

INTEGRATED SIMULATION AND SAFETY-UK

FINAL REPORT



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16. Abstract The need to balance safety and operational efficiency at intersections requires special attention for accommodating left turn movements. Signalized intersections epitomize this need because unnecessary protection of left turns can significantly increase operational delay. Left turn protection however, increases safety and there is a need for proper balancing between the conflicting goals of safety and operations. The long time required to collect crash data to evaluate the use of existing warrants render them frequently ineffective and the need for a preliminary design tool to assist in left turn phasing decisions is needed. This research developed a quantitative safety assessment tool that predicts left turn related conflicts and uses them to determine the appropriate phasing scheme for left turns. The model was developed based on VISSIM micro-simulation software in conjunction with the Surrogate Safety Assessment Model.			
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EXECUTIVE SUMMARY

A fundamental objective of traffic signals is the development of signal plans that improve efficiency of operations and reduce delays while maintaining a high level of safety. One issue of concern is the treatment of left-turn phasing, which can operate as a protected movement, a permitted movement yielding to conflicting traffic, a combination protected-permitted movement or as a split-phase intersection. While protected-only movements and split phasing can improve safety, they can also increase delays and congestion at the intersection.

Permitted movements can safely serve traffic when volumes are low, such as during off-peak periods, but may experience safety or capacity problems with high volumes, such as during the AM and PM rush hour. Due to the varying traffic demands throughout the day, the choice of left-turn phasing is not always clear. The lack of any nation-wide acceptable criteria or prediction models for the installation and usage of left-turn phasing generated the need for improving existing guidelines for the use of left-turn phasing. Most the current state policies prescribe the use of protected-only phasing for certain geometric configurations, such as when three or more opposing through lanes are present, when dual left-turn lanes exist, if there is insufficient sight distance for the turning vehicle and opposing traffic, or if the intersection geometrics prevent adequate sight distance due to lane configuration and offsets.

The objectives of the study are to improve existing understanding of the safety performance of signalized intersections though the use of simulation is undeniable and develop models aiming to estimate the safety impacts of the use of permitted, protected, and protected-permitted left-turn phasing.

The literature review conducted here points to the wide variety of factors considered for the selection of the left-turn phase among the various agencies. There seems to be an overall agreement on the various factors to be used in determining the appropriate left-turn phase but there is little agreement on the specific values to be used. Several agencies consider left-turn volume warrants based on the constant cross product of left-turn and opposing volumes. However, there is little agreement on the numbers to be used.. Many studies also indicate that

there is a need to consider a wide variety of factors in addition to the cross product. One of the issues that has been identified in the early studies, and has been addressed to a certain extent more recently, is that most of the warrants were developed based minimizing intersection delay with little consideration to intersection safety and thus minimizing potential conflicts. It should be noted here that most of the warrants and guidelines developed consider only operational efficiency or safety impacts and very few consider the combined impacts of both. In general, almost all studies that develop left-turn volume warrants consistently applied the cross product as the main warrant. However, a limitation of this approach is the inability to allow for distinctions among different intersection geometric features and has not been evaluated for three or more opposing through lanes. Furthermore, additional research is needed to understand how other factors affect and interact with each other to provide a more appropriate and balanced operational and safety performance. As it was noted above, there is very little work that has successfully combined safety and operational aspects and this should be addressed in the future.

The approach undertaken is a combination of micro-simulation with surrogate safety measures in order to develop safety prediction models. Conflicts are considered a viable surrogate to crashes due to their frequency and relatability to crash events and current micro-simulation models can be used to determine their frequency. The literature also indicated that the number of opposing lanes and length of green times and cycles are the most common variables used in prediction models but the use of cross product or individual volumes is still debated. Variables considered here include the number of opposing lanes, opposing volume, left-turning volume, cycle length and percent green. A total of 2,250 cases were simulated and the first step evaluated the potential ability of each variable alone to be a predictor. However, no variable was a good predictor alone and a combination of variables was sought that could provide a higher predictive model power.

Through an iterative process, a series of powers of the individual root variables were evaluated resulting in (Eq. 1) that can predict the number of crossing conflicts:

$$X_{Crossing} = (LTDown^2 \times OppVolOut \times OpposingLanes^3)/(\%Green^{1/3}) \quad (1)$$

This model also supports the notion that opposing and left turn volumes may have a different impact on the potential for a conflict since the left turning movements have more of an influence (higher power) than the opposing through movements when predicting Crossing conflicts. The reason for the need of differentiating between each of these volumes is their potential effects on safety, since this cannot be accounted for in a cross product. It is therefore reasonable to assume that combinations of left turn and opposing volumes resulting in the same cross product, would have a different safety performance and this was captured in the Crossing conflict model developed here though the inclusion of the independent variables and their relative impact.

