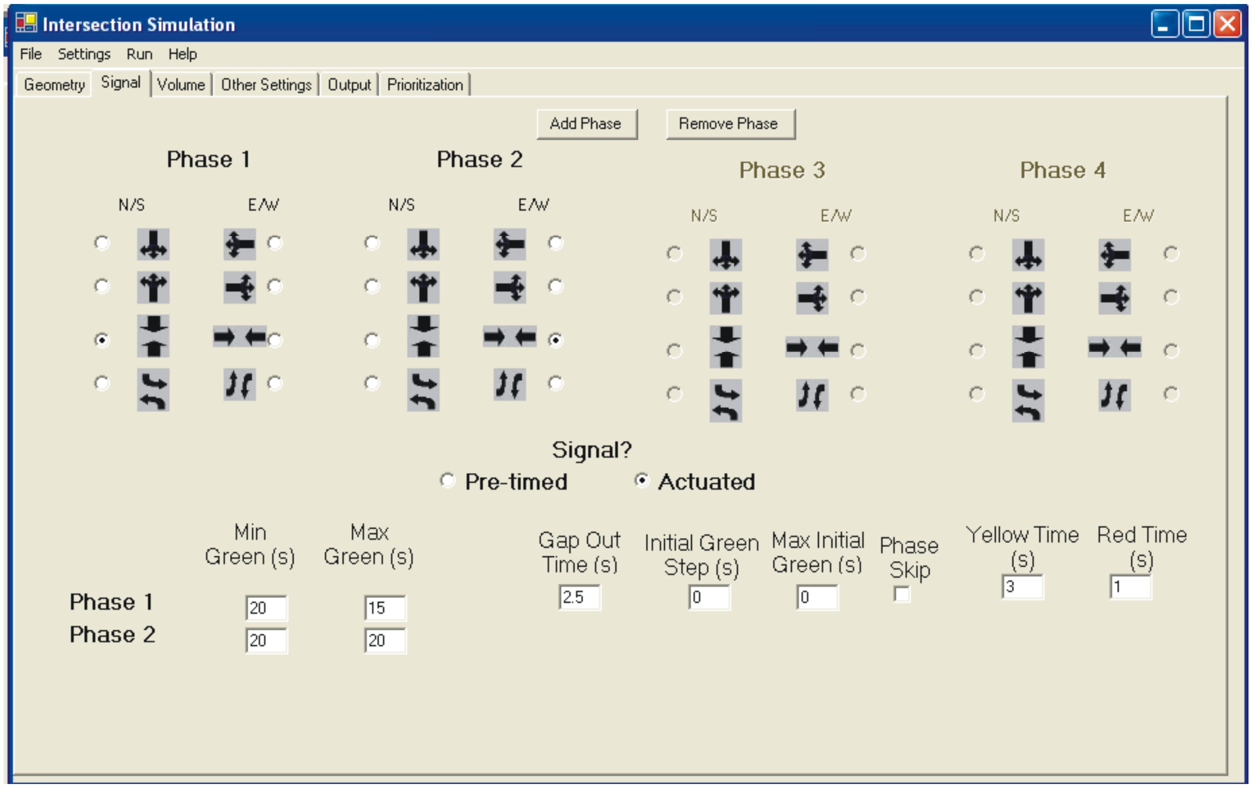

Figure 10. Screen Shot of Input Data Entry Interface in LTGAP

Unsignalized Program

The unsignalized intersection simulation is simpler than the signalized simulation since there are fewer conflict opportunities that occur. At unsignalized intersections, the only events are the arrivals and the departures of vehicles on various approaches. Cars on the minor streets have a lower priority than the major street traffic. In addition, the left-turning vehicles must look for a sufficient gap in the opposing traffic before they can successfully execute the left-turn maneuver.

Left-turn and rear-end conflict opportunities are counted in the program during the simulation. The method in which they are counted is explained in the "Methodology" section. These conflict opportunities are used as safety surrogate measures and are used to prioritize the candidate sites.

Vehicle Generation and Arrival-Departure Module

The arrivals of vehicles in LTGAP are predetermined by the program and depend on the volumes entered by the user. The average time-headway is calculated from the volumes, and the vehicles are generated on that approach with that mean headway according to a negative exponential distribution. The departures are calculated "on the fly" by the program. If the vehicle did not stop at the intersection, the departure time is equal to the arrival time, but if the vehicle had to stop at the intersection, its departure time is calculated and assigned. At unsignalized intersections, left-turn vehicles might have to stop because of the lack of a suitable gap and through vehicles may be forced to stop while a left-turning vehicle is waiting for an acceptable gap. A turning movement is assigned to every vehicle depending on the proportion of vehicles turning left and right on the approach as entered by the user. For example, the user enters a left-turning proportion of 0.3, and then 30% of all the vehicles generated by the program on that approach will be left-turning vehicles.

Stochastic Gap Acceptance Module

As discussed earlier, critical gap plays an important role in determining the delay experienced by the left-turning vehicles. In the real world, the critical gap is not constant for the driver population. To account for this variability, the program estimates the mean critical gap of the driver population based on the HCM (1985) unless the user provides a field-measured critical gap value. As the field data matched better with the 1985 HCM critical gap model than that of 2000 HCM, the 1985 HCM was adopted for this study. It is noted that the proposed 2000 HCM critical gap model was developed on the basis of a limited number of sites, and the R^2 value of the regression model was 0.12 for the major street left-turn vehicles (Tian et al., 2000).

To estimate the standard deviation of the critical gaps, the bootstrap method (Efron and Tibshirani, 1993) was used. The bootstrap method is a procedure in which the samples are selected from the original samples with replacement and the standard deviation of the critical gap is estimated over multiple samples. The results indicated that the standard deviation was almost constant at 0.25. It is assumed that the critical gap varies according to a normal distribution. Thus, the mean critical gap is determined from the 1985 HCM and the standard deviation of 0.25 was used. The impact of heavy vehicles on the critical gap was not explicitly considered in this study.

During the simulation, every left-turning vehicle simulated by LTGAP uses a stochastic critical gap. If the gap available to the left-turning vehicle is greater than or equal to its critical gap, the left-turning vehicle is discharged. Otherwise it has to wait (thereby blocking the lane) until a suitable gap is obtained. If two or more consecutive left-turn vehicles were making left-turn maneuvers, the gap should be greater than or equal to the summation of the critical gap assigned to the first left-turn vehicle and the follow-up times of the second and following left-turning vehicles. LTGAP uses the follow-up time of 2.2 seconds from the HCM (2000).

Lane Blockage Module

Whenever the lane is blocked during the simulation, the vehicles will be queued. Every vehicle has a length attribute assigned to it when it is generated. If the sum of the lengths of the vehicles in the queue is greater than the left-turn lane length, then the adjacent lanes are blocked and vehicles in that lane queued up.

Queue Dissipation Module

When the queue starts dissipating in LTGAP, the basic assumption is that vehicle headways at saturation flow are constant at 2 seconds. Therefore, departure times of successive vehicles in the queue differ by 2 seconds.

MOE Counter

LTGAP was coded with a counter that keeps the counts of applicable MOEs throughout the simulations. These counters do not start counting the MOE until the warm-up time is passed at the beginning of each run. These MOEs were used to validate LTGAP results. For the unsignalized intersection validation, the MOE used was "number of left-turning vehicles stopped" in the simulation (per hour). This MOE was updated whenever the left-turning vehicle on the subject link was stopped.

Example

The operation of the unsignalized module is best illustrated through a simple example. Assume that the user wants to simulate a T-intersection (three approaches) with one lane of traffic on each direction (NB, SB, and EB) as shown in Figure 11. All lanes are shared and are assumed to be of infinite length; the subject link is the NB approach (subject link is the link where the left-turn improvement study is being conducted). Assume there are no right turns at the intersection (right-turn volume = 0) and the percentage left-turn is 10%. Further assume that the volumes on the NB and SB approaches (as entered by the user) are 500 vph each and the volume on the EB approach is 100 vph.

In the LTGAP simulation program, vehicles are generated at random intervals by following a negative exponential distribution and the turn intention is assigned based on the percentages of left, through, and right turns. When the left-turn vehicle is being processed in the program (say, on the NB approach), the program checks for gaps on the opposing approach (the difference in the arrival times of opposing vehicles, in this case, SB vehicles). If the observed gap is greater than the critical gap of the vehicle, the maneuver takes place. If not, the left-turn vehicle waits until a suitable gap is obtained. While the vehicle is waiting, newly arriving vehicles are forced to wait (since the lane is blocked). The arrival and departure log is maintained at all times in the simulation. The arrival and departure time of each vehicle, its turn direction (left, through, or right), and the lane/approach used are also recorded in the log.

The instances of left-turn vehicles blocking the through vehicles are counted during the simulation. If the counted number is greater than the critical probability value in Table 1, then the left-turn lane is warranted for that particular volume combination and in that simulation run. This is the MOE used in recommending the left-turn lane for unsignalized intersections. Moreover, there are counters in the program that count the left-turn and rear-end conflict opportunities occurring on the subject link. These conflict opportunities were used for the prioritization tool.

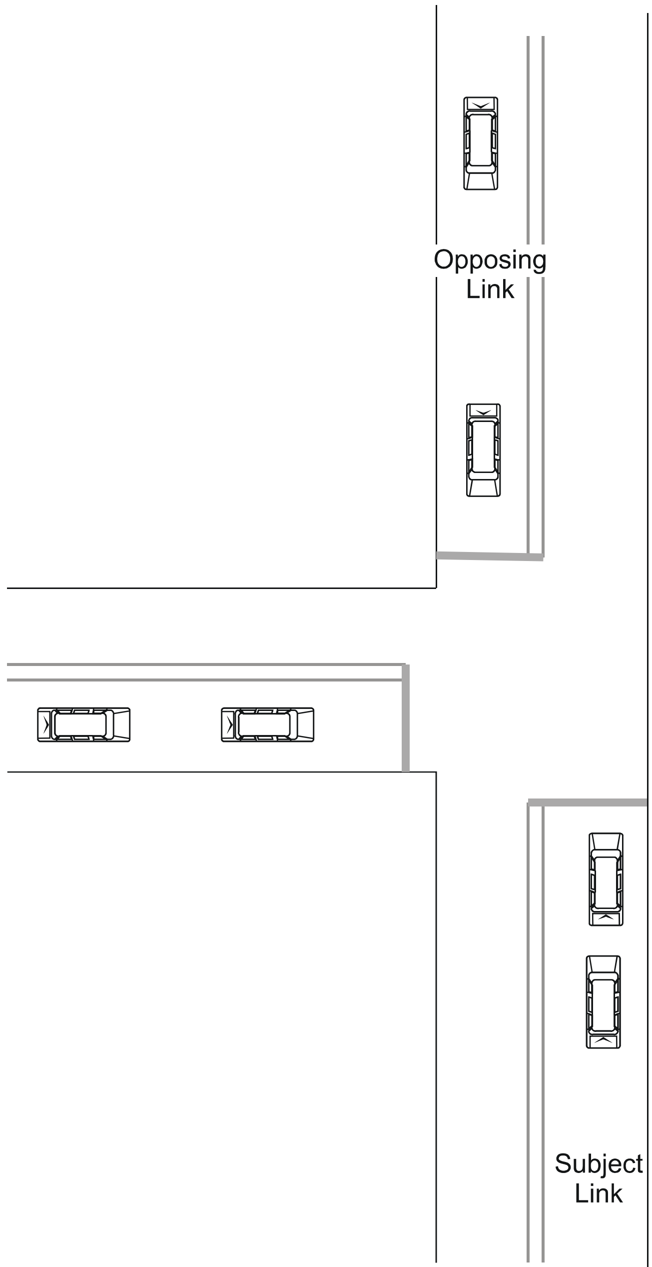

Figure 11. Layout of Typical T-Intersection

Termination of the Simulation

The simulation run ends when the specified time limit of the run is reached. The user, in the configuration file, specifies the duration of each run and the number of runs required. The LTGAP program will cease running when all the runs are completed. Since all the MOEs are written in the text files on the fly, LTGAP need not perform any calculations once the simulations are completed.

Actuated Signal Program

The signalized program was used to generate left-turn guidelines for a two-phase pre-timed signal, although it is capable of modeling actuated signals. All of the sites where field data were collected were actuated signals. For actuated signals, each phase has a maximum and minimum green with a gap-out time. The program has the features of simultaneous gap out and phase skip, which often occur at rural intersections. Simultaneous gap-out allows the current phase to change to the next phase only when both approaches of the current phase had gap-outs. This feature plays an important role where there are unequal volumes on the major street. Some candidate sites had unequal volumes on the major street. In the sites where data were collected, phase skipping was observed. This meant that unless there was a demand call on the side street, major street green would continue even after the maximum green. The events in the signalized program are vehicle arrivals, vehicle departures, and signal changes.

Although the program has the above-described features, its functions are limited and it does not consider the following features:

- pedestrian phases
- delayed presence detection and locking/non-locking type detectors
- overlap of phases in the timing plan
- reduction of gap-out times with time
- protected lefts (with or without exclusive left-turn lanes) on the subject link
- recall on/off feature
- signal preemption.

Optimization of Signal Timing Plan Before Simulation

In the signalized simulation, the cycle length entered by the user is optimized before the simulation was started since the existing timing plan might be outdated. The user also has an option of not optimizing the timing plan and just simulating the current conditions in the field. Since optimization of cycle length is not the primary focus of this study, Webster's equation for optimum cycle length was used.

$$C_o = \frac{1.5L + 5}{1 - \sum Y_i} \qquad [5]$$

where

C_o = optimum cycle length
L = total lost time for the cycle, which is the sum of the lost times for individual phases
Y_i = maximum of v/S for all phases, where v is the volume and S is the adjusted saturation flow rate.

The saturation flow rate has to be adjusted for shared lane approaches, and the adjustment depends on the g/C ratio. Therefore iteration has to be performed with an initial approximation of the cycle length. Since the cycle length, C, of an actuated signal varies, an initial cycle length has to be assumed between minimum and maximum cycle lengths. The maximum cycle length occurs when all the phases max out, and the minimum cycle length is obtained when all the phases gap-out after minimum green. With this initial approximation, a C_o was calculated and in the next iteration the cycle length was assumed to be C_o. The HCM 2000 methodology was used to calculate the adjusted saturation flow. (See Appendix B for a sample calculation.) The iterations continued until two consecutive iterations yielded cycle lengths differing by less than 5 seconds. All the modules explained for the unsignalized program are valid for the signalized program. The signalized program uses a few more modules that are explained below.

