Warrants for Protected Left-Turn Phasing

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ABSTRACT

A comprehensive decision tree was developed to aid in the choice of left-turn treatment at signalized intersections. Protected left-turns should be chosen in cases of high prevailing speeds, multiple left-turn lanes, limited sight distances and frequent crash occurrence. The rest of the cases constitute the majority of conditions at signalized intersections. Therefore, a methodology is proposed for combining a volume warrant with a delay warrant to resolve the issue generally. Threshold values of the left-turn volumes, above which protected left-turn phasing is justified, can be determined based on average delay. Reliable and easy-to-use regression models for warrants for protected left-turn phasing can be developed for typical intersection configurations, which would enable traffic engineers to rapidly and accurately determine the proper left-turn treatment.

INTRODUCTION AND BACKGROUND

There are various options and combinations of options for serving left turns at signalized intersections. The main options are prohibited, permitted, and protected. Common combinations of options include protected-permitted and permitted-protected. Some of them have inherent safety problems such as the "yellow trap" issue. To this end, NCHRP Report 493 (Brehmer et al. 2003) concluded with a recommendation for a flashing yellow arrow to provide a clear distinction between permitted and protected left turns.

The larger issue, however, is the absence of nationally accepted warrants for left-turn phasing at signalized intersections. The Manual on Uniform Traffic Control Devices (MUTCD 2003) does not provide specific guidance for left-turn phasing and the Highway Capacity Manual (HCM 2000) only mentions that "local practice is an important determinant in the selection of a phase plan."

To fill the void of a national standard, warrants or guidelines for protected left-turn phasing have been developed by research institutes or state and local agencies. In general, the warrants fall into six categories depending on the metric used: delay, traffic volume, crash/conflict experience, intersection geometrics, speed, and other considerations. These are summarized in Table 1 and are briefly described below.

Delay has been used widely as a warrant for protected left-turn phasing. The installation of protected left-turn phasing is suggested if a left-turn delay of 2.0 vehicle-hours or more is observed and the average left-turn delay exceeds 35 seconds at a signalized intersection (Agent 1979, Cottrell 1986, Lalani et al. 1986). Delay warrants found in the literature are based on delay experienced by left-turn drivers only.

Three **traffic volume**-based criteria have developed into warrants for protected left-turn phasing. They are listed bellow for left-turn (LT) volume, opposing through (TH) volume, and volume cross product (VCP).

- Left-Turn Volume: Protected left-turn phasing is warranted only if left-turn volume is at least 50 vph or 2 vehicles per cycle during peak hours (Agent 1979, Cottrell 1986, ITE 1991, Lalani et al. 1986, Upchurch 1986). If the left-turn volume exceeds 300 vph (Stamatiadis et al. 1997) or 320 vph (Asante et al. 1993), protected left-turn phasing should be considered.

- Opposing Through Volume: If opposing volume is greater than 1,100 vph during a peak hour, then protected left-turn phasing may be necessary (Asante et al. 1993).
- Volume Cross Product: Volume cross product is the left-turn volume multiplied by the opposing through volume. If the volume cross product exceeds a certain value, then protected left-turn phasing should be installed. Several different criteria are presented in the literature (Agent 1979, ITE 1991, McShane and Roess 1990, Stamatiadis et al. 1997, Upchurch 1986).

Crash experience is a basic warrant for signalization and a critical warrant for protected left-turn phasing. Most existing guidelines have specific threshold values, above which protected left-turn phasing should be considered (Agent 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997). Based on a traffic conflict study, if ten or more left-turn conflicts occur during a peak hour, protected left-turn phasing is also justified (Agent 1979). Another study suggested a threshold value of four left-turn conflicts per 100 left turns as a warrant for protected left-turn phasing (Cottrell 1986). In this context, conflicts are defined as near-misses observed in the field by trained observers.

Certain **intersection geometric characteristics** that affect safety may warrant protected left-turn phasing. Sight distance, number of opposing through lanes and number of left-turn lanes have been identified in the literature and warrants have been suggested, as follows.

- **Sight Distance**: Protected left-turn phasing is warranted if the sight distance for left-turn vehicles is inadequate. When the speed of opposing traffic is 35 mph or less, a sight distance of 250 ft. or less justifies protected left-turn phasing. The introduction of protected left-turn phasing is also necessitated if opposing traffic speed is 40 mph or more and sight distance is limited to 400 ft. or less (ITE Florida Section 1982, Upchurch 1986).