Future efforts will develop relationships between conflicts and crash propensity developing nomographs capable of guiding signal phasing decisions. Figure 1 demonstrates a line of equality representing a single conflict for the left turn and opposing volume combinations. Guidance such as this can be used to establish thresholds for safety performance to provide guidance on left turn phasing selection.

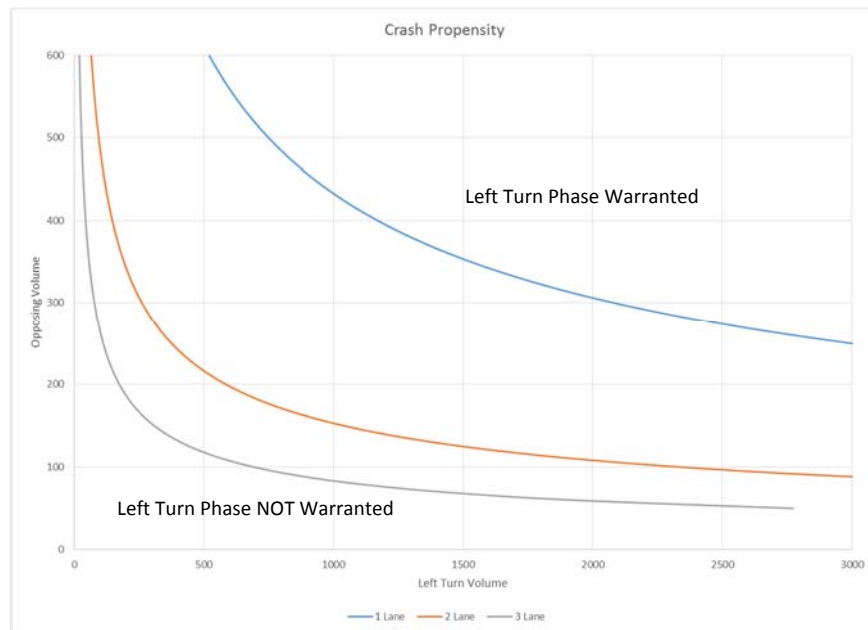


Figure 1. Left turn phasing guidance, one conflict

DESCRIPTION OF PROBLEM

Signalized intersections are a critical component of the roadway system and frequently act as choke points on the transportation system. In addition, intersection crashes account for approximately 26 percent of all crashes in Kentucky (Kentucky State Police 2012). A fundamental objective of traffic signals is the development of signal plans that improve efficiency of operations and reduce delays while maintaining a high level of safety. One issue of concern is the treatment of left-turn phasing, which can operate as a protected movement, a permitted movement yielding to conflicting traffic, a combination protected-permitted movement or as a split-phase intersection. While protected-only movements and split phasing can improve safety, they can also increase delays and congestion at the intersection. Permitted movements can safely serve traffic when volumes are low, such as during off-peak periods, but may experience safety or capacity problems with high volumes, such as during the AM and PM rush hour. Due to the varying traffic demands throughout the day, the choice of left-turn phasing is not always clear.

Left-turning maneuvers are considered as one of the most hazardous traffic movements, since turning vehicles have to cross in front of the opposing through traffic. The difficulty of completing this movement is evident in crash statistics indicating that 45 percent of all crashes that occur at intersections throughout the United States involve left-turning vehicles even though left-turning movements represent a disproportionate small percentage (10-15 percent) of all the approach traffic (Maze et al. 1994). To alleviate this problem and improve safety, exclusive left-turn phasing is frequently installed at traffic signals.

The issue of left-turn phasing is a two-step process. The first question is whether an exclusive left-turn phase is warranted. Major factors affecting this decision are left-turn volumes, opposing volumes, left-turn delays, and left-turn accidents. After a decision is reached to add a left-turn phase, one of two basic phasing methods is commonly used: 1) protected-only, where the driver is allowed to turn left only during the green arrow portion of the cycle while the opposing traffic is stopped; or

2) a combination of protected and permitted left-turn movements, where during a portion of the left-turn phase the left-turning movement is protected from opposing traffic but drivers can continue to turn left during the remaining green through phase when there are available gaps in the opposing traffic.

In addition to the factors affecting the decision for the installation of left-turn phasing, a constant trade-off between the goals of efficiency and safety is present and thus, influences the final decision.