Signal Change Module

The module for starting and ending the green times is explained in Figure 12. The minimum green can vary from a minimum value to a maximum initial value provided by the user. Figure 12 provides details on the duration of green signal to be displayed. The assumption is that the phase skip feature is disabled and therefore the maximum displayed green time cannot be greater than maximum green.

Both pre-timed and actuated signals can be simulated in the LTGAP program. For actuated signals, all the green times were varying between minimum green and maximum green. Phase skip would cause the green to extend beyond maximum green if there is no conflicting demand call. For pre-timed intersections, minimum and maximum greens were equal.

When the signals are green on an approach, the through and right-turning vehicles can proceed without any delay as long as the vehicle is the first one in the queue. A left-turn vehicle could proceed provided that the gap on the opposing flow is greater than the critical gap assigned to the left-turn vehicle.

When the signal is yellow, it is treated as a "green" in the first 50% of the yellow time and is treated as "red" in the remaining 50% of yellow time. The arrival and departure module for signalized intersection is shown in Figure 13.

When the signal is red on an approach, the through and left-turning vehicles had to stop until the signal changed to green. The right-turning vehicles could proceed if the following conditions were met:

1. Right turn on red (RTOR) Boolean variable in the configuration file is set to "enabled."

2. Gap greater than the critical gap was available on the lane in which the turn is being made. The critical gap is determined by the same module used in the left-turning vehicle critical gap.

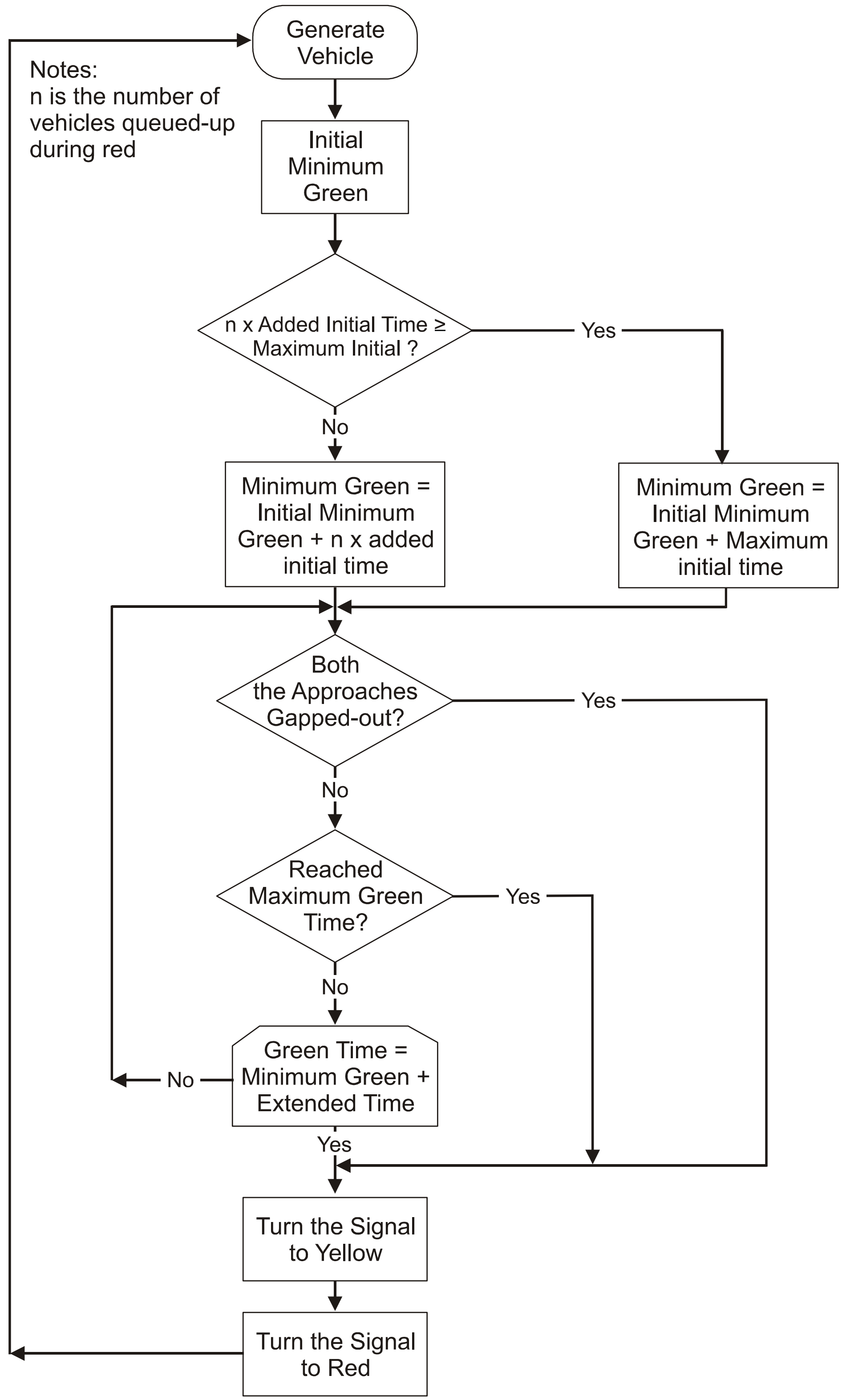

Figure 12. Flowchart of Green Time Module for Actuated Signal in LTGAP

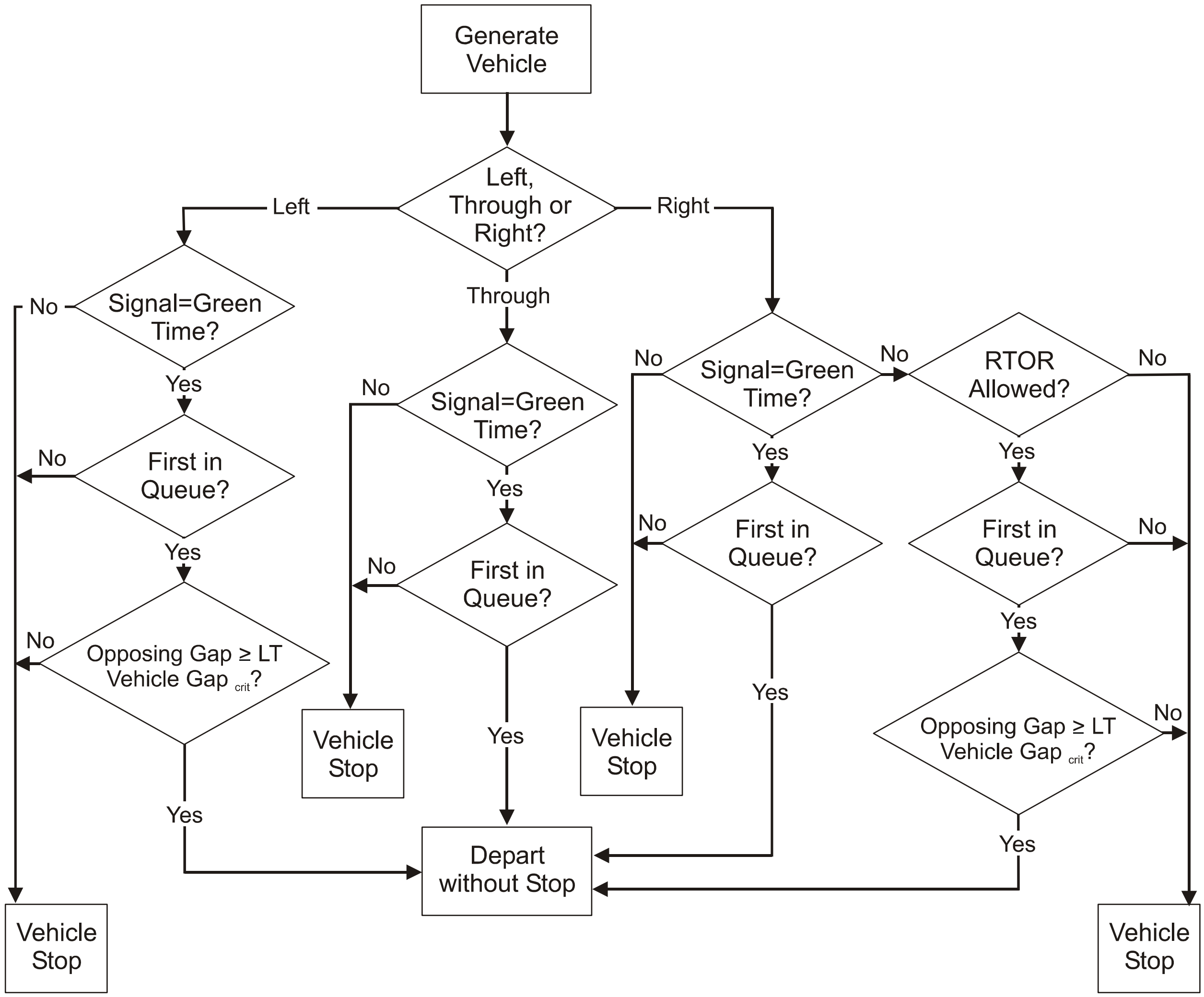

Figure 13. Vehicle Arrival-Departure Module for Signalized Intersections in LTGAP

MOE Counter

The counters in the signalized program generate the MOEs used in the validation. The MOEs are maximum queue length and stop delay for the left-turn vehicles on the subject link. The maximum queue length counter in the program was updated whenever a vehicle joined the queue and the signal was red. The maximum queue length counter did not update itself when the signal was green. In other words, this counter did not consider the queue build-up that would continue (for the initial portion of the green) even as the signal turns green. When this MOE was reduced from the tapes, this point was kept in mind and vehicle counting stopped as soon as the signal turned green.

Example

Consider a fully actuated, two-phase, intersection with four approaches and one lane of traffic for all directions of traffic as shown in Figure 14. Assume all lanes are shared and the

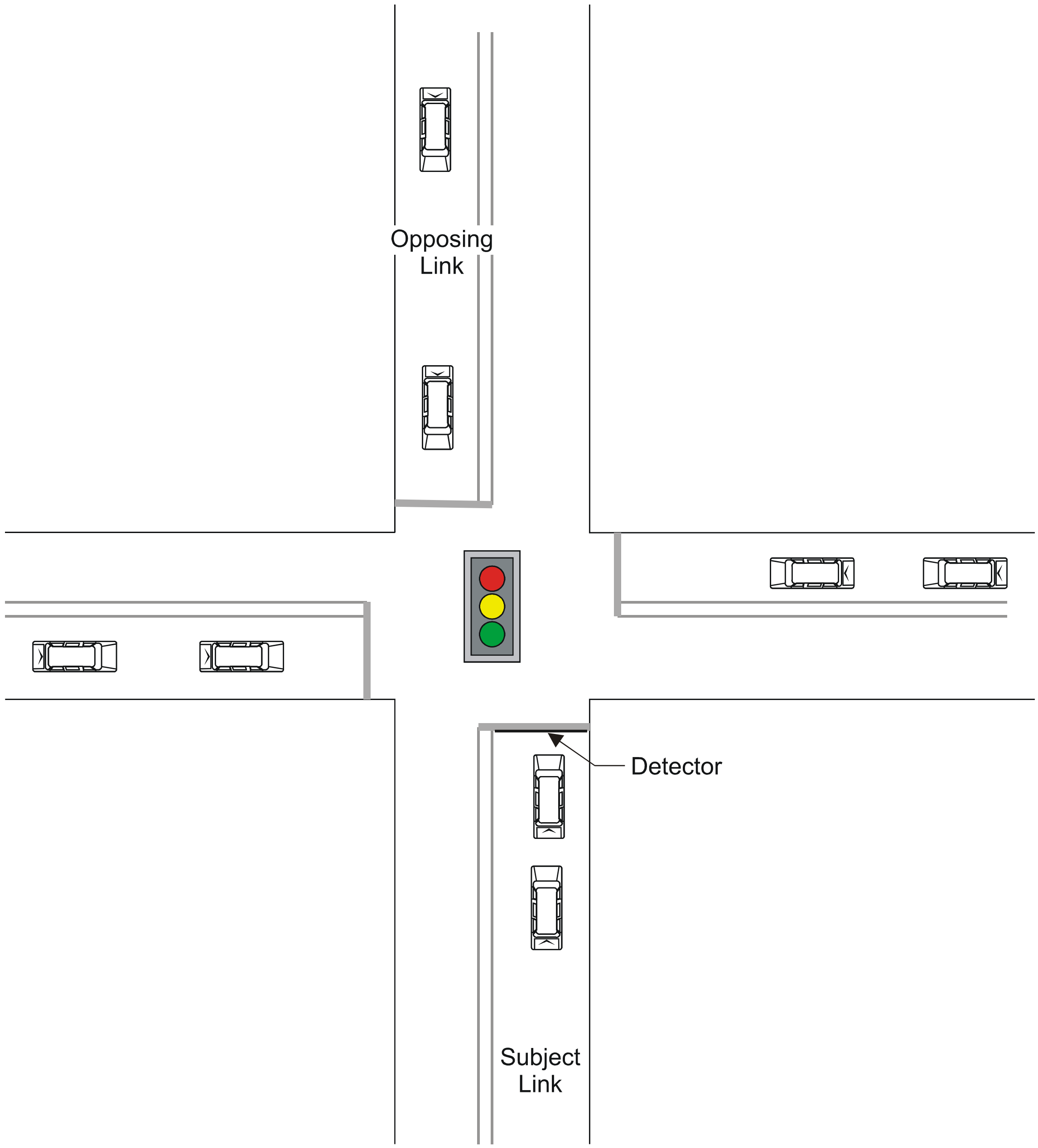

Figure 14. Layout of Typical Four-Leg Signalized Intersection

maximum and minimum greens are 10 and 30 seconds, respectively. Further assume that there are 10% left-turn vehicles and 10% right-turn vehicles on all approaches and the volume on each approach is 500 vph. The gap-out time for that particular controller is 2.5 seconds, with the yellow and all red times being 4 and 2 seconds, respectively.

The program generates vehicles on each approach according to the demand volumes (500 vph on all approaches in this case). It also generates the left-turn and right-turn vehicles according to the user defined percentages (10% in this case). This module for generation of the vehicles is identical in the actuated and unsignalized simulation programs.

The actuated program handles two more events than does the unsignalized simulation program. These events are the change of signal from green to red and the change of signal from red to green. The vehicles have to start discharging (or stop discharging) depending on these events. Moreover, these events depend on the arrivals of the vehicles (i.e., gap-outs). The program keeps track of the times of vehicle arrivals on each approach and checks for gaps on green approaches until the gap-out or max-out occurs.