- **Opposing Through Lane**: Making left turns becomes more difficult when the number of opposing through lanes increases. Some guidelines state that three or more opposing through lanes may warrant protected left-turn phasing (Agent 1987, Asante et al. 1993, Cottrell 1986).
- **Left-Turn Lane**: Two or more exclusive left-turn lanes require protected left-turn phasing (Agent 1987, Asante et al. 1993, ITE Florida Section 1982).

High **speeds** of opposing through traffic may contribute to severe crashes with left-turn traffic. Therefore, the speed of opposing traffic has been identified as one of the warrants for protected left-turn phasing. Most suggest an average opposing traffic speed of 45 mph as a threshold value above which protected left-turn phasing is justified (Agent 1979, Agent 1987, Asante et al. 1993, Upchurch 1986).

Some other considerations for protected left-turn phasing have also been identified. Fisher (1998) argued that some more direct indicators such as the number of failed cycles should be used as criteria for the justification of protected left-turn phasing. Etelamaki (1982) applied benefit/cost analysis to determine if protected left-turn phasing is justified. A survey conducted by the Colorado/Wyoming section of the Institute of Transportation Engineers (ITE) revealed that vehicle queue, left-turn storage length, percent of heavy vehicles, political motivation and public demand were also employed for the justification of protected left-turn phasing (Lalani et al. 1986).

The absence of intersection delay as a factor in left turn treatment determination is conspicuous among the proposed criteria in Table 1 that may warrant protected left-turn phasing. Rouphail (1986) noticed the absence of an intersection-wide basis for judgment and proposed a warrant for selecting left turn treatment by establishing a fixed volume-to-capacity ratio for all intersection movements. This was an early attempt to keep delays throughout the intersection in balance. Al-Kaisy and Stewart (2001) advanced this concept considerably by using optimization in developing warrants for protected left turns.

The logic behind the use of optimization for the development of left-turn phasing warrants is as follows. Permitted left-turn phasing is usually suitable for light traffic conditions since opposing traffic allows for an adequate number of gaps of sufficient length for left-turn vehicles, whereas protected left-turn phasing in light volume conditions may increase average delay to all vehicles because a smaller share of green time is available for other phases and intersection efficiency is impaired by longer cycles, additional start-up lost times, and additional change intervals.

If traffic volume at an intersection is heavy, then, under permitted left turn operation, it is difficult for turning vehicles to find appropriate gaps in the opposing flow and long delays are likely for them. Furthermore, a long delay may generate long queues and the spillback of the left-turn vehicles may cause the blockage of the adjacent through lane and impact neighboring intersections. Increased delays may force left-turn drivers to utilize shorter gaps in the opposing traffic which increases the potential for crashes.

Therefore, as traffic volume increases at a signalized intersection, there is a point beyond which protected left-turn phasing provides a better signal operation than permitted left-turn phasing. A reliable method to determine the best left-turn phasing treatment under different traffic conditions is needed. This paper describes a method to do this.

STUDY OBJECTIVE AND METHODOLOGY

The objective of the study is to develop a comprehensive procedure for selecting left-turn phasing treatment at signalized intersections. This is done by combining both existing empirical warrants and an optimization-based warrant similar to that proposed by Al-Kaisy and Stewart (2001). Another objective is to prove that using a constant volume cross product as a warrant for protected left-turn phasing is inappropriate.

A decision tree for determining the type of left-turn phasing was developed as shown in Figure 1. Six categories including crash experience, opposing speed, number of opposing through lanes, sight distance, number of left turn lanes, and *volume & delay*, are defined in the decision tree for the determination of the type of left-turn phasing. A high crash rate related to left turns is certainly a strong warrant for protected LT phasing. High opposing speed, several opposing lanes to cross, poor sight distance, and the existence of more than one LT lane may cause safety problems and warrant a protected LT phasing.

Volume and delay are also important factors for determining the type of left-turn phasing. Volume warrants and delay warrants can be combined together through optimization to form a *volume & delay warrant*. The proposed warrant accounts for overall intersection performance and removes the need for determining threshold values which vary by jurisdiction and the wisdom of their use has been questioned by some researchers (Al-Kaisy and Stewart 2001, Lin and Machemehl 1983).

