Left-Turn Signal Phasing for Full-Actuated Signal Control

FENG-BOR LIN

Many warrants and guidelines exist concerning left-turn phasing at signalized intersections. However, there is still a lack of understanding about the left-turn phasing requirements for full-actuated signal control. Using computer simulation, a knowledge base is developed to assist in the choice between permissive phasing and protected/permissive phasing for this type of signal control. The important factors concerning such a choice include left-turn volume, opposing volume, the number of opposing lanes, length of left-turn bay, and the volume of cross traffic. The collective impact of these factors on left-turn phasing cannot be adequately assessed through the use of simple rules of thumb. The lengths of left-turn bays that allow protected/permissive phasing to be effectively used are also identified.

Left-turn movements are a major source of traffic conflicts at signalized intersections. The existence of such movements aggravates traffic delays and safety problems; it also complicates the selection of left-turn phasing plans for the optimization of signal operations. Many of factors have been used as criteria for left-turn signal phasing. Accident experiences, left-turn and opposing traffic volumes, delays, gap acceptance, traffic conflicts, and intersection capacity are some examples of such factors. Agent and Dean (*1*) presented a very informative review of the application of these various factors in developing warrants for left-turn phasing.

Several guidelines for left-turn phasing are set forth in the *Traffic Control Devices Handbook* (*2*). In terms of traffic volume, these guidelines suggest that separate left-turn phasing be considered when the product of left-turn and opposing volumes during peak hours exceeds 100,000 on a four-lane street or 50,000 on a two-lane street, provided that the left-turn volume is more than two vehicles per cycle during the peak-hour period. In terms of delay, the guidelines suggest that separate left-turn phasing be considered when the following conditions are met: left-turn delay is at least 2.0 vehicle-hours in a peak hour on a critical approach; left-turn volume is greater than two per cycle during the peak hour; and average delay per left-turning vehicle is more than 35 sec. More recently, several researchers (*3–5*) proposed additional warrants and guidelines for left-turn phasing.

Despite the existence of a number of guidelines, there is still a lack of understanding about the left-turn phasing requirements for full-actuated signal control (*6*). Full-actuated control is a primary means for isolated control of individual intersections. The performance characteristics of this type of control are governed by timing settings, detector configuration, phasing arrangement, geometric design of intersection, and prevailing traffic conditions. Changing the phasing arrangement for the traffic on one street can create a chain reaction in the operation of every phase. The dynamic nature of full-actuated signal operations makes the selection of proper phasing arrangements difficult.

This study determines, for full-actuated control that relies on long inductive loop detectors for presence detection of vehicles, how left-turn phasing should be selected to make the signal operations as efficient as possible. The analysis is based on data derived from a microscopic simulation model. The simulation analysis concerns the choice between permissive left-turn phasing and protected/permissive left-turn phasing.

SCOPE OF STUDY

From the perspective of the efficiency of signal operations, a number of geometric design, traffic, and signal timing factors can affect the phasing decisions for left-turn movements. The geometric design and traffic factors considered in this study are depicted in Figure 1. These factors include the effective length (L) of left-turn bay; left-turn volume (Q_L); straight-through volume (Q_s) in the lane adjacent to the left-turn bay; opposing volume (Q_o) and the number of opposing lanes; and the cross-traffic volume, such as Q_{c1} and Q_{c2}.

The effective length of a left-turn bay refers to the length within which stopped vehicles will not block the vehicular movements in the adjacent lane. The minimum length of a left-turn bay is assumed to be 50 ft. In the absence of a left-turn bay, the left lane of an intersection approach is assumed to be for the exclusive use of the left-turn vehicles.

The opposing volume (Q_o) is a primary factor affecting the need for separate left-turn phasing. The impact of this volume depends on the number of opposing lanes involved. An opposing volume concentrated in one lane has a more severe detrimental impact than when the same volume is distributed over several lanes. This study considers only the left-turn movements that are faced with either one or two opposing lanes.