The program first optimizes the timing plan, if opted, entered by the user for the particular volumes before it starts the simulation. This optimization is performed using the optimum cycle length equation as proposed by Webster. The user has an option of evaluating the current signal settings without optimizing them. For the calculation of v/s for the shared lanes, the HCM procedure is adopted.

For phase 1, NB and SB approaches have green. The vehicles are currently being discharged from these approaches. The through vehicles leave the intersection as the green is on, where left-turn vehicles will make turning maneuvers as long as sufficient gaps in the opposing flow are available. Assume that the gap-out occurs for this phase at t = 20 seconds. The program calculates the gap in the traffic flow by subtracting the departures of consecutive vehicles on the approach. If this gap is greater than the specified gap-out time (say, 2.5 seconds), the approach is termed as gapped-out for that phase. Then the vehicles queued up on the other approaches (EB and WB) are discharged at a saturation headway of 2 seconds at t = 26. Note that 6 seconds is the sum of the yellow and all red times. Again the same conditions for the signal change have to be satisfied (max-outs and conflicting demand call, or simultaneous gap-out) for the green to be served to the NB-SB phase again. The system keeps track of the vehicle arrivals, and the time the signal changes are also determined ahead of time by the program.

The MOEs used for validation of this program are stop delay for the left-turning vehicles on the subject link and the maximum queue length on the subject link. The program calculates the amount of time the signal was green on a particular approach. In addition, the program calculates the number of vehicles that are in the queue at the end of the red phase. They were compared with the values reduced from the videotapes. The performance of the program and the results of the validation of the program are discussed in detail in the "Results" section.

Pre-timed signals are a special case of actuated signal. If the minimum green and the maximum green of the actuated signal become equal, the signal becomes a pre-timed signal. So the discussions are valid for pre-timed signals as well. To use the simulation program for pre-timed signals, the maximum green and the minimum green must be set to be identical.

Validation of Program

Unsignalized Simulation Program

As mentioned in the "Methodology" section, the number of left-turning vehicles that stopped at the intersection was selected as an MOE in the validation of the event-based program. This field MOE was reduced from the videotapes. The results of this data reduction are shown in Table 11.

These sites were simulated in the program, and the same MOE was calculated for 100 times through multiple simulation runs. Two sample histograms of the MOE that were output from the program and the appropriate field value are shown in Figures 15 and 16.

Similar validation was done at other sites, and the field values were observed to vary close to the mean of the simulations. It can be concluded that the unsignalized simulation program reflects field conditions very well.

Table 11. Field Measured MOEs at Unsignalized Intersections

Site ID	Intersection Name	Total Left-Turn Volume on the Subject Link (vph)	Observed Number of Left Turning Vehicles That Stopped (vph)	Simulated Average of Number of Left Turning Vehicles that Stopped (100 Simulations)
1	SR 20 and SR 6	101	31	37
2	US 15 and SR 636	40	0	0.95
3	SR 151 and SR 6	108	20	17
4	SR 22 and SR 731	8	0	2.6
5	US 15 and SR 650	14	6	5.44

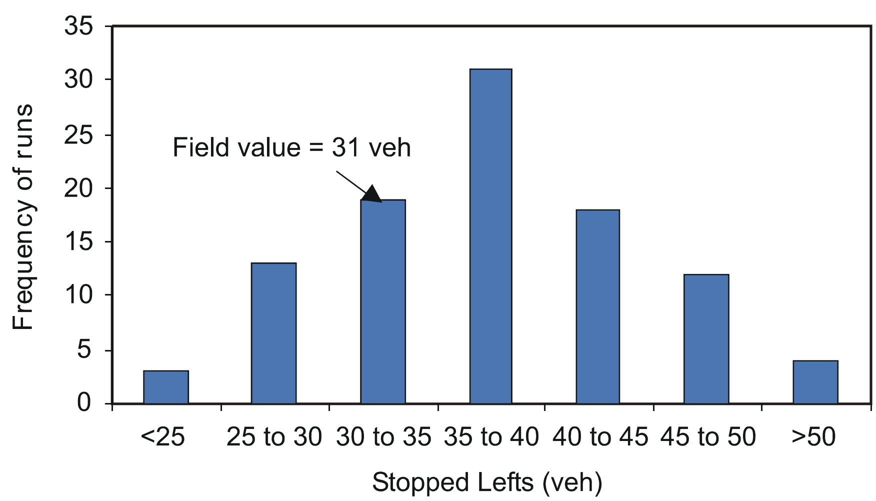

Figure 15. Histogram of Number of Stopped Left-turn Vehicles at SR 20 and SR 6

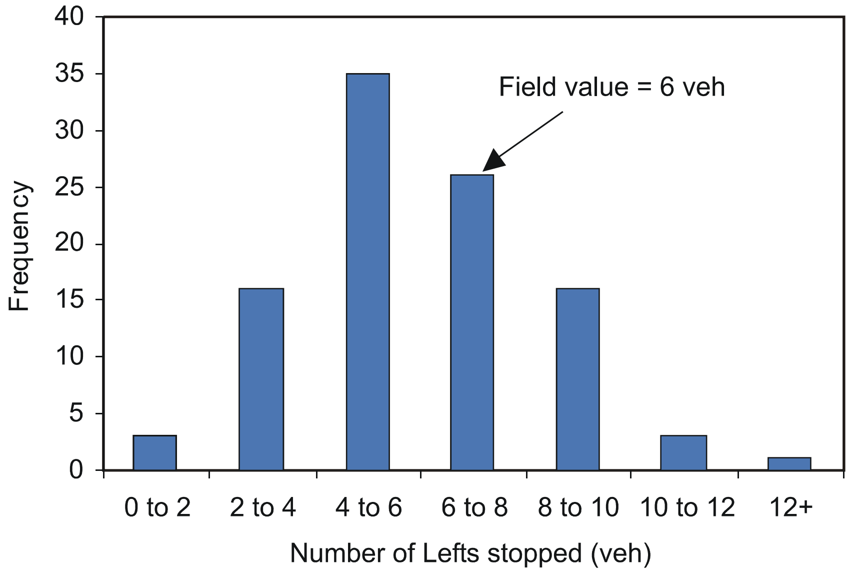

Figure 16. Histogram of Number of Stopped Left-turn Vehicles at US 15 and SR 650

Signalized Intersection Simulation Program

The data from the signalized intersections were reduced, and the simulation program was validated with the reduced field data. For the validation of the signalized sites, the MOEs used were stop delays for the left-turning vehicles on the subject link and maximum queue length on the subject link.

The queue length on the subject link was recorded at the end of each red time for every site. This was done for 1 hour of the data on the videotape. The maximum of these queue lengths was the maximum queue length shown in Table 12. The field value of the maximum queue could not be obtained at the intersection of US 250 and SR 616 because the STV was placed in such a way that the camera could not capture the end of the queue. The STV had to be placed in a particular manner because of the lack of sufficient shoulder width on the desired approach.

Table 12. Field Measured and Simulated Average Maximum Queue Lengths at Signalized Intersections

Site ID	Intersection	Max Queue in Field (number of cars)	Average of Max Queue (100 Simulations)
1	US 340, US 522 and SR 277	15	15.31
2	US 15 and US 250	11	9.45
3	US 33 and New bridge road	5	2.16
4	US 1 and Lakeside Avenue	11	1.83
5	US 250 and SR 616	–	7.84
6	SR 28 and SR 652	8	6.06

In general, the simulation program replicates field maximum queue lengths fairly well except for site 4. This was due to the difference in the number of signal phases used in the simulation program and the field. The field signal uses three phases, whereas the simulation program was implemented as two phases.

A counter was added in the simulation program that counts the number of vehicles stopped at the end of each red interval and output the maximum value. This was done for every run of the simulation; so for 100 runs of simulations, 100 maximum queues were generated. This was plotted as a histogram and compared with the observed field value. Figures 17 and 18 show the histograms for each of the signalized sites. Since the observed field value of the maximum queue lies within the simulation results (histogram), the program was considered validated.

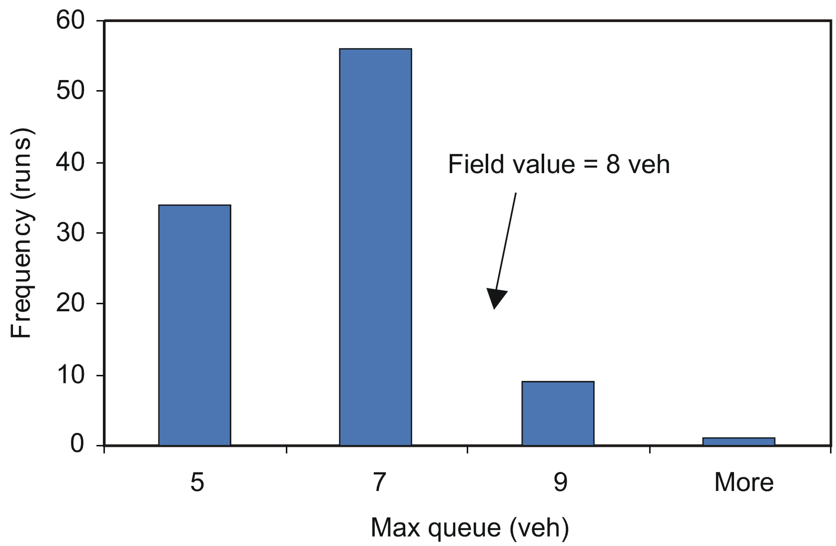

Figure 17. Histogram of Maximum Queue Length at SR 28 and SR 652

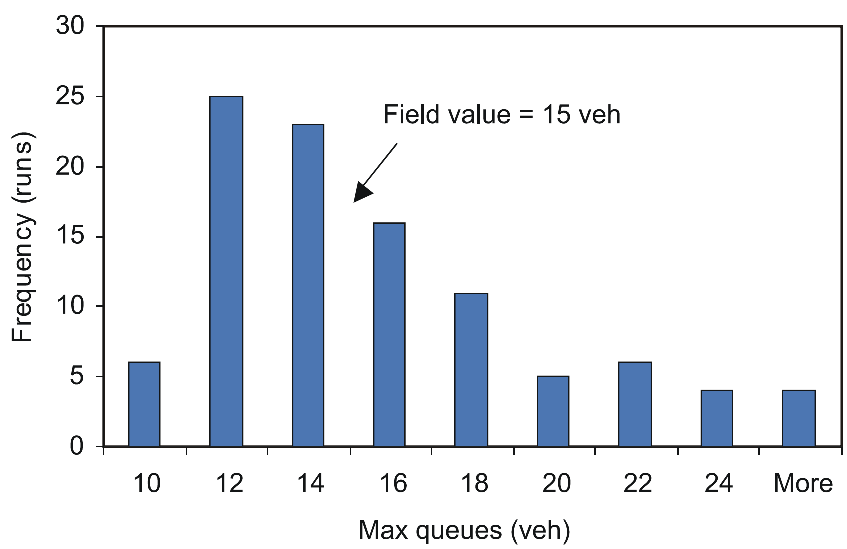

Figure 18. Histogram of Maximum Queue Length at US 340, US 522, and SR 277

Another MOE was the stop delay of the left-turning vehicles. The field value of this MOE was reduced from the videotapes. The results of this data reduction are shown in Table 13. The total time each left-turning vehicle on the subject link had to stop before proceeding through the intersection was calculated by viewing the videotapes. This delay was summed up for 1 hour of data reduction and was divided by the total number of left-turning vehicles. This gave the average stop delay for the left turns on the subject link. This MOE was later generated from the program. The program outputs this parameter for every simulation run. This was repeated for 100 simulation runs and the histogram was plotted. Figures 19 and 20 show the histograms of this MOE at each signalized sites. Since the observed field value of the left-turn stop delay lies within the simulation results (histogram), the program was considered validated.

Table 13. Field Measured and Simulated Left-turn Stop Delay at the Signalized Intersections

Site ID	Intersection Name	Stop Delay for Left Turns From Field (Sec/Veh)	Average of Left-Turn Stop Delay for 100 Simulation Runs
1	US 340, US 522 and SR 277	47.2	37.25
2	US 15 and US 250	16.9	13.64
3	US 33 and New Bridge Road	11.7	11.94
4	US 1 and Lakeside Avenue	23.5	30.52
5	US 250 and SR 616	N/A	13.26
6	SR 28 and SR 652	23.9	22.03

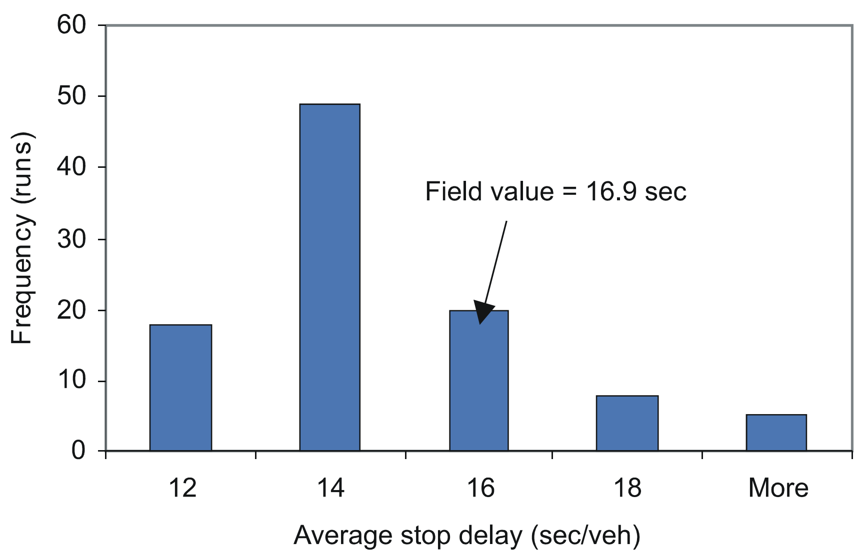

Figure 19. Histogram of Left-turn Stop Delays at US 15 and SR 250

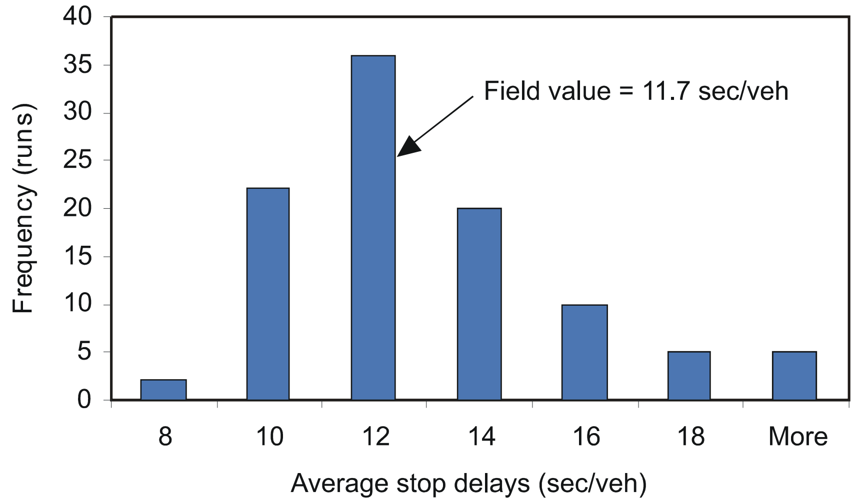

Figure 20. Histogram of the Left-turn Stop Delays at US 33 and New Bridge Road

New Guidelines

Evaluation and Determination of Guideline Criteria

None of the creators of the existing guidelines used cost-benefit analyses in the development of the guidelines. For example, Harmelink (1967) used probability of left-turn vehicles blocking through vehicles on the subject link, and Kikuchi and Chakroborty (1991) used an arbitrary delay (i.e., LOS A/B transition value) of through vehicles.