Average delay is used in the *volume & delay warrant*. If the average delay for all the entering traffic under the signal timing plan with protected left-turn is less than that with permitted left-turn, a protected left-turn phasing is preferred.

The methodology proposed for determining the *volume & delay warrant* is outlined in Figure 2. The input parameters include the intersection geometry, traffic volumes, and signal phasing plans. In order to demonstrate the methodology, TRANSYT-7F, version 9, 2003 was used to optimize signal timing for different signal phasing plans with various traffic volumes. Therefore, the estimates of average delay are all optimal for permitted and protected left-turn phasing under prevailing traffic conditions. As mentioned before, when traffic volume increases at a signalized intersection, there is a point beyond which protected left-turn phasing provides a better signal operation (in terms of delay) than permitted left-turn phasing. Hence, based on the average delay, the threshold values are determined for the subject left-turn traffic volume beyond which protected or protected/permitted (P/P) left-turn phasing is warranted. The threshold left-turn volume is chosen as the dependent variable and the other traffic volumes are selected as independent variables. Regression analysis is performed to find the *volume & delay warrant* for protected or protected/permitted left-turn phasing. Regression modeling is a suitable tool for the analysis of this type (Al-Kaisy 2001).

The proposed methodology improves on Al-Kaisy and Stewart’s methodology by

(1) Combining empirical warrants for left turns to form an easy-to-use decision tree (Figure 1).

(2) Using an established traffic signal analysis tool such as TRANSYT-7F for optimizations instead of their *Signal Expert* signal software which is based on the Canadian Capacity Guide for Signalized

Intersections. TRANSYT-7F was chosen for this application because it includes the HCM 2000 delay equations.

(3) Using real intersection configurations instead of hypothetical ones. The case study conducted by Al-Kaisy and Stewart (2001) focused on intersections with only one lane in each direction. Furthermore, no left- or right-turns were allowed in the cross street and on the opposing approach. In this paper, however, a typical intersection with left- and right-turn traffic is analyzed. A more reliable regression model (R^2>0.95) is developed, comparing with their relatively low coefficient of determination (R^2 varied from 0.55 to 0.82).

CASE STUDY

The proposed methodology is illustrated with a case study. Figure 3 shows the geometric configuration of an intersection and two different signal phasing plans, one with permitted LT phasing and another with protected LT phasing. Protected/permitted phasing was not analyzed at this stage but the same methodology can also be applied. The signalized intersection has one left-turn lane, one through lane and one through and right-turn lane on each approach.

East-bound (EB) and west-bound (WB) traffic volumes were assumed to vary from 400 vehicles per hour (vph) to 1,400 vph, with increments of 200 vph equally distributed in each direction. North-bound (NB) through as well as right-turn and south-bound (SB) were loaded with traffic varying from 800 vph to 1,800 vph, with increments of 200 vph equally distributed in each direction. Three turning distribution combinations were considered herein, as shown in Table 2; they are:

- 10%(left) – 80%(through) – 10%(right)
- 20%(left) – 60%(through) – 20%(right), and
- 30(left) – 40%(through) – 30%(right).

The subject movement for determining the left turn treatment with threshold values is the north-bound traffic that turns left. Therefore, the turning distribution for the north-bound approach did not include those turning left.

The average overall delay was determined using TRANSYT-7F with its Disutility Index optimization function. Other analysis assumptions for demonstrating the proposed methodology include 1800 vphpl for the saturation flow rate, 3 s yellow time, 1 s all red time. It was also assumed that traffic volumes are determined to the nearest 10 vph. In total, there were 108 cases, as shown in Table 2. For each case, two signal timing plans (permitted vs. protected left-turn phasing) needed to be optimized using TRANSYT-7F. The delay comparison between permitted and protected left-turn phasing was a trial-and-error process and about ten optimization runs were usually necessary to determine the threshold value of NB_L at which delays under protected phasing were lower than those under permitted phasing. As a result, about 1,080 TRANSYT-7F optimization runs were performed and the final threshold values for all 108 cases are presented in Table 2.

The threshold values for the north-bound left turning traffic volume (NB_L) were chosen as the dependent variable. Regression models were developed so that NB_L can be predicted using several independent variables, as defined below.