The cross traffic influences the amount of green time available to the left-turn vehicles. This available green time in turn affects the delays and congestions associated with a signal operation. Because many simulation runs are needed to analyze a specific combination of the factors involved, it is impractical to examine the impact of the cross traffic by allowing the traffic volume in each cross-street lane to vary independently. As an alternative, fixed cross-traffic patterns, representing low, moderate, and heavy traffic movements on the cross street, are used for the analysis.

Department of Civil and Environmental Engineering, Damon Hall, Clarkson University, Potsdam, N.Y. 13676.

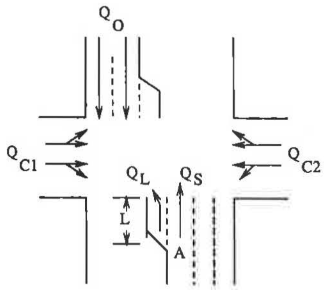

FIGURE 1 Major geometric and traffic factors affecting opposed left-turn movements.

Regarding signal timing, the analysis performed in this study allows each traffic lane to have a 65-ft detector loop. This loop length is reduced for a left-turn bay that has an effective length of less than 65 ft. The minimum green of each phase is set at 0 sec, while the vehicle interval and the maximum green are varied according to the flow pattern being analyzed.

By analyzing the interactions among the various governing factors and the resulting signal operations, this study attempts to establish guidelines concerning the choice between permissive phasing and protected/permissive phasing. This study also examines how protected/permissive phasing can be made more effective through the choice of proper effective lengths for left-turn bays.

When a left-turn bay exists, the adjacent approach lane can be used by both left-turn and straight-through vehicles. The queues formed by these vehicles may extend upstream of the diverging point denoted as A in Figure 1. In such a case, other arriving vehicles will be blocked even if unused storage spaces are downstream of the diverging point. Whatever the left-turn phasing arrangement, this blockage of traffic can greatly reduce the capacity of an intersection and lead to frequent lane changes. The severity of the impact of such blockage depends in part on the left-turn volume (Q_L) and its interacting straight-through volume (Q_s). This study establishes a knowledge base to facilitate the selection of effective bay length in support of the implementation of protected/permissive left-turn phasing.

TOOL FOR ANALYSIS

The simulation model used in this study was developed at Clarkson University. This microscopic model simulates the signal operations at isolated intersections. The model has two major components. One component is a flow processor that generates vehicles and moves them downstream through the intersection according to the prevailing flow and signal control conditions. The other component is a signal processor that is essentially a collection of various signal control logics.

In the flow processor, the location and the speed of each simulated vehicle are updated once per second. Each simulated vehicle is probabilistically assigned a set of attributes related to vehicle length, maximum desired speed, directional movement, desired space headway from the vehicle ahead in a stationary queue, desired stopped location with respect to the stop line, driver reaction time, and driver sensitivity in a car-following situation. The model simulates the traffic movements at intersections where the following features may or may not exist: right turns on red, auxiliary turning bay, mixed directional movements from a given lane, and opposed left turns.

The signal processor determines when the signal indications should be changed, according to the control logic being analyzed. For traffic-actuated signal operations, this processor can accept inputs from a variety of detectors. Each traffic lane may have a combination of several motion detectors and presence detectors. Such detectors may have call-delay or call-extension features.

The vehicular movements as simulated by the Clarkson model agree reasonably well with the observed characteristics related to right turns on red, opposed left turns, and queue dissipation. Because the model is developed for the purpose of comparative analysis of alternative signal controls, special care has been taken to realistically duplicate the interactions between vehicles and detectors. Some aspects of the model output are described elsewhere (7).

The model has been tested in terms of its ability to provide accurate estimates concerning the operations of traffic-actuated signals. The data used in this test were related to six hourly flow patterns observed at four intersections. The observed and simulated values of average cycle lengths, average green intervals, and the average delays in certain lanes are shown in Table 1. The largest difference between the observed and the simulated average greens is 1.9 sec. The simulated stopped delays deviate from the observed values by no more than 1.4 sec per vehicle.