The installation costs of left-turn lanes in Virginia were examined. Tables 14 and 15 show the installation costs of unsignalized and signalized intersections from several districts in Virginia as determined by VDOT's Cost Estimation System. A preliminary study indicated that

Table 14. Installation Cost ($) of Left-Turn Lane at Unsignalized Intersections

District	Fixed Cost per Left-Turn Lane	Cost per Foot of Deceleration Lane
NOVA	135,000	1,200
Salem	117,750	1,025
Bristol	110,250	975
Lynchburg	110,250	975
Richmond	128,500	1,150
Hampton Roads	135,000	1,200
Fredericksburg	123,250	1,075
Culpepper	123,250	1,075
Staunton	117,750	1,025
Average	*$122,333*	*$1,078*

Table 15. Installation Cost ($) of Left-Turn Lane at Signalized Intersections

District	Fixed Cost per Left-Turn Lane	Cost per Foot of Deceleration Lane
NOVA	226,000	1,200
Salem	195,750	1,025
Bristol	185,250	975
Lynchburg	185,250	975
Richmond	215,500	1,150
Hampton Roads	226,000	1,200
Fredericksburg	206,250	1,075
Culpepper	206,250	1,075
Staunton	195,750	1,025
Average	*$204,667*	*$1,078*

the delay saving itself would not be adequate to justify the installation of a left-turn lane. For example, consider a signalized intersection where a left-turn bay with 550 ft of deceleration lane (including taper length) is being installed on an approach. From the average construction cost in Table 15, the cost would be $204,667 + 550 ft × ($1,078/ft) = $797,567. If peak hour subject link volume at a hypothetical site is 515 vph and a delay saving of 10 sec/vehicle, the estimated delay saving, assuming $10 per person hour time value and an interest rate of 8%, over 20 years would be $55,367. If the cost-benefit analysis was used to justify the left-turn lane installation, it would not be practical. An MOE based solely on delay would not be adequate to evaluate the economic value of installing a left-turn lane at an intersection.

Thus, this study developed general guidelines and investigated a prioritization tool. The general guidelines are based on operational analyses, and the prioritization tool considers both operational and safety aspects when multiple candidate intersections need to be ranked for prioritization.

The proposed guidelines for unsignalized intersections used Harmelink's critical probability values for two reasons. First, the Harmelink guidelines have been used over 35 years and the concept used in the guideline development is well accepted by practitioners. Second, the Harmelink guidelines consider the impact of operating speed. As discussed earlier, Harmelink obtained the tolerable probabilities of the time that through vehicles were delayed via a survey of engineers. This study also adopted the probability numbers used by Harmelink (see Table 1), as they seemed reasonable. In addition, the decrease in the tolerable probability with increasing speed made sense because left-turn lanes are more likely to be warranted from a safety perspective at higher speeds than at lower speeds.

To determine the criteria for left-turn lane guidelines at signalized intersections, the criteria used in existing guidelines were evaluated. The guidelines of Oppenlander and Bianchi (1990) were evaluated through a microscopic traffic simulation program, SimTraffic (Trafficware, 2001), and it was found that their recommended guidelines provide unacceptably high delays. In other words, these guidelines are too conservative and users would experience extremely high delays if they were used. Further, from the survey conducted among VDOT traffic engineers, none used Oppenlander and Bianchi (1990) guidelines.

A combination of delay and v/c ratio was used to determine the need for a left-turn lane at signalized intersections. When the 85th percentile capacity volume was used for the guideline, left-turn vehicle delays higher than 55 seconds per vehicle were often observed. In order to maintain left-turn vehicle delay at or lower than LOS E, a delay criterion was also added. Thus, the proposed general guidelines for signalized intersections were based on two criteria: 85% of left-turn capacity and average left-turn delay of 55 seconds per vehicle. The guidelines were developed using the lowest value of these two criteria obtained from the event-based signalized intersection program.

To determine the capacity of a signalized intersection, several steps had to be followed. Traffic demand volume on a subject link volume was increased to a large value (e.g., 2000 vehicles/lane), and turning percentages and all other demands were kept as they were. An average left-turn throughput on a subject link from 100 multiple simulation runs determined estimated left-turn capacity.

LTGAP Guidelines

Unsignalized Intersection Guidelines

The LTGAP guidelines for unsignalized intersections were developed by analyzing the percentages of left turns blocking through vehicles using the unsignalized intersection simulation program. Multiple simulation runs were made for each combination of opposing and advancing vehicle volumes and left-turn percentages under varying operating speed conditions. An intersection meets the requirement for left-turn lane installation if the intersection of advancing and opposing volumes lies above the guideline line. LTGAP guidelines are in the form of graphs for unsignalized intersections. A sample of LTGAP guidelines under 20% left-turn vehicles on advancing volume is shown in Figure 21. A complete set of guidelines is provided in Appendix C.

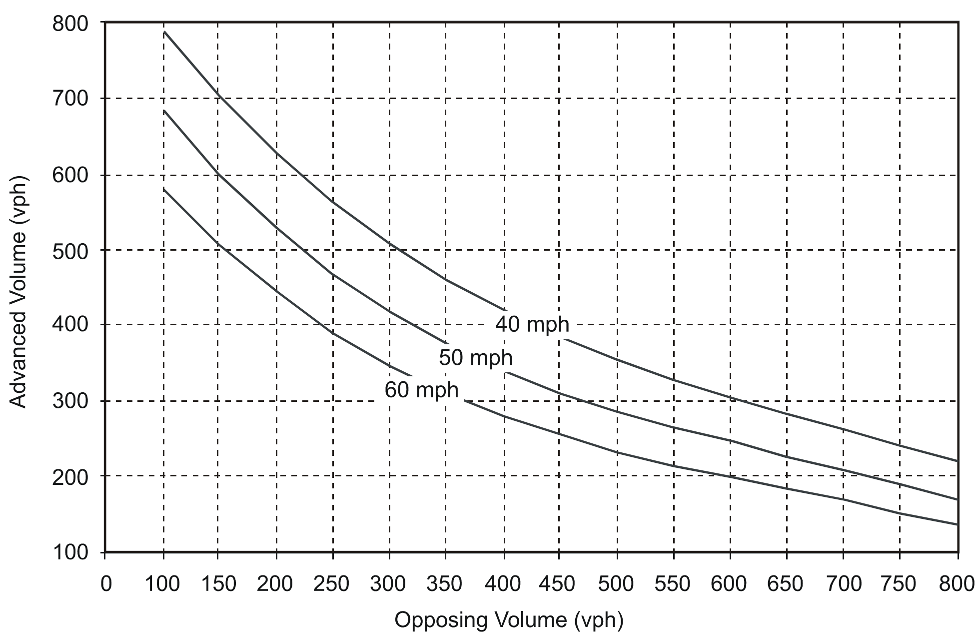

Figure 21. Sample LTGAP Guideline for Unsignalized Intersections (20% left turn)

Two samples of LTGAP guidelines were compared with the existing Harmelink (1967) and Kikuchi and Chakroborty (1991) guidelines as shown in Figures 22 and 23. The proposed

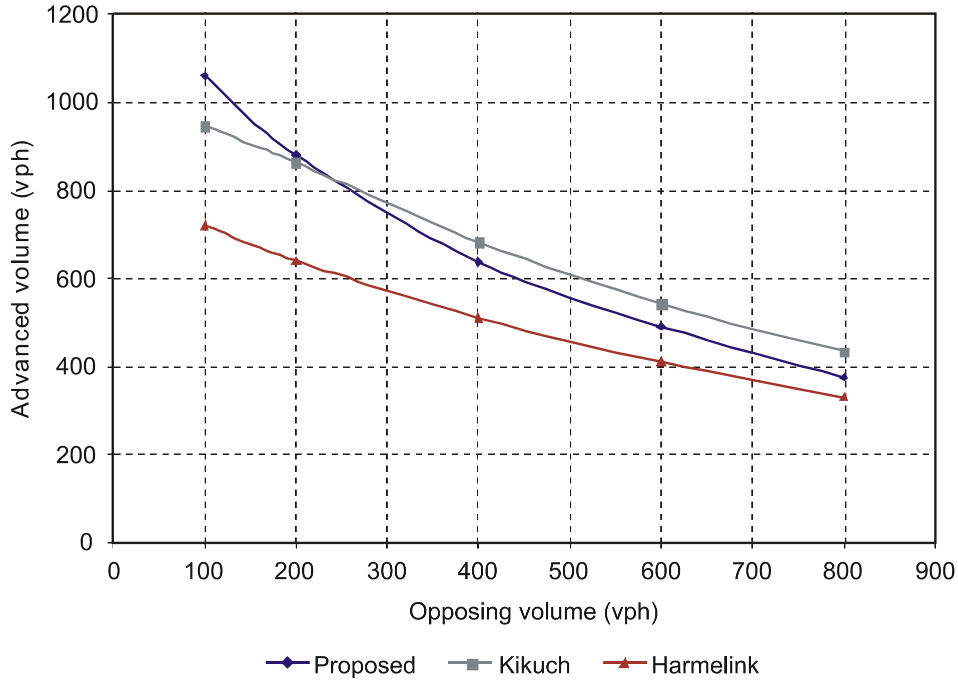

Figure 22. Comparison of LTGAP and Harmelink, and Kikuchi Guidelines (5% left turns, 40 mph speed)

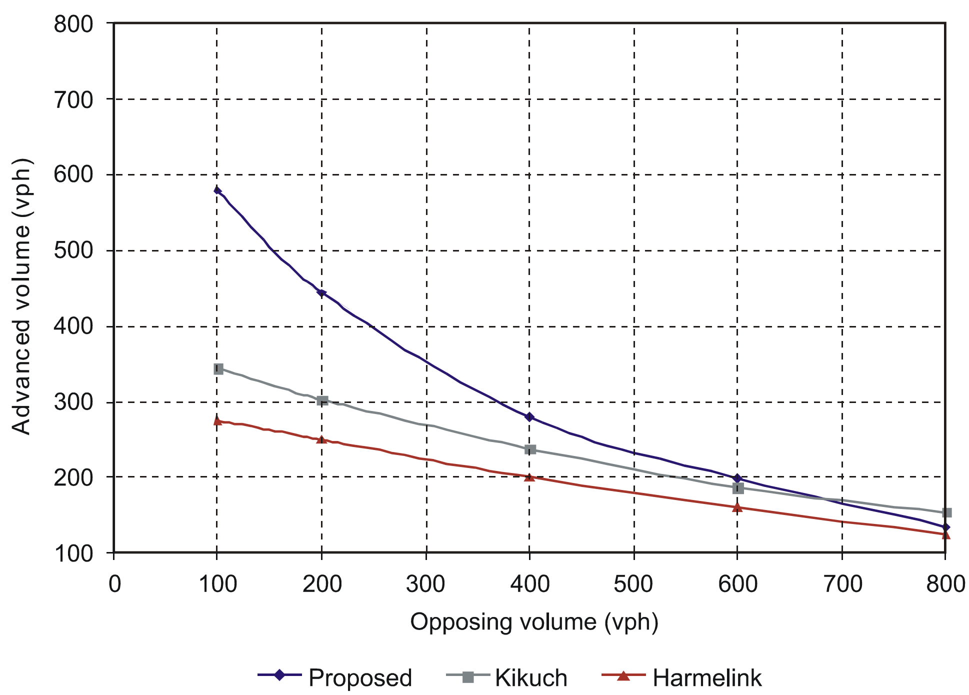

Figure 23. Comparison of LTGAP, Harmelink, and Kikuchi and Chakroborty Guidelines (20% left turns, 60 mph speed)

LTGAP guidelines are different from the other two guidelines because they were developed from analytical equations with a fixed critical gap of 6 seconds, whereas LTGAP is a stochastic simulation model with advanced features such as a variable critical gap for left-turn vehicles. Note that the critical gap of 6 seconds is a little higher than that of the 1985 HCM recommended value especially for left turn from major road. As can be seen in Figures 22 and 23, the LTGAP guidelines would recommend left-turn lanes at higher advancing volumes for lower opposing volumes when compared with the Harmelink and Kikuchi and Chakroborty guidelines. This is because the proposed guidelines use a smaller critical gap value (5 to 5.5 seconds vs. 6 seconds) and follow-up time (2.2 seconds vs. 3 seconds). The discrepancies become more apparent for high left-turn percentage with low opposing volumes.

Signalized Intersection Guidelines

The LTGAP signalized intersection guidelines were again developed using the event-based simulation program. Multiple simulation runs were made for each combination of opposing vehicle volumes, left-turn percentages, cycle length, and green split ratios under varying geometry conditions. The proposed guidelines were presented in the form of tables. A sample of left-turn guidelines at signalized intersections is shown in Table 16. The complete sets

Table 16. Sample of Signalized Intersection Guidelines for 30% Left Turn, Cycle Length = 100 sec, Two Lanes (Advancing Volumes in Vehicles per Hour Are Shown)

Opposing Volume (vph)	Green Split Ratio (g/C) at Study Approach						
	0.2	0.3	0.4	0.5	0.6	0.7	0.8
100	125	325	500	645	785	930	1075
150	50	250	445	595	735	875	1010
200	50	165	365	540	680	815	945
250	50	60	285	470	630	760	890
300	50	50	200	390	565	700	830
350	50	50	115	315	485	640	770
400	50	50	50	230	410	575	710
450	50	50	50	160	340	495	655
500	50	50	50	70	260	425	575
550	50	50	50	50	185	350	505
600	50	50	50	50	120	285	430
650	50	50	50	50	50	210	360
700	50	50	50	50	50	155	295
750	50	50	50	50	50	80	225
800	50	50	50	50	50	50	155
850	50	50	50	50	50	50	105
900	50	50	50	50	50	50	50
950	50	50	50	50	50	50	50
1000	50	50	50	50	50	50	50
1050	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50

of guidelines for two-lane and four-lane approaches are provided in Appendices D and E, respectively. The guidelines are shown in terms of advancing volumes in vehicles per hour for a given left-turn percentage, opposing volume, cycle length, and green split ratio. For example, for a left-turn percentage of 30%, cycle length of 100 sec, green ratio of 0.5, and opposing volume of 400 vph, an advancing volume of 230 vph (from Table 16) or above would justify the installation of a left-turn lane.