There is no nation-wide acceptable criteria or prediction models for the installation and usage of left-turn phasing despite the fact that studies exist that have developed guidelines for the use of left-turn phasing. Most the current state policies prescribe the use of protected-only phasing for certain geometric configurations, such as when three or more opposing through lanes are present, when dual left-turn lanes exist, if there is insufficient sight distance for the turning vehicle and opposing traffic, or if the intersection geometrics prevent adequate sight distance due to lane configuration and offsets. Additionally, the common ground of the existing guidelines is the use of traffic volumes and threshold values for crashes and acceptable delays as means to make a decision. Moreover, each state has its own criteria in determining when a severe crash problem occurs and when a left-turn treatment is needed or warranted.

The potential for improving existing understanding of the safety performance of signalized intersections though the use of simulation is undeniable and has led to this study aiming to develop crash prediction models for signalized intersections estimating the impact of left-turn phasing decisions. The resulting models will aim to estimate the safety impacts of the use of permitted, protected, and protected-permitted left-turn phasing. It is expected that the findings of this research will be used to improve intersection operations and assist in creating a more appropriate left-turn phasing guidance.

LITERATURE REVIEW

This literature review primarily focuses on evaluating current research findings and reviewing policies of other state agencies relative to permitted left-turn guidelines.

Guidelines

For most state practices, guidelines, not warrants, are used when determining a certain phasing plan. The NCHRP Synthesis 225 (1996) has identified that the general national practices utilize traffic volume, delay, crash history, and visibility as factors when considering the selection of the appropriate left-turn phase. However, the study does not provide any general guidance on the values to be used but rather identifies the need for local guidance.

In 1979, Agent developed one of the first efforts addressing protected left-turn phasing. He proposed a set of warrants for intersections with a left-turn lane that were based on crash experience, delays, volumes, and traffic conflicts (Agent 1979). The warrants were based on a set of Kentucky intersections and state practices at the time of the research. These warrants were evaluated and augmented with guidelines for protected-permitted left turns in 1985 (Agent 1985). It should be noted that this reports defines for the first time the concept of using a cross product threshold of left turn and opposing through volumes (50,000 for one and 100,000 for two opposing lanes) to determine the need for protected phase.

The updated guidelines by Agent in 1985 were based on a study of 58 intersections in Kentucky where protected/permitted phasing was in place. Agent found that a considerable increase in left-turn crashes occurred when protected-permitted phasing replaced protected-only phasing and where protected-permitted phasing was in place at approaches with a speed limit greater than 45 mph. After further analysis, the study recommended that protected-permitted phasing could be used to decrease delay at an intersection, unless certain conditions exist that could produce an increase in crashes, including the following:

- Speed limit is greater than 45 mph.

- Protected phasing is currently in place and the speed limit is greater than 35 mph.
- There are three or more opposing through lanes.
- Left-turn lane has a separate signal head due to intersection geometrics. 10
- Dual left-turn lanes are present.
- Left-turn crash problem is present at the intersection.
- Potential left-turn crash problem exists.
- Current sight distance is less than a sight distance based on the speed limit or the 85th percentile speed, a perception-reaction time of 1.5 seconds, and a coefficient of friction of 0.2.