CV_L = total left-turn traffic volume in the cross street (EB and WB)

CV_{TR} = total through and right-turn traffic volume in the cross street (EB and WB)

NB_{TR} = through and right-turn traffic volume on the NB approach

SB_L = left-turn traffic volume on the SB approach

SB_{TR} = through and right-turn traffic volume on the SB approach

A multiple linear regression model (Equation 1) was developed with SB_{TR}, CV_L, and CV_{TR} resulting as the significant predictor variables. The coefficient of determination (R^2) of the model is 0.952 and the standard error is 27.7 vph. The F-test in the analysis of variance (ANOVA) showed that the regression model is statistically significant at 99% confidence level. Furthermore, the T-test also showed that all model coefficients are significant at 99% confidence level.

$$NB_L = 1104 - 0.549 SB_{TR} - 0.255 CV_L - 0.264 CV_{TR} \quad (1)$$

The threshold values for NB_L is negatively correlated with SB_{TR}, which is expected since increasing opposing traffic results in fewer turning opportunities for left-turn vehicles. NB_L is also negatively correlated with cross-street traffic (CV_L, CV_{TR}), although to a lesser degree, which could be explained by the smaller green time ratio allocated to NB and SB due to longer green time assigned to serve the increasing cross street traffic volume.

Figure 4 shows the model predictions for NB_L. The dotted diagonal line depicts an ideal match between actual and predicted NB_L. In general, the model provides a good fit to the data simulated with TRANSYT-7F. The minimum and maximum absolute prediction errors are 0.4 vph and 66 vph, respectively.

The volume cross product was calculated for the 108 cases; Figure 5 shows its distribution. The volume cross product varied from 50,000 to 400,000, with about one third of its values falling between 150,000 and 200,000. This suggests that using a constant volume cross product as a criterion for the warrants for protected left-turn phasing is questionable due to the wide distribution of the cross-product values.

SUMMARY AND FUTURE STUDY

A general procedure for determining the type of left-turn phasing was developed based on a synthesis of warrants and guidelines found in the literature. A methodology was developed for combining a volume warrant and a delay warrant to form a *volume & delay warrant*. The average delay at a signalized intersection, for permitted and protected left-turn phasing for prevailing traffic conditions, were compared and a threshold value of the left-turn volume on the subject approach was determined for various combinations of traffic volumes. TRANSYT-7F was used in this application because it includes the HCM 2000 delay formulae, but other traffic signal optimization software may be selected for deploying the proposed methodology.

Regression analysis with the volume of the subject left turn movement as the dependent variable was applied to find best-fit models for the *volume & delay warrant* for protected LT phasing for one specific intersection configuration. The proposed method overcomes the shortcomings of current volume warrants for protected left-turn phasing using various rules-of-thumb as criteria.

The findings of this study may be summarized as follows:

- The left-turn volume that warrants protected left-turn phasing is heavily dependent on the opposing traffic volume. Higher opposing through volume results in lower left-turn volume.
- The left-turn volume that warrants protected left-turn phasing is also dependent on the cross-street volume. The left-turn volume warrant decreases significantly with increasing cross-street traffic.
- The inclusion of all significant traffic volumes as predictor variables explain as much as 95.2% of the variation of the left-turn traffic volume. Consequently, easy-to-use and highly statistically significant models can be developed for typical intersection configurations.
- Current volume warrants using a constant volume cross product as a criterion for the warrant for protected left-turn phasing are questionable. In the case study, the volume cross product varied widely; thus, the use of a constant threshold based on volume cross product is counterintuitive and it likely produces unreliable decisions for left turn treatment at signalized intersections.

This research is being done as a continuation of past efforts to develop a comprehensive method for determining the appropriate type of left-turn phasing. Several elements requiring further study include the following:

- Neither pedestrian nor bicycle traffic was considered in the analysis procedure, but this can be accounted for with more comprehensive models.
- No shared left-turn lanes were considered in the case study. Also, no protected/permitted (P/P) left-turn phasing was illustrated. Future research may include both of them for left-turn phasing warrants.