Since the actuated signalized intersection does not maintain fixed cycle length and green times, these parameters are estimated from the event-based simulation. The simulation program uses minimum and maximum green times, gap-out times, and other parameters and outputs average green times and cycle length. Thus, these estimated average cycle lengths and g/C ratios are applied to the developed guidelines.

The LTGAP guidelines were compared with the Oppenlander and Bianchi (1990) capacity curve. Figure 24 plots the Oppenlander and Bianchi capacity curve and the LTGAP guidelines for different percentages of left turns of 3%, 5%, 10%, 20%, and 30%. As expected, the curves of the LTGAP guidelines are much lower than that of the Oppenlander and Bianchi.

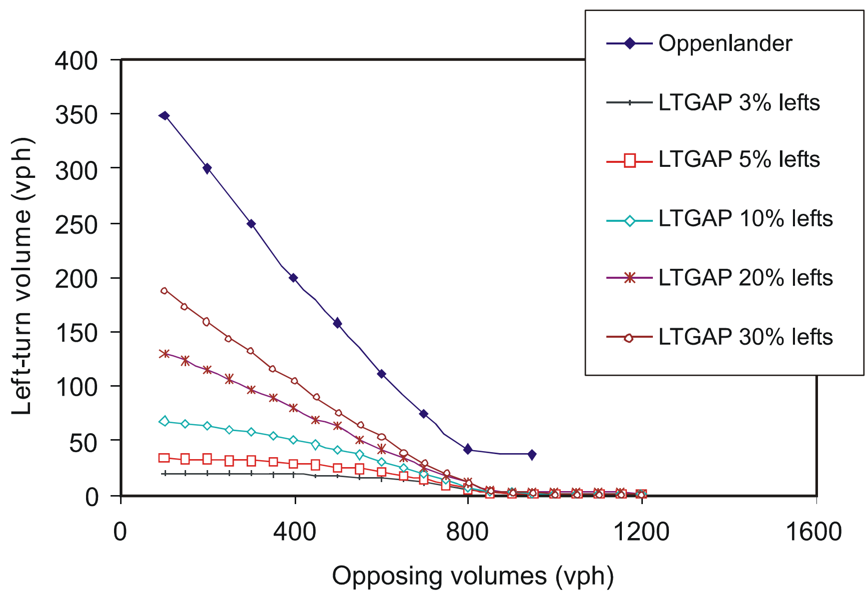

Figure 24. Comparison of LTGAP Guidelines and the Oppenlander and Bianchi Capacity Curve

Recommended Left-turn Lane Length

Signalized Intersections

Although recommending a left-turn lane length for a given volume condition was outside the scope of this study, a preliminary study was conducted using LTGAP, and the results are explained in this section. A hypothetical four-legged, simple two-phase, signalized intersection was simulated using LTGAP. The assumptions made were: pre-timed signal, g/C = 0.5, C = 60 seconds, $V_A = V_O$ = 500 vph, 30% left-turn vehicles on V_A. The MOE used was "percent of time the left-turn lane overflow occurred" in the simulation. LTGAP was modified to output this MOE, and it was plotted for different left-turn lane lengths on the subject link. The results shown in Figure 25 were based on 100 simulation runs.

Using this feature in LTGAP, a desired lane length could be determined for the candidate intersection by defining an acceptable probability of left-turn lane overflow. Comparison of these lane blockage conditions developed by LTGAP with the ones developed by Oppenlander and Bianchi is not directly possible because they recommended the left-turn volume at which there is a particular percentile (e.g., 50th, 85th, or 95th) storage of at least one left-turning vehicle whereas Figure 25 of LTGAP plots the percent of time left-turn bay overflow for a fixed volume, percentage of left-turn, and lane length.

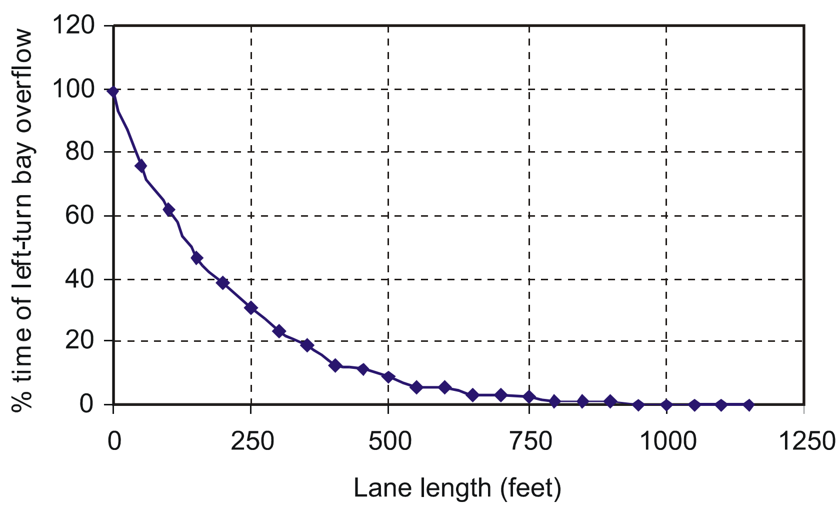

Figure 25. Example of Left-Turn Lane Length Analysis at Signalized Intersection Using LTGAP for Approach and Opposing Volumes of 500 vph, Cycle Length of 60 Seconds, G/C Ratio of 0.5, and 30% Left-Turn Vehicles

Unsignalized Intersections

The unsignalized program was used to investigate the required lane length for a specific combination of advancing volumes, opposing volumes, percentage of left turn vehicles and speed. The numbers used for this preliminary analysis were V_A of 800 vph, V_O of 500 vph, 20% of left-turn vehicles, and operating speed of 60 mph. The MOE obtained is plotted against the different left-only lane lengths and can be seen in Figure 26.

This analysis is an in-built feature of LTGAP and could be done for any volume and speed combination desired by the user. The result of the analysis could be used in determining the left-turn lane length to be installed at the intersection given the through blockage that is acceptable to the engineers.

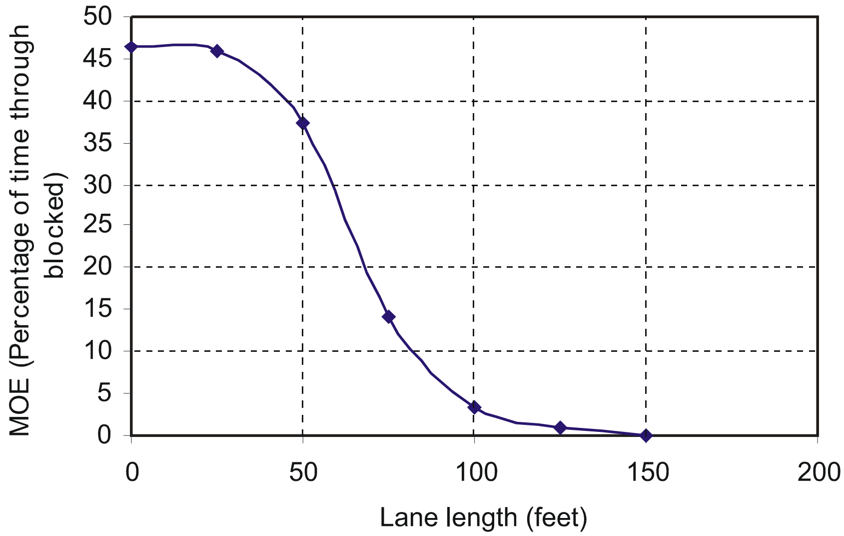

Figure 26. Example of Left-Turn Lane Length Analysis at Unsignalized Intersections Using LTGAP for Approach Volume of 800 vph, Opposing Volume of 50 vph, With 20% Left-Turn Vehicles

Prioritization Tool

The proposed prioritization tool was applied to the candidate intersections for demonstration purposes. Unsignalized and signalized intersection results are shown in Tables 17 and 18, respectively. As can be seen in Table 17, rankings based on operational score changed at unsignalized intersections when safety surrogate scores were considered. However, for signalized intersections, the consideration of safety surrogate scores did not change the rankings.

Table 17. Results of Prioritization Tool at Unsignalized Intersections

Site Name	Operational Score (% left blocking through)	Normalized Operational Score (NOi)	ΔCO (reduction in potential conflicts)	Normalized Safety Surrogate Score (NSi)	Final Rank Score	Final Rank
SR 151 and SR 6	0.79	0.64	6.00	1.00	0.82	1
SR 20 and SR 6	0.64	0.52	5.00	0.83	0.68	2
US 15 and SR 650	1.23	1.00	1.30	0.22	0.61	3
SR 22 and SR 731	1.00	0.82	1.00	0.17	0.49	4
US 15 and SR 636	0.24	0.20	0.90	0.15	0.17	5

Table 18. Results of Prioritization Tool at Signalized Intersections

Site Name	Operational Score	Normalized Operational Score (NO_i)	ΔCO (reduction in potential conflicts)	Normalized Safety Surrogate Score (NS_i)	Final Rank Score	Final Rank
US 15 and US 250	0.50	1	259.1	1	1	1
US 250 and SR 616	0.45	0.89	235.1	0.90	0.90	2
SR 28 and SR 652	0.34	0.68	154.7	0.59	0.64	3
US 33 and New Bridge Rd.	0.23	0.47	0.02	0.000077	0.23	4

CONCLUSIONS

In this study, new left-turn guidelines for unsignalized and signalized intersections were developed on the basis of well-validated event-based simulation programs. Guidelines for unsignalized intersections were based on the percentage of left-turns blocking through vehicles, and guidelines for signalized intersections were developed using minimum left-turn volume of either 85% left-turn capacity or LOS E delay (55 seconds/vehicle). In addition to the general guidelines, a prioritization tool that can be used to prioritize candidate intersections was developed. The prioritization tool accounts for both operational and safety aspects.

The following conclusions were drawn from this study.

- *The existing guidelines for unsignalized intersections proposed by Harmelink (1967) and Kikuchi and Chakroborty (1991) are applicable for only particular (fixed) percentages of left turns, and they are based on analytical deterministic models.*

- *The existing guidelines for signalized intersections developed by Oppenlander and Bianchi (1990) are not applicable for actuated intersections, and they do not consider the effect of percentages of left-turn vehicles.* A simulation-based evaluation indicated that these guidelines are conservative (i.e., difficult to justify left-turn lane installation) such that left-turn vehicles would experience a high delay.

- *Most surveyed engineers are satisfied with the performance of the existing guidelines.* However, there seems to be confusion regarding the application of Harmelink's guidelines. In some cases, they were used for signalized intersections even though they were developed for unsignalized intersections.

- *Left-turn lane guidelines cannot be economically justified with only vehicle delay savings because the cost of construction is very high and delay savings are so small,* especially for low-volume unsignalized intersections. In addition, the benefits of safety improvements are not easily quantified. This may be why none of the existing guidelines were developed using cost-benefit analysis.

- *The guidelines proposed in this study require higher volumes than those of the Harmelink guidelines in justifying the installation of left-turn lanes at unsignalized intersections.* This is mainly because the critical gap of today's drivers is likely to be smaller than that of 1960s when Harmelink developed his guidelines. This is primarily due to better vehicle performance.

- *The prioritization tool developed in this study allows traffic engineers to determine rankings of candidate intersections using operational and safety surrogate measures.* Users can change weights between operational and safety surrogate aspects. For unsignalized intersections, reduction in conflict opportunities with the added left-turn lane is used as the MOE for a safety surrogate; for signalized intersections, the normalized left-turn volume/capacity ratio on the subject link is used.

RECOMMENDATIONS

1. *The guidelines, shown as Appendices C, D, and E, developed in this study should be pilot tested in a few districts in Virginia to obtain general opinions of the engineers. If the responses are positive enough, the guidelines should be included in the VDOT Road Design Manual. They should also be integrated into existing efforts regarding land development, site access, and access management work.*

2. *It should be made clear that the Harmelink guidelines were developed for unsignalized intersections and should not be applied to signalized intersections. In addition, left-turn lane guidelines should be identified as either "signalized intersection guidelines" or "unsignalized intersection guidelines" in the literature to minimize potential misuse.*

3. *As the proposed guidelines are solely based on the operational performance measures, traffic engineers need to consider the impact of safety before making decisions on installing left-turn lanes.*

CONSIDERATIONS FOR FUTURE RESEARCH

- The LTGAP program developed in this study does not fully implement multi-phase actuated signal controls. An installation of a left-turn lane at a signalized intersection could further improve its operation by implementing an exclusive left-turn phasing. It is recommended that further research be conducted for developing left-turn phasing guidelines.

- If the proposed guidelines are accepted by VDOT, the interface of the prototype LTGAP program should be enhanced for professional use. Especially, the prioritization tool demonstrated in the project needs to be further incorporated into LTGAP.

- The safety surrogate measure used in this study was solely based on conflict opportunities. Future research should quantify the extent to which conflict opportunities can predict crashes such that the impact of safety can be better incorporated into the prioritization tool.

ACKNOWLEDGMENTS

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APPENDIX A

SURVEY QUESTIONNAIRE

The following survey was conducted from 03/24/2003 to 03/28/2003 on the usage of left-turn lane guidelines in the state of Virginia. The responses were collected from resident engineers as well as the district traffic engineers throughout Virginia Department of Transportation (VDOT).

Questions:

- How do you determine whether a left-turn lane is needed at a signalized intersection? Please state the source of any guideline that you use.