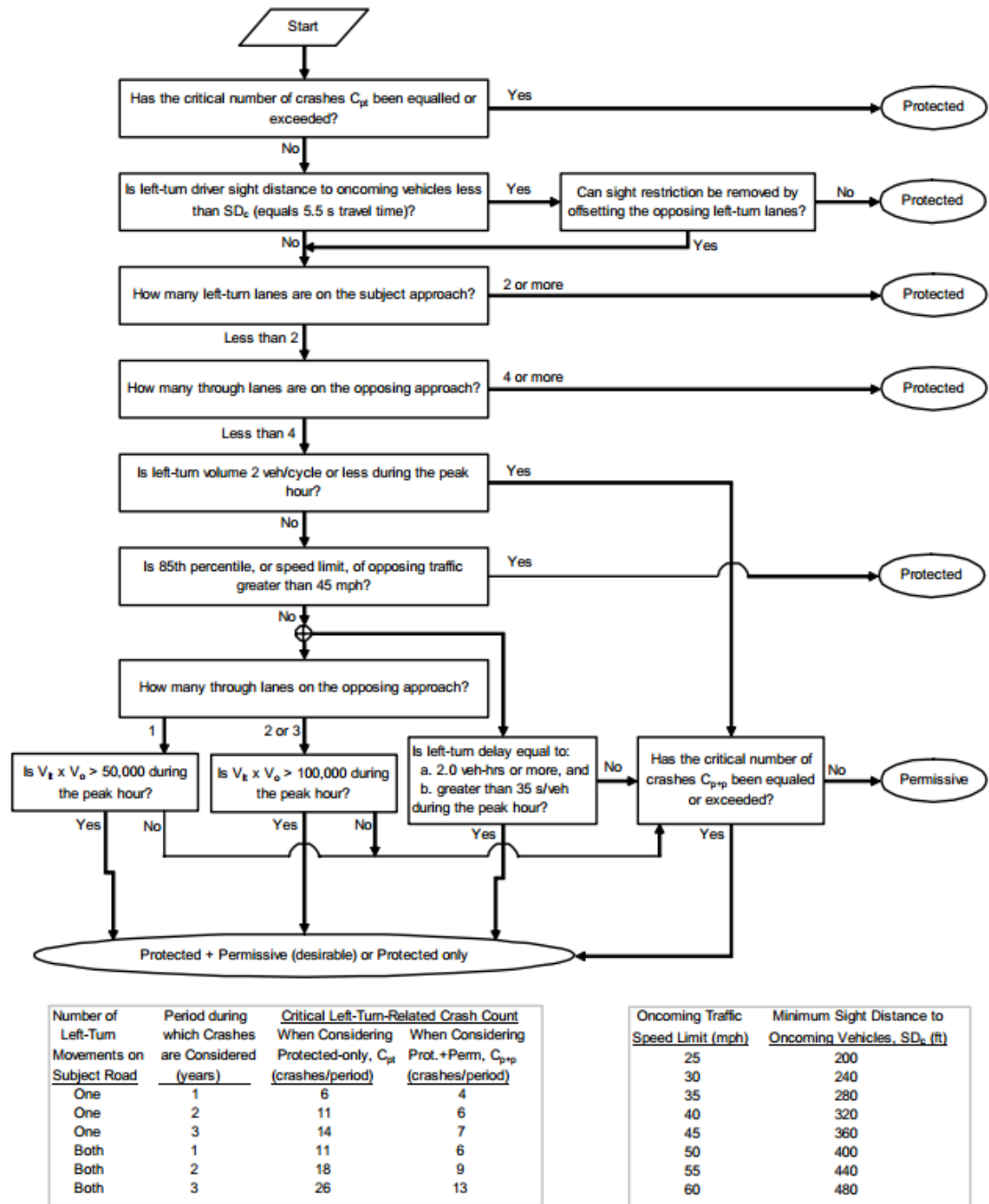
In 1982, the Florida Section of the Institute of Transportation Engineers (FL-ITE) conducted a before and after crash analysis of intersections that were converted from protected to permitted/protected as well as those with a reverse change, i.e., from permitted/protected to protected. The study utilized this analysis along with a survey of FL-ITE members to develop a set of guidelines for left-turn phasing selection. The guidelines developed were very similar to those described above because of the Agent (1985) study. Cottrell (1985) also developed a set of guidelines in an effort to address this issue for the Virginia DOT. The study concluded in very similar recommendations as those reported by Agent (1985) and emphasized the need for engineering judgment as part of the entire process.

The potential delays at an intersection where only permitted phasing is used resulted in another study that evaluated the warrants developed thus far and resulted in a revised set of guidelines that consider delays during the evaluation process (Agent, Stamatiadis and Dyer 1995). The study recommended the use of protected-permitted left-turn phasing unless a combination of some specific factors shows that there is an existing left-turn problem or a potential left-turn crash problem may be created. The factors to be considered for protected-only phase include:

- Crash history: four or more left-turn related crashes in a year, six in two or eight in three years

- Traffic volumes: cross product of left turn and opposing through volume greater than 300,000 for a four-lane or 150,000 for a two-lane approaches
- Delay: more than 2.0 vehicle-hours of delay for an approach during peak hour
- Number of turn lanes: more than one turn lane requires protected-only phasing
- Number of opposing lanes: more than two lanes require protected-only phasing
- Sight distance: per AASHTO guidance
- Left turn volume: 300 vehicles per hour routinely require protected-only phasing
- Opposing volume: 750 for one lane or 1,500 for two lanes and high left-turn volume require protected-only phasing
- Approach speed: greater than 45 mph require protected-only phasing

It should be noted that these guidelines have formed the basis for the guidelines proposed in the FHWA Signalized Intersections: Informational Guide (Rodegerds et al. 2004), the Traffic Signal Timing Manual (Koonce et al. 2008), and the Left Turn Operation Guidelines developed by Bonneson et al. (2009) summarized in Figure 1.



Variables

V_L = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

Figure 1 Left-turn operation guidelines (Bonneson et al. 2009)

Several states use a combination of considerations to determine whether a left-turn phase is required. For example, Arizona (ADOT 2011) and California (CALTRANS 2002) use cross-

product, left-turn volume, delay of left turns, and crash history while Indiana (INDOT 2013) uses left-turn volume and delays and Virginia (VDOT 2011) uses cross-product and crash history. Even though several states use similar guidelines, there is no agreement on the threshold values to be used when a left-turn phasing decision is required. For example, the use of cross-product threshold value varies among the states using this criterion. In this case, Virginia uses 50,000, California 100,000, Arizona 50,000-225,000 depending on lane configuration and intersection location (urban/rural), Oregon 150,000 or 300,000 depending on the number of opposing lanes and phasing type (ODOT 2013) and Texas 130,000 or 93,000 per lane based on number of opposing lanes (Yu et al. 2008).