- The statistical analysis revealed that the subject left turn volume (dependent variable) is not correlated with the left turn volume on the opposite approach. This independence is convenient but it may be an artifact of the assumed data set. Additional analysis is required to reveal whether this finding can be generalized.
- The illustrated method is based on a point beyond which protected left turn phasing is advantageous to permitted left turn phasing. In reality, however, given the general flux of traffic demand and the uncertainty in several inputs in the analysis, the illustrated "point" is likely to be a "gray area" which can be investigated by using fuzzy analysis (Lin et al., 2005). This feasible extension was beyond the scope of this investigation.
- Due to the large number of computer optimization runs involved, a batch processing interface along with an intelligent trial-and-error algorithm are necessary for developing a reasonably comprehensive set of left-turn phasing warrants that include pedestrian and bicyclist effects as well as accommodations for volume variations and other uncertainties.

In conclusion, the method presented in this paper can be applied for several typical intersection configurations. Regression models can be developed for various intersection configurations and compiled into a handy guide. This guide would provide traffic engineers with a means for quick determination of left-turn phasing that accounts for all relevant volumes while implicitly accounting for delays.

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TABLE 1. Current Warrants or Guidelines for Protected Left-Turn Phasing

Criterion	Warrant or Guideline		Reference
Delay	LT Delay	≥ 2.0 vehicle-hours	Agent 1979, Cottrell 1986, Lalani et al. 1986
	Average LT Delay	≥ 35 Seconds	
Volume	LT Volume	≥ 50 vph	Agent 1979, Cottrell 1986, ITE 1991, Lalani et al. 1986, Upchurch 1986
		≥ 2 Veh/Cycle	
		> 300 vph	Stamatiadis et al. 1997
		> 320 vph	Asante et al. 1993
	Opposing TH Volume	> 1,100 vph	Asante et al. 1993
	Volume Cross Product	> 50,000 (one opposing lane)	Agent 1979, ITE 1991, McShane and Roess 1990, Stamatiadis et al. 1997
		> 100,000 (two opposing lanes)	
		> 144,000 (two opposing lanes)	Upchurch 1986
		> 100,000 (three opposing lanes)	
Accident/Conflict Experience	LT-Related Accidents	≥ 4 in one year, or ≥ 6 in two years, or ≥ 8 in three years	Agent 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997
	LT Conflicts	≥ 10 during a peak hour	Agent 1979
		≥ 4 per 100 left-turn vehicles	Cottrell 1986
Intersection Geometrics	Sight Distance	≤ 250 ft (75 m) (opposing speed ≤ 35 mph (55 km/h))	ITE Florida Section 1982, Upchurch 1986
		≤ 400 ft (120 m) (opposing speed > 35 mph (55 km/h))	
	Number of Opposing TH Lanes	≥ 3	Agent 1987, Asante et al. 1993, Cottrell 1986
	Number of LT Lanes	≥ 2	Agent 1987, Asante et al. 1993, ITE Florida Section 1982
Speed	Opposing Speed	≥ 45 mph (70 km/h)	Agent 1979, Agent 1987, Asante et al. 1993, Upchurch 1986
Other	Number of Failed Cycles		Fisher 1998
	Benefit/Cost Analysis		Etelamaki 1982
	Vehicle Queue		Lalani et al. 1986
	LT Storage Length		
	Percent of Heavy Vehicles		
	Political Motivation		
	Public Demand		

TABLE 2. Threshold Values (NB_L)

Threshold Values (NB_L)						
10%(left)-80%(through)-10%(right) traffic volume distribution						
East/west bound	**North/south bound[1]**					
	800	**1,000**	**1,200**	**1,400**	**1,600**	**1,800**
400	760	700	690	640	570	510
600	760	690	630	570	520	500
800	740	670	620	560	510	460
1,000	670	620	580	530	480	430
1,200	630	590	530	480	430	390
1,400	500	430	390	360	320	260
20%(left)-60%(through)-20%(right) traffic volume distribution						
East/west bound	**North/south bound[2]**					
	800	**1,000**	**1,200**	**1,400**	**1,600**	**1,800**
400	780	770	690	680	640	600
600	780	730	670	630	610	520
800	750	680	650	600	560	510
1,000	690	630	590	550	490	450
1,200	580	520	460	430	390	380
1,400	570	500	440	400	380	370
30%(left)-40%(through)-30%(right) traffic volume distribution						
East/west bound	**North/south bound[3]**					
	800	**1,000**	**1,200**	**1,400**	**1,600**	**1,800**
400	840	820	800	750	710	660
600	800	780	720	710	680	610
800	750	690	650	620	590	550
1,000	720	660	640	590	510	480
1,200	610	560	520	510	490	450
1,400	600	560	510	480	460	420