- How do you rate the effectiveness of this method? (Check one)
    i. Guidelines often call for a left-turn lane where it is not needed.
    ii. Guidelines sometimes call for a left-turn lane where it is not needed
    iii. Guidelines usually do a good job of determining when a left-turn lane is needed.
    iv. Guidelines sometimes do not call for a left-turn lane when one is needed.
    v. Guidelines often do not call for a left-turn lane when one is needed.

b. Are there any special situations that you think the guidelines handle poorly?

c. How do you determine whether a left-turn lane is needed at an unsignalized intersection? Please state the source of any guideline that you use.

d. How do you rate the effectiveness of this method (check one)
    i. Guidelines often call for a left-turn lane where it is not needed.
    ii. Guidelines sometimes call for a left-turn lane where it is not needed
    iii. Guidelines usually do a good job of determining when a left-turn lane is needed.
    iv. Guidelines sometimes do not call for a left-turn lane when one is needed.
    v. Guidelines often do not call for a left-turn lane when one is needed.

e. Are there any special situations that you think the guidelines handle poorly?

f. Do you have any general comments about the methods used by VDOT to determine whether a left-turn lane is needed at an intersection?

g. Your name
h. Title
i. District
j. Residency
k. Phone number.

APPENDIX B

CYCLE LENGTH OPTIMIZATION IN LTGAP

LTGAP determines the max greens for the different phases at an actuated signal using the HCM 2000 methodology and optimum cycle length using Webster's formula. The cycle length at an actuated signal is assumed to be the sum of maximum greens of all phases and yellow and red clearance times. Webster proposed the following formula for the optimum cycle length.

$$C_o = \frac{1.5L + 5}{1 - \sum Y_i} \qquad \text{[B-1]}$$

where

C_o = Optimum cycle length
L = Total lost time for all phases
Y_i = Sum of volume to saturation flow ratio (i.e., v/s) for critical movements.

In order to estimate Y_i, saturation flow rate should be known. The cycle length and green times should be known to calculate adjusted saturation flow rate. Thus, the determination of green times and saturation flow rate requires iteration.

LTGAP starts from a cycle length and determines maximum green times according to equal degree of saturation, and calculates adjusted saturation flow rate using the sample procedure shown in Table B-1. Then, optimum cycle length, C_o, is calculated using Webster's equation shown above. The C_o, if different from initial cycle length, provides new maximum green times and used to calculate updated adjusted saturation flow rate. These iterations continue until two consecutive cycle lengths are close enough, say less than 5 seconds.

Table B-1. Sample Calculation in HCM 2000 Exhibit C16-10

Input				
Approach	EB	WB	NB	SB
Cycle length, C (s)	60			
Total actual green time for LT lane group, G (s)	30	30	30	30
Effective permitted green time for LT lane Group, g(s)	30	30	30	30
Opposing Effective Green time, g_o (s)	30	30	30	30
Number of lanes in LT lane group, N	1	1	1	1
Total volume on the lane group, v_a (veh/h)	100	100	200	2000
Adjusted LT flow rate, v_{LT} (veh/h)	10	10	0	100
Proportion of LT vehicles in LT lane group, P_{LT}	0.1	0.1	0	0.01
Proportion of LT vehicles in opposing flow, P_{LTo}	0.1	0.1	0.05	0
Proportion of RT vehicles in the lane group, P_{RT}	0	0	0	0
Adjusted flow rate of opposing approach, V_o, (veh/h)	100	100	2000	300
Lost time for LT lane group, t_L	0.2	0.2	0.2	0.2
Computation				
LT volume per cycle, LTC= $v_{LT}C/3600$	0.17	0.17	0.00	1.67
Opposing flow rate per lane per cycle, V_{olc}	1.67	1.67	33.33	5.00
Opposing Platoon ratio R_{po}	1.0	1.0	1.0	1.0
g_f	22.50	22.50	29.80	8.97
Opposing queue ratio, qr_o	0.5	0.5	0.5	0.5
g_q	3.30	3.30	34.08	7.88
g_u	7.50	7.50	-4.08	21.04
N	0.0	0.0	2.1	0.0
P_{THo}	0.90	0.90	0.95	1.00
E_{L1}	1.7	1.7	2.1	1.7
E_{L2}	1.0	1.0	2.1	1.0
g_{diff}	0.0	0.0	4.3	0.0
f_{LT}	0.98	0.98	1.00	1.00
f_{RT}	1.0	1.0	1.0	1.0
S	1770.58	1770.58	1800.0	1791.23

APPENDIX C

LTGAP GUIDELINES FOR UNSIGNALIZED INTERSECTIONS

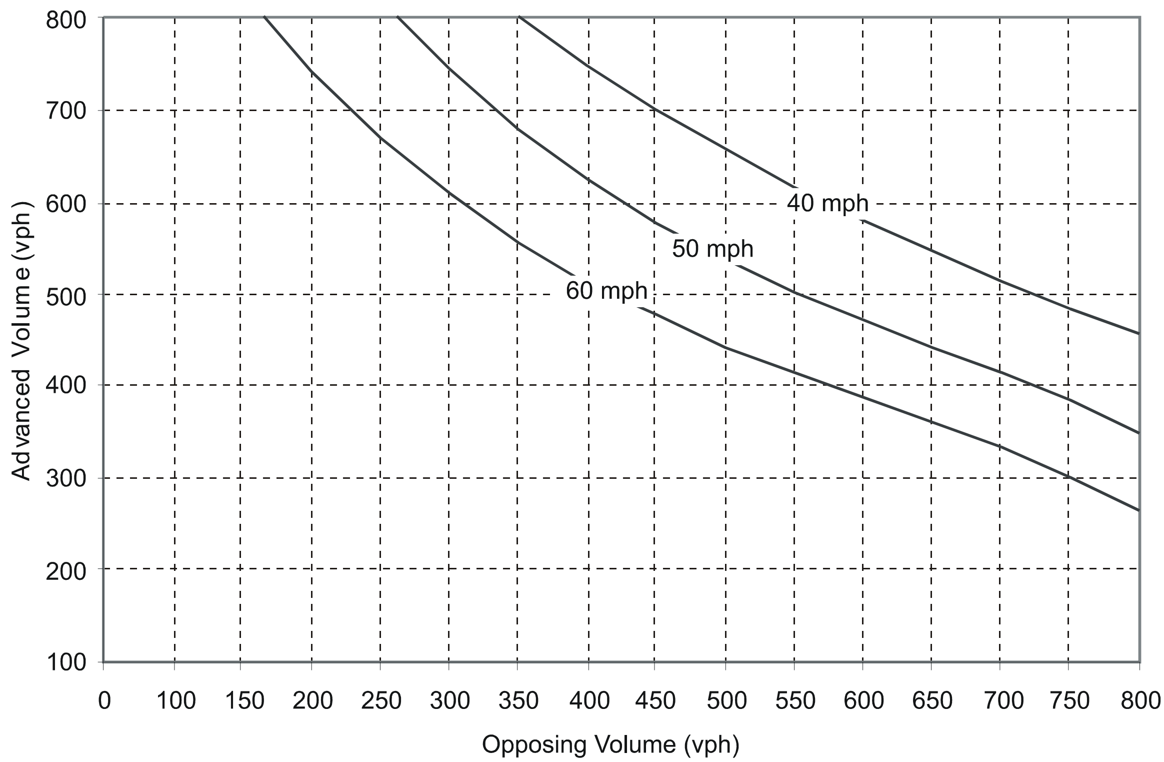

Figure C-1. Left-turn Lane Guidelines for 3% Left-turn Vehicles on Advancing Volumes

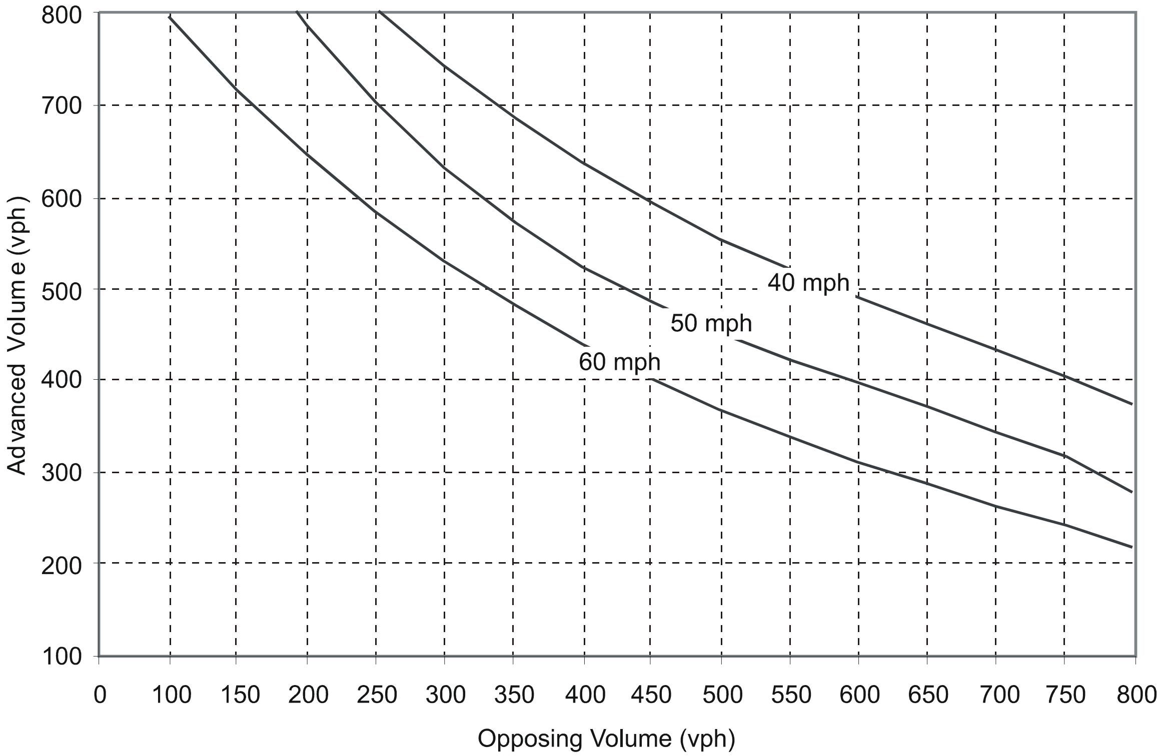

Figure C-2. Left-turn Lane Guidelines for 5% Left-turn Vehicles on Advancing Volumes

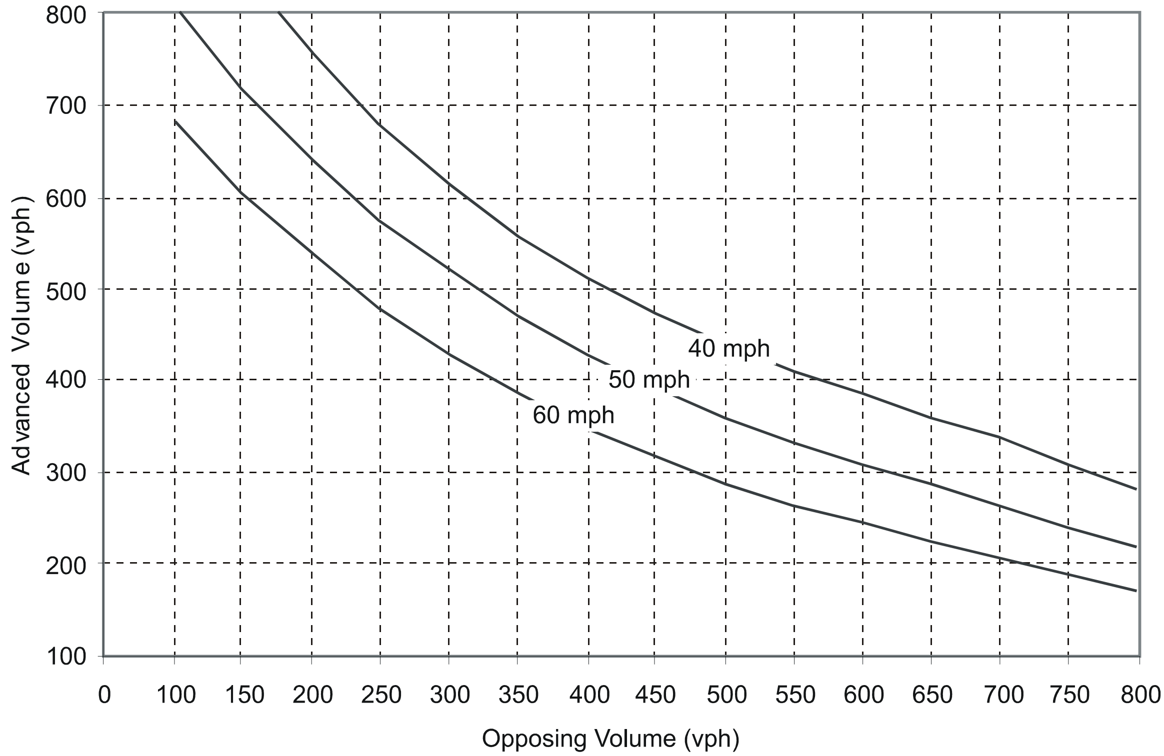

Figure C-3. Left-turn Lane Guidelines for 10% Left-turn Vehicles on Advancing Volumes

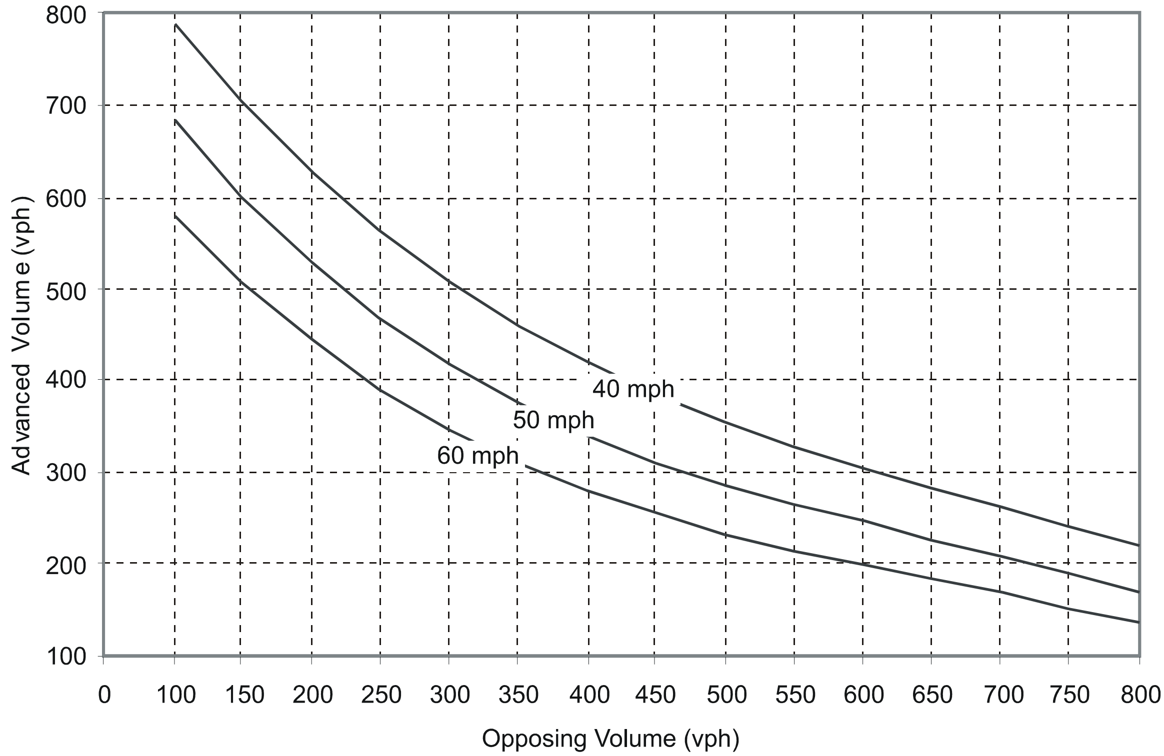

Figure C-4. Left-turn Lane Guidelines for 20% Left-turn Vehicles on Advancing Volumes