Stamatiadis, Agent and Bizakis (1997) considered delays and crashes in developing guidelines and boundary conditions for selecting the appropriate left-turn phase. The study utilized micro-simulation for the operational decisions and crash history for the safety and developed nomographs that allow for the selection of the phase type (permitted, permitted/protected or protected) based on cross product and left-turn delays or crashes. It should be noted that this was one of the first studies that developed nomographs to be used combining safety and operational criteria (Figure 2) as well as considering the impacts of the number of opposing lanes in establishing guidelines for phase.

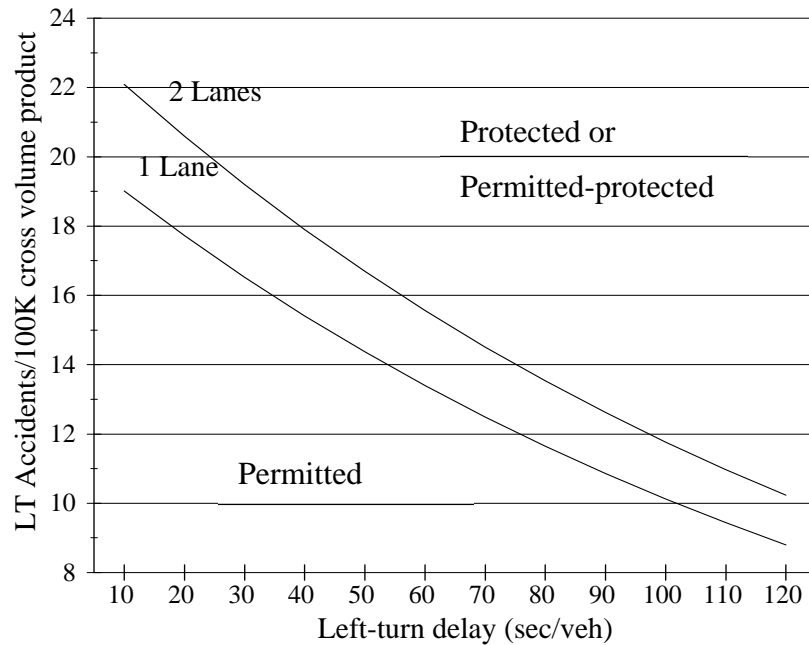


Figure 2 Protected-permitted left-turn phase decision (Stamatiadis, Agent and Bizakis 1997)

The use of the cross-product has been questioned as an indicator for determining phase selection (Al-Khaisy and Stewart 2001). Their evaluation concluded that the opposing volume is not as significant as initially considered when a permitted/protected left-turn phase is considered. It should be noted though that these conclusions were based on single lane approaches with a shared lane for through and left-turn movements.

The guidelines identified here are mostly applied in a singular manner, i.e., decisions are made based on any of the factors considered. This implies that all factors have an equal weight and that they are viewed as not having any interactions. Recent efforts have been undertaken to reconsider this approach and establish a more balanced approach in considering more than a single factor simultaneously. Ozmen, Tian and Gibby (2010) have developed a process that utilized a Multi-Criterion Decision Analysis in selecting appropriate left-turn phase. The approach developed considers volumes, geometry and crashes while ranking possible left-turn phasing options. Their approach provided an index-based

recommendation using weights and scores resulting in a numerical scale for comparing each type of left-turn control with the others instead of an absolute type.

State Guidelines

The review of current literature indicates that there is no consistent nationwide policy. The Traffic Signal Timing Manual (Koonce et al. 2008) provides left turn phasing guidance based on a reformulation of the original guidance proposed by Agent in 1985 and 1995. A review of state design manuals to identify common practice found that several states use similar criteria to determine phasing type, though the thresholds for making these decisions are not uniform. The review indicated that 11 states have no specific guidelines for the left turn phasing (Alaska, Arkansas, Illinois, Indiana, Iowa, Maine, Montana, New Mexico, Oklahoma, South Dakota, and Virginia [although Virginia is currently developing a formal policy]). States lacking a formal policy primarily use experience and engineering judgment to make decisions regarding phasing.