([1,2,3]) *The turning distribution on the north-bound (NB) approach is 90%, 80% and 70% for through traffic, and 10%, 20% and 30% for right turning traffic, for each respective portion of the table.*

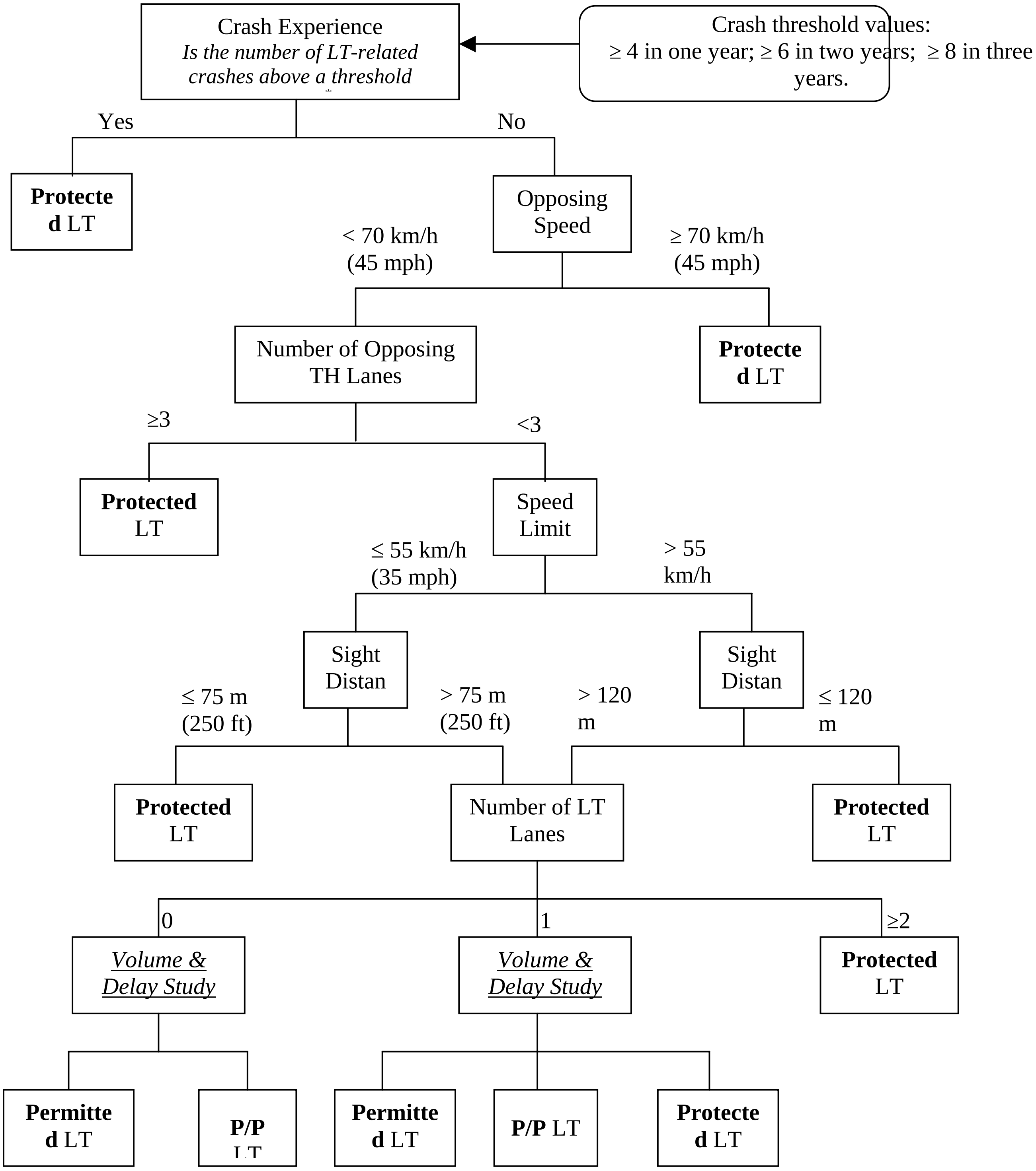

FIGURE 1. Procedure for determining type of left-turn phasing.