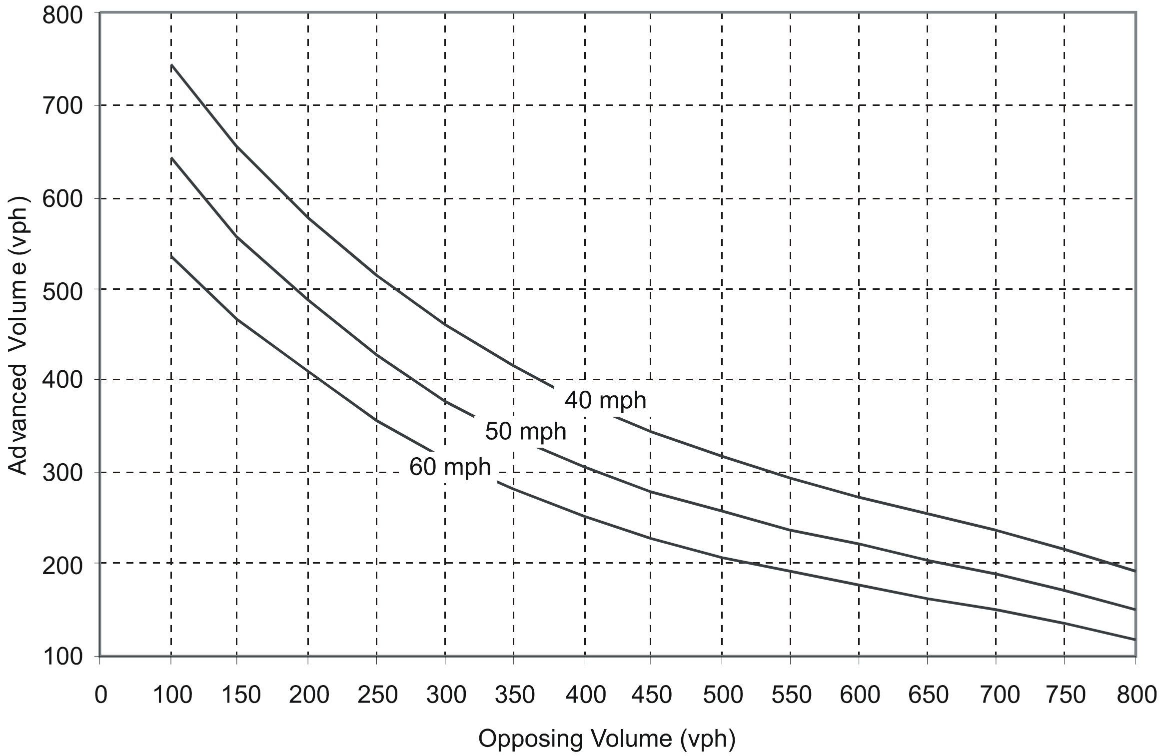

Figure C-5. Left-turn Lane Guidelines for 30% Left-turn Vehicles on Advancing Volumes

APPENDIX D

LTGAP GUIDELINES AT PRE-TIMED SIGNALIZED INTERSECTIONS (TWO-LANE APPROACHES)

Advancing volume (vph) for 3% left turn

3	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.2	0.3	0.4	0.5	0.6	0.7	0.8
100	225	400	550	705	855	1005	1155	235	415	565	715	865	1020	1170	230	420	570	720	875	1025	1175
150	155	395	545	695	845	995	1145	155	405	555	710	860	1010	1160	120	395	565	715	865	1020	1165
200	50	365	540	685	840	985	1130	50	370	550	695	850	1000	1145	50	355	550	705	855	1005	1160
250	50	295	520	675	825	975	1120	50	290	535	685	840	985	1135	50	250	540	695	845	990	1140
300	50	75	500	665	810	965	1110	50	85	505	670	825	970	1125	50	75	475	675	830	980	1135
350	50	50	425	645	800	950	1095	50	50	425	660	810	960	1110	50	50	400	660	815	965	1120
400	50	50	245	630	785	935	1075	50	50	240	625	795	945	1090	50	50	155	615	800	950	1100
450	50	50	65	540	760	915	1055	50	50	70	535	770	930	1075	50	50	60	520	775	925	1080
500	50	50	50	395	740	890	1035	50	50	50	390	740	905	1055	50	50	50	395	730	905	1065
550	50	50	50	120	650	865	1020	50	50	50	125	645	880	1030	50	50	50	120	630	890	1035
600	50	50	50	55	515	830	1000	50	50	50	50	515	845	1005	50	50	50	50	490	840	1015
650	50	50	50	50	300	755	975	50	50	50	50	310	740	975	50	50	50	50	270	745	990
700	50	50	50	50	80	660	905	50	50	50	50	85	635	945	50	50	50	50	65	680	955
750	50	50	50	50	50	475	825	50	50	50	50	55	465	820	50	50	50	50	50	435	845
800	50	50	50	50	50	130	725	50	50	50	50	50	205	705	50	50	50	50	50	290	730
850	50	50	50	50	50	75	530	50	50	50	50	50	75	605	50	50	50	50	50	70	580
900	50	50	50	50	50	50	330	50	50	50	50	50	55	375	50	50	50	50	50	50	370
950	50	50	50	50	50	50	140	50	50	50	50	50	50	200	50	50	50	50	50	50	90
1000	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	65
1050	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle

Advancing volume (vph) for 5% left turn

5	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	220	395	545	695	845	995	1145	220	410	560	710	855	1010	1160	210	410	565	715	865	1015	1170
150	130	385	535	680	835	980	1130	125	395	545	695	845	995	1145	85	380	550	705	850	1005	1150
200	50	335	520	670	820	965	1110	50	340	530	675	830	980	1125	50	320	535	685	835	985	1135
250	50	245	505	655	800	945	1090	50	240	510	665	815	960	1110	50	205	500	670	820	970	1115
300	50	50	445	635	785	925	1070	50	55	445	645	790	945	1085	50	50	425	645	800	945	1095
350	50	50	360	605	760	905	1055	50	50	345	620	770	920	1070	50	50	315	605	775	925	1070
400	50	50	180	545	735	885	1030	50	50	180	550	745	895	1045	50	50	125	530	750	900	1050
450	50	50	50	455	710	860	1000	50	50	50	455	710	860	1020	50	50	50	420	695	870	1020
500	50	50	50	285	630	820	965	50	50	50	290	630	835	980	50	50	50	265	625	835	990
550	50	50	50	80	530	790	935	50	50	50	85	530	800	960	50	50	50	75	515	790	955
600	50	50	50	50	395	720	905	50	50	50	50	400	700	915	50	50	50	50	370	695	920
650	50	50	50	50	190	605	855	50	50	50	50	195	605	870	50	50	50	50	180	605	870
700	50	50	50	50	50	485	770	50	50	50	50	65	490	775	50	50	50	50	50	475	770
750	50	50	50	50	50	305	650	50	50	50	50	50	315	665	50	50	50	50	50	290	665
800	50	50	50	50	50	100	515	50	50	50	50	50	100	540	50	50	50	50	50	90	545
850	50	50	50	50	50	50	365	50	50	50	50	50	50	385	50	50	50	50	50	50	380
900	50	50	50	50	50	50	190	50	50	50	50	50	50	210	50	50	50	50	50	50	200
950	50	50	50	50	50	50	50	50	50	50	50	50	50	55	50	50	50	50	50	50	65
1000	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1050	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle

Advancing volume (vph) for 10% left turn

10	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	200	380	530	680	830	975	1120	200	395	545	690	840	990	1135	180	385	550	695	845	995	1145
150	80	350	510	660	805	950	1095	80	350	520	670	815	960	1105	50	340	525	675	820	965	1115
200	50	285	485	630	780	920	1060	50	290	495	640	785	935	1075	50	260	485	650	790	940	1085
250	50	185	440	600	750	890	1030	50	175	435	615	755	900	1045	50	145	410	615	760	910	1050
300	50	50	365	575	715	855	990	50	50	365	575	725	875	1010	50	50	335	560	725	875	1015
350	50	50	260	510	680	815	955	50	50	250	505	690	830	970	50	50	220	495	690	840	975
400	50	50	95	425	645	785	920	50	50	105	415	645	790	930	50	50	65	405	635	800	940
450	50	50	50	330	560	750	885	50	50	50	315	560	750	890	50	50	50	300	555	765	905
500	50	50	50	185	475	685	835	50	50	50	190	480	690	855	50	50	50	165	455	690	855
550	50	50	50	50	370	610	795	50	50	50	50	375	610	805	50	50	50	50	360	600	810
600	50	50	50	50	265	515	720	50	50	50	50	245	520	735	50	50	50	50	240	515	730
650	50	50	50	50	115	415	635	50	50	50	50	115	425	645	50	50	50	50	90	430	645
700	50	50	50	50	50	295	555	50	50	50	50	50	310	555	50	50	50	50	50	325	570
750	50	50	50	50	50	190	435	50	50	50	50	50	210	470	50	50	50	50	50	185	465
800	50	50	50	50	50	50	330	50	50	50	50	50	70	360	50	50	50	50	50	50	350
850	50	50	50	50	50	50	220	50	50	50	50	50	50	245	50	50	50	50	50	50	255
900	50	50	50	50	50	50	90	50	50	50	50	50	50	105	50	50	50	50	50	50	120
950	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1000	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1050	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle

Advancing volume (vph) for 20% left turn

	Cycle length = 60 seconds							**Cycle length = 80 seconds**							**Cycle length = 100 seconds**						
	Green Ratios							**Green Ratios**							**Green Ratios**						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	170	360	505	650	795	940	1080	170	360	515	665	805	950	1095	150	355	520	670	815	960	1105
150	65	300	475	615	755	900	1035	55	300	485	625	770	910	1045	50	285	485	625	770	910	1055
200	50	225	425	575	715	850	985	50	220	420	580	725	860	1000	50	195	410	590	725	865	1005
250	50	125	350	535	665	800	935	50	120	345	540	675	815	945	50	85	335	525	680	815	955
300	50	50	270	465	620	750	885	50	50	265	465	630	770	900	50	50	250	460	635	770	900
350	50	50	175	390	565	705	835	50	50	170	385	565	715	850	50	50	155	370	560	720	850
400	50	50	50	295	490	660	780	50	50	50	300	490	665	795	50	50	50	285	490	670	805
450	50	50	50	215	410	585	735	50	50	50	220	420	590	740	50	50	50	205	405	595	740
500	50	50	50	115	330	510	675	50	50	50	115	325	510	685	50	50	50	110	325	510	685
550	50	50	50	50	250	440	605	50	50	50	50	240	445	605	50	50	50	50	250	430	605
600	50	50	50	50	155	365	515	50	50	50	50	165	355	530	50	50	50	50	160	350	530
650	50	50	50	50	65	270	440	50	50	50	50	70	275	450	50	50	50	50	60	270	450
700	50	50	50	50	50	190	355	50	50	50	50	50	190	370	50	50	50	50	50	195	370
750	50	50	50	50	50	120	285	50	50	50	50	50	120	295	50	50	50	50	50	95	290
800	50	50	50	50	50	50	220	50	50	50	50	50	50	220	50	50	50	50	50	65	215
850	50	50	50	50	50	50	140	50	50	50	50	50	50	140	50	50	50	50	50	50	155
900	50	50	50	50	50	50	60	50	50	50	50	50	50	75	50	50	50	50	50	50	65
950	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1000	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1050	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle

Advancing volume (vph) for 30% left turn

	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	150	335	485	625	770	910	1050	150	335	495	640	780	925	1065	125	325	500	645	785	930	1075
150	50	270	445	580	720	855	990	50	265	445	590	730	865	1005	50	250	445	595	735	875	1010
200	50	190	375	530	665	795	930	50	185	370	540	675	810	945	50	165	365	540	680	815	945
250	50	95	300	470	610	745	870	50	90	295	475	620	755	880	50	60	285	470	630	760	890
300	50	50	220	400	565	685	805	50	50	220	395	565	700	820	50	50	200	390	565	700	830
350	50	50	140	325	490	630	750	50	50	135	320	485	640	765	50	50	115	315	485	640	770
400	50	50	50	245	410	565	695	50	50	50	250	415	575	705	50	50	50	230	410	575	710
450	50	50	50	170	340	490	635	50	50	50	165	340	500	650	50	50	50	160	340	495	655
500	50	50	50	85	260	420	560	50	50	50	85	275	420	575	50	50	50	70	260	425	575
550	50	50	50	50	190	340	485	50	50	50	50	195	350	495	50	50	50	50	185	350	505
600	50	50	50	50	125	275	415	50	50	50	50	130	285	430	50	50	50	50	120	285	430
650	50	50	50	50	60	210	360	50	50	50	50	60	210	355	50	50	50	50	50	210	360
700	50	50	50	50	50	140	280	50	50	50	50	50	155	285	50	50	50	50	50	155	295
750	50	50	50	50	50	80	220	50	50	50	50	50	75	225	50	50	50	50	50	80	225
800	50	50	50	50	50	50	150	50	50	50	50	50	50	170	50	50	50	50	50	50	155
850	50	50	50	50	50	50	95	50	50	50	50	50	50	105	50	50	50	50	50	50	105
900	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
950	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1000	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1050	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1100	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1150	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle

APPENDIX E

LTGAP GUIDELINES AT PRE-TIMED SIGNALIZED INTERSECTIONS (FOUR-LANE APPROACHES)