The 24 states with formal policies often contain similar criteria to those used in the Traffic Signal Timing Manual. Phasing type is used to summarize these policies to allow for comparisons among the various states. The data in Table 1 presents the criteria used for selecting a protected only phasing and meeting the criterion threshold value will result in implementing a protected only phasing. Each state utilizes a combination of the available criteria and there is none that utilizes all of them. It should be noted that several states consider additional, unique criteria not shown in Table 1 and those are discussed below.

Table 1: Protected-Only Phasing Requirements

States	Opposing Lane Threshold	Dual Left Turn Lanes	Insufficient Sight Distance	High Opposing Speed (45mph +)	High Opposing Volume	Crash Frequency
Alabama		X	X	X	X	X
Arizona	3	X	X	X		X
Delaware	4	X	X	X		X
Florida	3	X	X	X		X
Georgia	3	X	X	X		X
Idaho	3	X	X			X
Kansas	3		X	X		X
Kentucky	3	X	X			
Louisiana	3	X	X	X		X
Maryland	3		X	X		
Massachusetts	3	X	X	X		
Michigan	3		X	X		X
Minnesota	3	X	X	X		X
New York	3	X	X			X
North Dakota	4	X	X	X		X
Oregon	3	X	X	X		X
Pennsylvania		X			X	
Rhode Island	3	X	X	X	X	
South Carolina	3		X			
Tennessee	3	X	X	X		
Texas	4	X	X	X		X
Washington	3	X	X	X		X
Wisconsin	2	X	X	X		X
Wyoming		X	X			X

The Texas left turn phasing policy (Bonneson et al. 2009) is also utilized by Delaware and North Dakota. These three states are the only ones to implement a four opposing lanes for minimum threshold. The high opposing volume is a metric utilized only by two states. The Alabama policy mentions that intersections with opposing volumes too large to allow for

permitted turning movements should require a protected only phase (ALDOT 2007). Rhode Island, which uses the ITE Handbook left turn phasing policy, provides a numerical value to justify the phasing as “peak 15 minute flow rate of opposing traffic greater than 1,100vph” (Pline 1999).

The high left turn crash rate due to permissive movements category, while common amongst many states contains a variety of quantifiable values. Commonly, states use a specific number of crashes that they consider, most frequently five per year, but there are states with no specified number of crashes (Arizona, Idaho, Wisconsin, Wyoming). There are also state policies that have defined this in a more elaborate manner considering other factors as well. The Texas policy (Figure 1) utilizes a more complex pattern to identify the crash threshold value considering number of turning movements and whether a protected or permitted/protected phasing is considered. Moreover, Washington and Louisiana also have more than one threshold value to examine when decisions are to be made. The Washington policy indicates that protected only should be used when there are three left turn type collisions on any approach, or five in two consecutive years (WSDOT 2011). The Louisiana policy states that protected only phasing is needed if: on one approach there are four or more left turn crashes in one year or six years in two years, or on both approaches there are six crashes in one year or 10 in two years (LaDOTD 2012)

In addition to the common criteria used for protected-only phasing (Table 1) there are states that utilize additional unique criteria uncommon to other state policies. Georgia (GDOT 2013) and Oregon (ODOT 2013) consider high pedestrian volume as one of the factors contributing to the use of protected only phasing. The New York state guidelines recommend the use of protected phasing for multi-legged (5+ approach) intersections (NYSDOT 2002).

Guidelines used for determining the use of protected phasing are typically more stringent than those when considering protected/permitted phasing, since overall intersection efficiency is traded off for safety. The guidelines used for each state to justify protected/permitted phasing are usually just the guidelines used to signify a left turn phase (Table 2).

Table 2 Protected/Permitted Phasing Guidelines

States	Left Turn Crashes one approach (both)			Left Turn and Opposing Product During Peak Hour			Minimum Left Turn Delay of 2.0 Veh. Hrs.	Avg. Delay of Left Turn > 35s	2 left turns per cycle (peak hour)	Min. Left Turn Volume (peak hour)
	One Year	Two Years	Three Years	Two Lane	Four Lane	Six Lane				
Alabama										
Arizona	4 (6)	6 (10)		>50,000 (R) >75,000 (U)	>100,000 (R) >250,000 (U)	>150,000 (R) >225,000 (U)	X	X	X	100
Delaware	4 (6)	6 (9)	7 (13)	>50,000	>100,000		X	X	X	
Florida										
Georgia	4	6		>50,000						125
Idaho			5+							
Kansas	4 (6)	6 (10)								240
Kentucky	4+	6+	8+	>50,000	>100,000		X	X		50
Louisiana				>50,000	>100,000				X	
Maryland				>70,000	>100,000					
Michigan	4 (6)	6 (10)		>50,000	>100,000					
Minnesota										
New York	5+			>50,000	>100,000		X	X		50
North Dakota	4 (6)	6 (9)	7 (13)	>50,000	>100,000		X	X	X	
Oregon				>50,000	>100,000					200
Pennsylvania	5+			>50,000	>65,000					
Rhode Island				>144,000 (regardless of lanes)					X	
South Carolina	5			>100,000 (regardless of lanes)					X	100
Tennessee	4 (6)	6 (10)		>50,000	>90,000	>110,000	X	X	X	100
Texas	4 (6)	6 (9)	7 (13)	>50,000	>100,000		X	X	X	
Washington										
Wisconsin	4 (6)	6 (10)		>50,000	>100,000		X			
Wyoming	4 (6)	6 (9)		>50,000	>100,000		X	X	X	