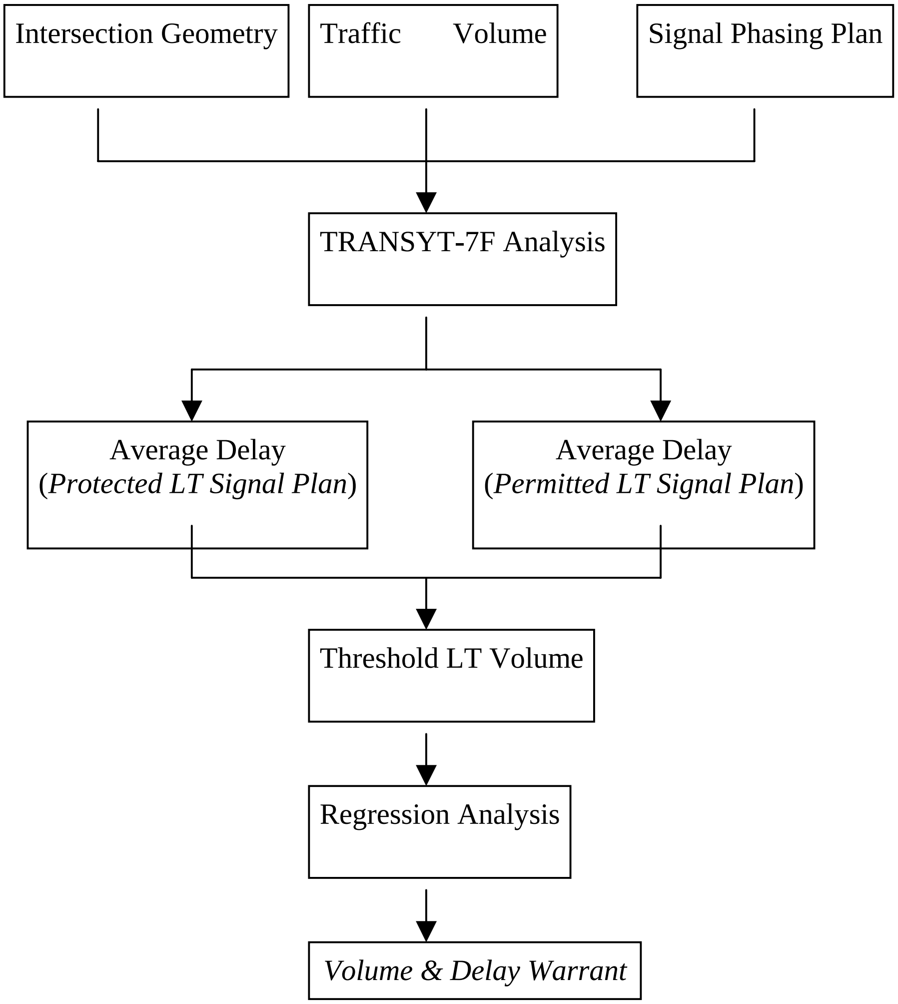

FIGURE 2. Proposed methodology for determining the *volume & delay warrant*.