Because opposed left-turn movements are the focus of this study, it is especially important that the simulation model realistically represents the interactions between the left-turn vehicles and their opposing flow. In this regard, simulated and observed saturation flows of the opposed left turns at two intersections were compared. The results of this comparison are shown in Figure 2. Data related to Case E of Table 1,

TABLE 1 OBSERVED CHARACTERISTICS OF SIX SIGNAL OPERATIONS AND ESTIMATES OBTAINED FROM CLARKSON MODEL

		Average Green, sec				Average Stopped Delay, sec/vh	
		Observed		Simulated			
Case (1)	Phase (2)	Mean (3)	S.D.[a] (4)	Mean (5)	S.D. (6)	Observed (7)	Simulated (8)
A	1 2	6.5 32.4	2.6 25.2	5.1 30.3	2.1 24.6	7.7[b]	6.6
B	1 2 3	33.8 5.4 24.0	18.2 2.1 0.0	31.9 5.1 24.0	17.6 2.3 0.0	11.1[c]	10.7
C	1 2	27.8 12.4	12.8 6.3	27.6 13.0	12.1 6.3	14.7[c]	14.9
D	1 2	18.8 10.7	9.2 5.8	17.5 9.5	8.1 5.2	not available	
E	1 2	29.3 20.5	7.6 0.7	30.2 20.2	9.1 0.9	42.3[d]	43.7
F	1 2 3	12.9 9.2 33.6	3.9 4.1 7.3	12.6 9.4 32.1	3.5 4.0 6.7	14.0[c] 3.1[e]	13.5 2.7

[a]S.D. = Standard Deviation
[b]single-lane flow with right turns and left turns
[c]exclusive left-turn flow
[d]shared-permissive left-turn flow (85% left turns)
[e]exclusive right-turn flow with right-turn-on-red

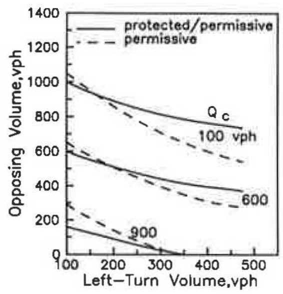

FIGURE 6 Maximum allowable combinations of left-turn volume and opposing volume to avoid unacceptable operations due to capacity constraint (one opposing lane).

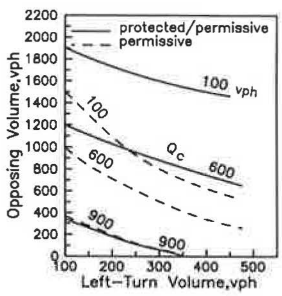

FIGURE 7 Maximum allowable combinations of left-turn volume and opposed volume to avoid unacceptable operations due to capacity constraint (two opposing lanes).

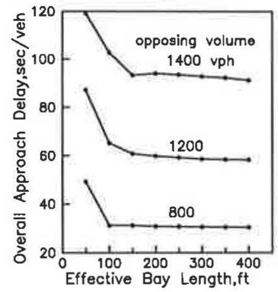

FIGURE 8 Example relationships between delay and the effective length of left-turn bay.

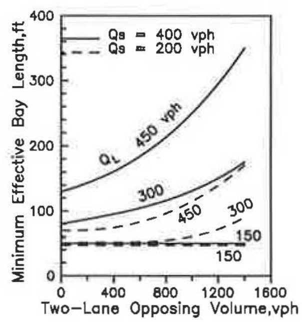

FIGURE 9 Minimum required effective length of left-turn bay (low cross traffic with critical movement volume Q_c = 100 vph).

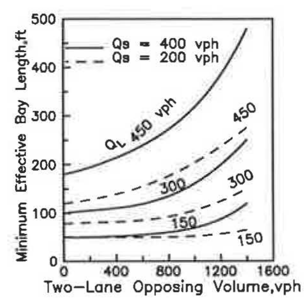

FIGURE 10 Minimum required effective length of left-turn bay (moderate cross traffic with critical movement volume Q_c = 600 vph).

can become rather limited. An example of the detrimental impact of inadequate bay lengths is shown in Figure 8. This figure is developed in two stages. First, for a bay length of 100 ft, the timing settings are adjusted to minimize the overall delay and to avoid, whenever possible, excessive delays and queue lengths. Next, the resulting timing settings are held constant while the bay length is varied. Thus, the delay curves shown in the figure are a function of the bay length alone.