Table 2 summarizes the common guidelines among states but it does not cover all guidelines included in the respective state policies. Such unique guidelines include the recommendation in New York of using protected/permitted phasing if providing a phase will improve the level of service of the intersection (NYSDOT 2002). Both Washington (WSDOT 2011) and Tennessee (TNDOT 2012) indicate the need for protected/permitted phasing when there is less than 400 feet of sight distance when the 85th percentile speed is above 35 mph. The Washington policy expands on this to indicate a need when the sight distance is less than 250 feet for intersections with 85th percentile speed of less than 35 mph. Washington and Wisconsin (WisDOT 2011) recommend phasing when consistent queue spillback into adjacent through lanes occurs. It should be also noted that Arizona is the only state with separate guidelines between urban and rural locations.

In addition to the common and unique guidelines noted in Tables 1 and 2, some state policies have unique features that distinguish them from the other states. The Florida state policy, revised in 2012 has very explicit guidelines that differ heavily from the mainline of other states, mainly in regards to the protected/permitted phasing (FDT 2012). Florida's policy in regard to the implementation of protected/permitted phasing is: "T-intersections where opposing U-turns are prohibited. Four-way intersections where the opposing approach has prohibited left turns or protected left turn phasing. Four-way intersections where the left turn volumes from opposing approaches do not substantially differ throughout the various time periods of a normal day, so that overlap phasing is not beneficial or required."

The Kansas policy also differs in both protected-only and protected/permitted guidelines from other state policies. In addition to the information shown in Table 1, the policy indicates that protected only phasing requires a minimum left turn volume threshold of 240 vph. For protected/permitted phasing Kansas also utilizes the cross-product, but with additional criteria making it incomparable to other cross-products shown in Table 2. According to the Kansas DOT, the cross product criteria used is: "If left turn volume for a single approach is between 50-120 vph and the cross product exceeds 100,000. Or if left turn volume for a

single approach is between 120-240 vehicles per hour cross product exceeds 50,000 (where opposing through and right turn volume is multiplied by 0.55 if two opposing lanes).”

The Oregon state policy, which is one of the most recently adapted, has also some unique criteria (ODOT 2013). Protected phasing should be used when any of the following conditions are met:

- Left turn volumes exceed 300 vph
- If the left turn cross product exceeds 150,000 for one opposing lane (300,000 for two opposing lanes)
- U-turns are permitted
- If there are high volumes of heavy vehicles performing left turns.

The additional protected/permitted phasing requirements include, intersections where the opposing approach has protected/permitted phasing or if the projected volumes for the area warrant a protected/permitted phase within the next five years.

The Pennsylvania policy also includes additional considerations for both left turn phasing guidelines (PennDOT 2004). Pennsylvania is one of the only states along with Oregon that contains cross product volumes for protected-only phasing. The cross product threshold for protected-only phasing in Pennsylvania is 67,500 for a two-lane roadway or 90,000 for a four-lane roadway. The policy also requires that a separate turn lane exist for the protected-only phasing. For protected/ permitted phasing, the policy also utilizes cross product values. The typical cross product values, included in Table 2, are for use when exclusive turn lanes are present (the common scenario). However, Pennsylvania also has cross product threshold values for shared lanes; 35,000 for a two-lane or 45,000 for a four-lane roadway. This threshold lies 10,000 lower than that of the exclusive lane values.

It should be noted that even though many of the states share similar guidelines in both the protected-only and/or protected/permitted phasing, few are identical. The data in Tables 1 and 2 shows a general overview of the common categories, combinations, and values

associated. The guidelines provided by each state are generally just that, guidelines, and ultimately the decision falls upon a case-by-case basis founded upon engineering judgment and input of impacted stakeholders.

Safety

The safety of left-turning vehicles has been the topic of past research and few studies have resulted in developing guidelines for the installation of left-turn phasing (Agent 1979; FL-ITE 1982; Roupail 1986; McCoy and Malone 1989; Clark and Daniel 1994; Agent, Stamatiadis and Dyer 1995). These studies use two distinct methods, empirical analysis and microsimulation.