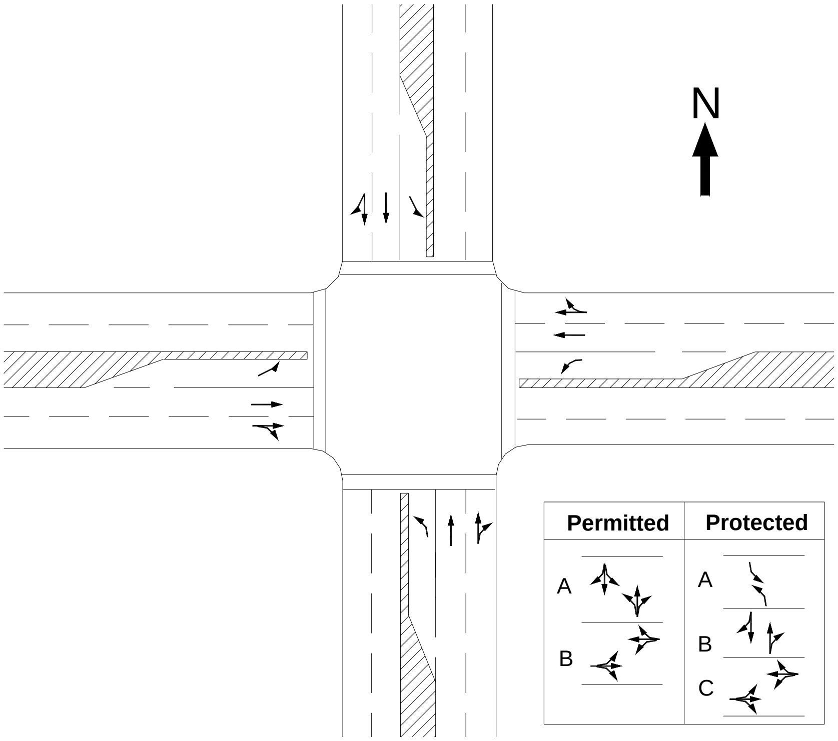

FIGURE 3. Case study intersection.

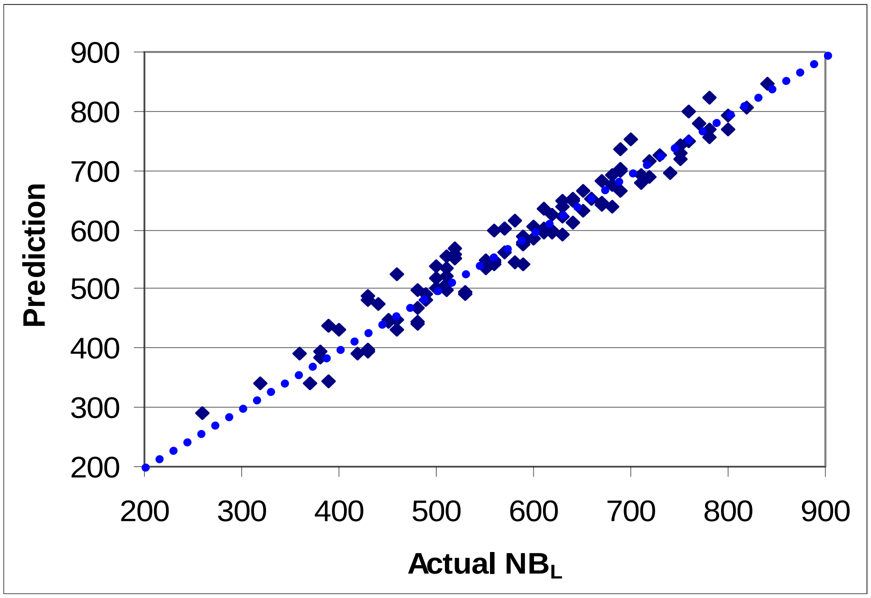

FIGURE 4. Model Prediction.

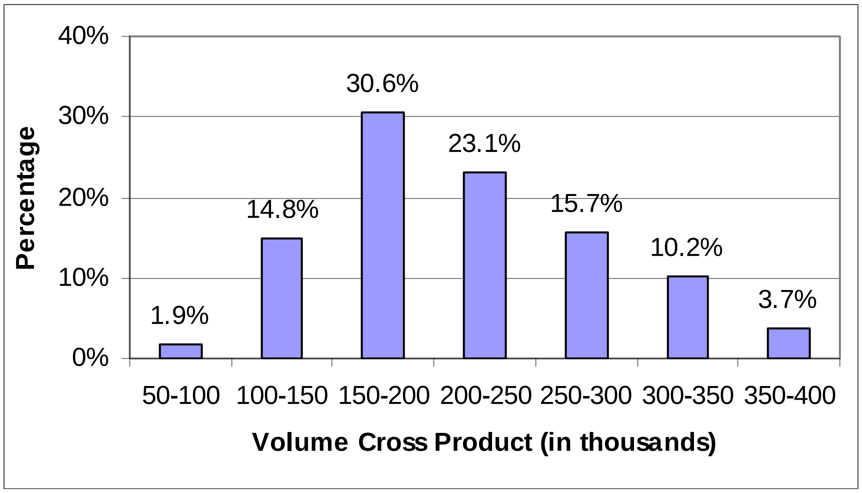

FIGURE 5. Volume cross product distribution.