Figure 8 shows that the overall delay can increase dramatically when the bay length is shorter than the critical length. For the flow pattern shown in the figure, the critical length is about 100 ft when the left-turn vehicles are faced with a two-lane opposing volume of 800 vph. This critical length is raised to about 150 ft when the opposing volume is increased to 1,200 vph. Beyond such critical lengths, a very large increase in the bay length is needed in order to produce a noticeable improvement in the control efficiency.

Based on the critical bay lengths for a variety of flow conditions, Figures 9, 10, and 11 assist in the determination of the minimum bay length requirements. These figures can be used directly when left turns encounter two opposing lanes. To apply them to cases involving only one opposing lane, the one-lane opposing volume must first be transformed into an equivalent two-lane opposing volume. Through comparison of simulated bay length requirements, it is found that 1 vehicle in a one-lane opposing flow can be transformed into about 1.3 vehicles in a two-lane opposing flow. This conversion factor approximates the ratio of typical observed left-turn saturation flow facing two opposing lanes to that facing one opposing lane (*8*). The following example illustrates the applications of Figures 9, 10, and 11.

Given a left-turn volume of Q_L = 350 vph, a two-lane opposing volume of Q_o = 700 vph, and adjacent straight-through flow of Q_s = 300 vph, and a critical movement vol-

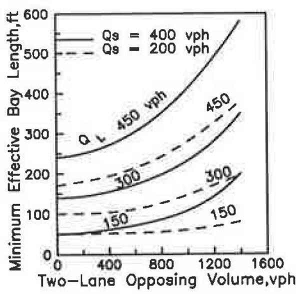

FIGURE 11 Minimum required effective length of left-turn bay (high cross traffic with critical movement volume Q_c = 900 vph).

ume of Q_c = 350 vph on the cross street, it is desired to know how long the minimum length of the left-turn bay should be. Because the critical movement volume on the cross street is 350 vph, Figures 9 and 10 should be used. Through interpolation, Figure 9 gives an estimated required length of 100 ft for a critical movement volume of 100 vph on the cross street. Similarly, Figure 10 gives an estimated required length of 140 ft for a critical movement volume of 600 vph on the cross street. Thus, the required length is approximately the average of 100 ft and 140 ft, that is, 120 ft.

For the conditions given in this example, Figure 5 shows that protected/permissive phasing may be a better choice when the opposing volume exceeds approximately 450 vph. Because the given opposing volume of 700 vph is much larger, protected/permissive phasing warrants serious consideration. If left-turn bays of at least 120 ft in length are provided, protected/permissive phasing can be effectively used. In such a case, Figure 7 shows that the intersection capacity will unlikely become inadequate unless the opposing volume exceeds about 1,100 vph. Because the given opposing volume is only 700 vph, there are flexibilities in using protected/permissive phasing to improve signal operations. In contrast, Figure 7 also shows that the intersection capacity will be inadequate if permissive phasing is implemented instead. With this additional understanding, it appears reasonable to conclude that protected/permissive phasing should be chosen over permissive phasing.

CONCLUSIONS

The selection of left-turn phasing plans for full-actuated signal control is a complicated problem. Ideally, such a problem should be solved with the aid of computer simulation. When an easy access to a simulation model is not available, the information presented here is useful, particularly for planning purposes.

The choice between permissive phasing and protected/permissive phasing is governed primarily by left-turn volume, opposing volume, the number of opposing lanes, and the level of cross traffic. Simple rules of thumb are not adequate in guiding such a choice. Protected/permissive phasing is generally preferred to permissive phasing if the intersection capacity cannot accommodate signal operations with permissive phasing but is still adequate to support operations with protected/permissive phasing.

In implementing protected/permissive phasing, the left-turn bays should be sufficiently long. Otherwise, the ability of such a phasing arrangement to improve signal operations can be seriously compromised.

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