Advancing volume (vph) for 3% left turn

3	**Cycle length = 60 seconds**							**Cycle length = 80 seconds**							**Cycle length = 100 seconds**						
	Green Ratios							**Green Ratios**							**Green Ratios**						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	500	800	1100	1400	1645	1650	1650	525	820	1120	1420	1640	1645	1650	510	835	1135	1430	1635	1645	1645
150	460	790	1090	1390	1635	1655	1660	470	815	1110	1410	1635	1650	1660	450	825	1125	1420	1635	1650	1650
200	395	780	1080	1375	1630	1660	1650	400	805	1105	1395	1635	1650	1655	330	795	1115	1410	1630	1645	1645
250	250	750	1070	1365	1610	1650	1650	215	755	1090	1385	1620	1650	1650	135	730	1105	1395	1620	1650	1650
300	70	685	1055	1350	1600	1650	1655	50	690	1075	1370	1605	1650	1650	50	640	1070	1380	1605	1650	1655
350	50	580	1010	1335	1585	1650	1655	50	580	1015	1355	1595	1650	1650	50	520	1000	1365	1600	1645	1650
400	50	425	930	1315	1570	1650	1650	50	435	950	1340	1575	1655	1655	50	300	885	1315	1585	1650	1650
450	50	205	830	1235	1555	1640	1655	50	170	835	1245	1550	1650	1650	50	130	800	1235	1560	1645	1645
500	50	90	715	1145	1520	1635	1645	50	80	750	1165	1535	1635	1660	50	70	640	1140	1530	1640	1650
550	50	50	585	1050	1425	1625	1650	50	50	545	1040	1435	1625	1650	50	50	495	1020	1455	1625	1655
600	50	50	375	945	1355	1595	1645	50	50	385	915	1370	1615	1650	50	50	320	895	1330	1610	1655
650	50	50	215	795	1235	1575	1645	50	50	155	795	1240	1600	1645	50	50	95	775	1205	1590	1650
700	50	50	65	610	1085	1480	1640	50	50	70	635	1090	1500	1645	50	50	50	600	1120	1505	1635
750	50	50	50	425	960	1345	1620	50	50	50	440	975	1370	1630	50	50	50	450	920	1415	1630
800	50	50	50	220	800	1210	1610	50	50	50	280	905	1230	1600	50	50	50	180	810	1225	1625
850	50	50	50	140	610	1075	1500	50	50	50	115	630	1110	1510	50	50	50	80	590	1075	1500
900	50	50	50	60	435	885	1315	50	50	50	60	425	915	1375	50	50	50	50	375	935	1320
950	50	50	50	50	205	740	1195	50	50	50	50	180	755	1170	50	50	50	50	185	715	1235
1000	50	50	50	50	65	595	1015	50	50	50	50	100	550	1020	50	50	50	50	90	550	1050
1050	50	50	50	50	60	375	830	50	50	50	50	50	375	875	50	50	50	50	80	350	870
1100	50	50	50	50	50	130	605	50	50	50	50	50	135	620	50	50	50	50	50	155	675
1150	50	50	50	50	50	90	380	50	50	50	50	50	155	460	50	50	50	50	50	70	445
1200	50	50	50	50	50	50	200	50	50	50	50	50	65	220	50	50	50	50	50	50	255

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle.

Advancing volume (vph) for 5% left turn

5	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	480	790	1090	1390	1630	1660	1655	495	815	1110	1410	1635	1655	1650	480	825	1125	1420	1630	1645	1650
150	430	780	1075	1370	1625	1660	1650	430	800	1095	1390	1625	1650	1655	405	810	1110	1405	1630	1645	1655
200	345	750	1060	1350	1610	1655	1650	335	750	1080	1370	1605	1655	1660	275	740	1090	1385	1610	1645	1655
250	185	680	1040	1335	1585	1650	1650	155	680	1060	1350	1590	1650	1655	95	650	1050	1365	1590	1645	1655
300	50	595	975	1315	1560	1650	1655	50	585	985	1330	1565	1650	1655	50	550	960	1340	1570	1645	1660
350	50	480	890	1250	1535	1640	1650	50	470	885	1260	1545	1640	1660	50	405	870	1260	1550	1635	1650
400	50	335	790	1160	1510	1630	1650	50	320	780	1180	1515	1630	1655	50	240	770	1165	1515	1625	1650
450	50	155	700	1070	1425	1610	1655	50	115	680	1070	1445	1610	1655	50	95	650	1070	1430	1615	1650
500	50	50	590	970	1340	1580	1650	50	50	565	985	1340	1590	1650	50	50	555	975	1325	1585	1645
550	50	50	420	850	1225	1550	1635	50	50	410	860	1205	1565	1645	50	50	365	825	1200	1560	1640
600	50	50	250	745	1105	1445	1620	50	50	220	735	1135	1455	1630	50	50	190	720	1100	1460	1625
650	50	50	75	600	1015	1355	1595	50	50	95	605	1015	1345	1600	50	50	50	555	975	1360	1605
700	50	50	50	450	870	1200	1550	50	50	50	440	850	1235	1540	50	50	50	485	870	1215	1555
750	50	50	50	290	725	1075	1400	50	50	50	335	730	1085	1440	50	50	50	250	715	1090	1410
800	50	50	50	170	570	930	1270	50	50	50	150	600	975	1310	50	50	50	70	560	960	1290
850	50	50	50	50	425	800	1110	50	50	50	50	445	820	1145	50	50	50	50	415	835	1180
900	50	50	50	50	305	655	990	50	50	50	50	270	710	1005	50	50	50	50	290	675	1000
950	50	50	50	50	135	550	845	50	50	50	50	135	565	870	50	50	50	50	85	515	850
1000	50	50	50	50	50	355	710	50	50	50	50	50	410	725	50	50	50	50	50	385	745
1050	50	50	50	50	50	235	590	50	50	50	50	50	245	570	50	50	50	50	20	205	650
1100	50	50	50	50	50	105	425	50	50	50	50	50	75	405	50	50	50	50	50	65	455
1150	50	50	50	50	50	50	245	50	50	50	50	50	90	260	50	50	50	50	50	50	310
1200	50	50	50	50	50	50	155	50	50	50	50	50	50	185	50	50	50	50	50	50	110

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle.

Advancing volume (vph) for 10% left turn

10	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	445	775	1070	1365	1615	1655	1650	450	795	1090	1385	1625	1650	1655	425	810	1105	1395	1625	1645	1645
150	365	730	1045	1335	1585	1655	1650	360	730	1065	1355	1595	1655	1650	320	720	1080	1360	1595	1645	1650
200	265	650	990	1305	1555	1650	1650	250	650	1010	1325	1560	1650	1655	185	630	995	1335	1555	1650	1650
250	115	555	900	1240	1515	1630	1660	90	550	905	1250	1525	1635	1650	50	520	895	1245	1530	1640	1650
300	50	445	805	1140	1465	1610	1650	50	450	805	1150	1485	1605	1650	50	410	790	1140	1490	1605	1650
350	50	340	705	1030	1350	1565	1650	50	335	700	1035	1370	1575	1645	50	290	685	1035	1370	1575	1640
400	50	210	590	925	1240	1525	1625	50	220	605	940	1250	1540	1640	50	155	575	920	1255	1540	1635
450	50	50	500	820	1125	1435	1600	50	55	500	820	1140	1440	1600	50	50	445	815	1130	1450	1615
500	50	50	375	710	1015	1310	1555	50	50	375	705	1020	1325	1570	50	50	340	690	1035	1325	1565
550	50	50	260	615	885	1200	1460	50	50	245	640	905	1205	1485	50	50	245	590	910	1240	1495
600	50	50	145	510	795	1070	1330	50	50	150	490	785	1085	1350	50	50	110	485	780	1080	1375
650	50	50	50	405	680	955	1215	50	50	50	390	685	980	1215	50	50	50	360	675	975	1230
700	50	50	50	285	585	860	1085	50	50	50	280	580	860	1100	50	50	50	245	550	875	1125
750	50	50	50	170	485	750	965	50	50	50	155	480	765	1000	50	50	50	145	480	745	995
800	50	50	50	70	345	615	870	50	50	50	50	360	620	875	50	50	50	50	345	645	890
850	50	50	50	50	235	525	760	50	50	50	50	270	530	770	50	50	50	50	235	535	775
900	50	50	50	50	155	410	640	50	50	50	50	165	425	635	50	50	50	50	170	440	670
950	50	50	50	50	50	330	530	50	50	50	50	100	310	560	50	50	50	50	95	355	595
1000	50	50	50	50	50	240	425	50	50	50	50	50	220	450	50	50	50	50	50	235	445
1050	50	50	50	50	50	110	330	50	50	50	50	50	125	340	50	50	50	50	50	110	335
1100	50	50	50	50	50	50	230	50	50	50	50	50	50	245	50	50	50	50	50	50	245
1150	50	50	50	50	50	50	160	50	50	50	50	50	50	185	50	50	50	50	50	50	165
1200	50	50	50	50	50	50	35	50	50	50	50	50	50	80	50	50	50	50	50	50	95

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle.

Advancing volume (vph) for 20% left turn

20	**Cycle length = 60 seconds**							**Cycle length = 80 seconds**							**Cycle length = 100 seconds**						
	Green Ratios							**Green Ratios**							**Green Ratios**						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	380	720	1035	1330	1575	1655	1655	385	735	1060	1350	1585	1655	1655	360	725	1070	1360	1590	1645	1655
150	285	625	955	1285	1525	1635	1660	290	630	965	1300	1535	1645	1655	250	615	965	1310	1535	1640	1655
200	180	530	845	1155	1475	1600	1650	175	530	845	1175	1485	1610	1650	130	505	850	1180	1490	1610	1650
250	75	420	735	1035	1340	1545	1645	55	415	735	1050	1355	1560	1640	50	395	725	1050	1360	1560	1645
300	50	330	625	915	1205	1495	1605	50	320	635	930	1220	1505	1615	50	285	615	910	1225	1510	1615
350	50	230	530	800	1080	1355	1545	50	220	525	815	1090	1375	1565	50	185	505	810	1095	1380	1570
400	50	130	435	700	955	1215	1485	50	120	435	705	970	1235	1500	50	90	405	695	975	1245	1510
450	50	50	325	605	845	1090	1350	50	50	345	605	850	1115	1355	50	50	325	605	855	1125	1380
500	50	50	250	515	745	975	1220	50	50	250	520	745	980	1250	50	50	235	505	755	990	1225
550	50	50	170	410	640	860	1080	50	50	165	420	645	880	1100	50	50	150	390	645	890	1125
600	50	50	70	335	565	750	980	50	50	95	330	570	775	980	50	50	50	330	540	770	990
650	50	50	50	245	455	650	875	50	50	50	250	455	675	870	50	50	50	225	460	660	890
700	50	50	50	170	370	570	760	50	50	50	180	400	580	775	50	50	50	140	375	585	770
750	50	50	50	95	290	475	650	50	50	50	95	290	485	680	50	50	50	80	295	485	670
800	50	50	50	50	205	390	585	50	50	50	50	225	420	590	50	50	50	50	215	400	580
850	50	50	50	50	140	315	490	50	50	50	50	155	330	495	50	50	50	50	165	350	510
900	50	50	50	50	80	240	410	50	50	50	50	90	250	410	50	50	50	50	65	250	420
950	50	50	50	50	50	190	335	50	50	50	50	50	180	325	50	50	50	50	50	175	325
1000	50	50	50	50	50	105	255	50	50	50	50	50	150	270	50	50	50	50	50	135	290
1050	50	50	50	50	50	65	200	50	50	50	50	50	65	200	50	50	50	50	50	70	210
1100	50	50	50	50	50	50	140	50	50	50	50	50	50	145	50	50	50	50	50	50	145
1150	50	50	50	50	50	50	65	50	50	50	50	50	50	95	50	50	50	50	50	50	90
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle.

Advancing volume (vph) for 30% left turn

30	Cycle length = 60 seconds							Cycle length = 80 seconds							Cycle length = 100 seconds						
	Green Ratios							Green Ratios							Green Ratios						
Opposing volume (vph)	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**	**0.2**	**0.3**	**0.4**	**0.5**	**0.6**	**0.7**	**0.8**
100	335	675	1010	1305	1555	1645	1655	340	685	1025	1325	1560	1645	1655	310	675	1025	1335	1560	1645	1650
150	240	560	880	1195	1495	1610	1655	240	575	885	1210	1495	1620	1655	205	550	885	1215	1505	1625	1650
200	140	455	750	1050	1360	1550	1640	135	455	765	1060	1375	1565	1645	95	435	750	1070	1380	1565	1650
250	50	350	640	915	1205	1485	1595	50	355	645	930	1220	1500	1610	50	330	635	930	1220	1510	1610
300	50	255	535	805	1060	1325	1540	50	265	535	805	1080	1345	1545	50	230	520	800	1085	1355	1560
350	50	180	445	685	935	1175	1430	50	175	440	695	940	1200	1450	50	150	420	700	950	1215	1475
400	50	90	350	580	840	1050	1290	50	110	365	585	825	1085	1305	50	50	325	580	820	1085	1320
450	50	50	265	480	705	920	1160	50	50	265	510	720	945	1175	50	50	235	480	715	950	1170
500	50	50	210	425	615	810	1015	50	50	185	410	625	820	1040	50	50	175	410	615	840	1050
550	50	50	120	330	515	700	900	50	50	120	335	530	715	910	50	50	105	325	525	725	930
600	50	50	60	245	430	625	795	50	50	55	250	440	630	805	50	50	50	235	440	625	800
650	50	50	50	180	360	525	695	50	50	50	180	365	535	715	50	50	50	170	355	540	710
700	50	50	50	120	285	440	600	50	50	50	115	285	465	610	50	50	50	125	295	445	630
750	50	50	50	60	230	380	510	50	50	50	55	230	380	535	50	50	50	50	235	400	530
800	50	50	50	50	160	290	445	50	50	50	50	155	315	455	50	50	50	50	165	310	455
850	50	50	50	50	110	245	365	50	50	50	50	110	260	395	50	50	50	50	105	240	375
900	50	50	50	50	55	195	305	50	50	50	50	50	195	330	50	50	50	50	65	180	310
950	50	50	50	50	50	130	250	50	50	50	50	50	145	255	50	50	50	50	50	140	250
1000	50	50	50	50	50	70	195	50	50	50	50	50	80	185	50	50	50	50	50	95	205
1050	50	50	50	50	50	50	135	50	50	50	50	50	50	160	50	50	50	50	50	50	160
1100	50	50	50	50	50	50	75	50	50	50	50	50	50	110	50	50	50	50	50	50	105
1150	50	50	50	50	50	50	65	50	50	50	50	50	50	55	50	50	50	50	50	50	55
1200	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50	50

Note: Criteria based on using 85% or less of left-turn capacity and providing average left-turn delay of 55 seconds or less per vehicle.