These studies have indicated that the intersection features that affect safety and are prominent in determining the left-turn treatment include traffic volumes (opposing through, left-turning, and their product), geometry (number of opposing lanes and presence of exclusive left-turn lanes), and operational characteristics (speed limits, sight distance, and delays). Among these features, traffic volumes are more widely used by establishing upper limits for specific phasing treatment. The number of left-turn related crashes has also been used in determining the left-turn phasing (Bonneson and McCoy 1993; Stamatiadis, Agent and Bizakis 1997).

There have been a number of efforts to develop Crash Modification Factors (CMFs) in order to estimate the safety effect of left-turn phase options and changes. Hauer (2004) reviewed 14 studies conducted over a 24-year period and concluded that the CMF for converting from permitted to protected left-turn phase most likely depends on the number of opposing lanes and that most of the other evidence is insufficient and contradictory. Hauer estimated that the CMF for changing to protected only phasing from either permitted only or permitted/protected is approximately 0.30 for left-turn crashes. However, he noted that for total crashes the CMF is 1.0, i.e., no effect. Hauer argued that a change to protected phase from a permitted/protected left-turn phasing will substantially reduce left-turn crashes but would have no difference in the total number of crashes.

Harwood et al. (2002) conducted a before-after study using the empirical Bayes (EB) approach to study the safety impact of adding left-turn lanes with protected or permitted-protected signal phasing. A total of 36 four-leg signalized intersections were included; 31 of these sites received a permitted-protected signal phasing while 5 received a protected signal phasing. The 31 sites with permitted-protected signal phasing system experienced a 9 percent reduction in crashes (CMF of 0.91); the five sites with protected signal phasing system experienced a 10 percent reduction in crashes (CMF of 0.90). The study report did not indicate if these results were statistically significant. The authors conclude that there is “essentially no effect of the type of signal phasing on the safety effectiveness of left-turn lanes”, and “there are too few data to obtain definitive results”.

Srinivasan et al. (2008) conducted a study to determine the safety effect of converting left-turn phasing schemes from one type to another. Their study considered changes to protected only phasing from either permitted only or permitted/protected. Their findings were very similar to those noted by Hauer (2004). The study indicated that the lack of overall crash reduction from such phase changes could be attributed to potential increase of rear end crashes. However, the authors indicate that the overall effect could be positive if one considers potential differences in severity between left-turn and rear end crashes. Even though their study examined conversions from permitted to permitted/protected phasing, there were no recommendations because the sample was very small.

In a more recent effort, Srinivasan et al. (2012) attempted to develop a CMF for left-turn phasing conversions based on a large number of intersections in North Carolina and Toronto. The study considered intersections that converted from permitted to permitted/protected and used an Empirical Bayesian approach to estimate the CMFs from such change. Safety Performance Functions (SPFs) were estimated for crash severity (injury), total number of crashes and crash type (left turn, rear end and left turn with opposing through). The study showed that target crashes, i.e., left-turn related, improve with the change and when more than one approaches is treated with the change, there is an overall crash reduction. However,

the total number of crashes increases with the change and this could be attributed to the increase in rear end crashes.

Cottrell (1985) determined that safety is not affected by use of protected/permited phasing at intersections with speed limits of 45 mph or higher. This finding could have an impact on determining the left-turn phase option. In most guidelines, the use of protected only phase is recommended for approaches with speeds greater than 45 mph. The current CMFs do not provide any distinction based on approach speeds and it is important to review this guideline in order to determine whether it is still valid.

The studies reviewed here show a general trend in decreased left-turn crashes with protected left-turn phasing. However, they do not provide the guidance necessary to identify crash performance as a function of other operational parameters and thus provide guidance as to when protected phasing should be selected. In order to develop such guidance, crash analysis must be approached differently identifying crash modification functions to determine the rate of reduction as a function of operational parameters or through direct analysis of the safety performance function to identify when predicted crashes increase to an unacceptable level.

Pedestrian Safety at Signalized Intersections

Remarkably, there is little conclusive evidence from crash-based studies on the effect of pedestrian signal presence on pedestrian crashes. Zegeer et al. (1982) found that there were no statistically significant differences in the pedestrian crashes between signalized intersections with concurrent pedestrian signals and signalized intersections without pedestrian signals. Robertson and Carter (1984) similarly concluded that the presence of pedestrian signals did not have a conclusive effect on pedestrian crashes. This gap in research knowledge has not been filled in the more than 20 years since these studies.

Exclusive pedestrian phasing, also called scramble timing or Barnes Dance, seems to have a positive effect on pedestrian safety. Zegeer et al. (1982) found that pedestrian crashes were significantly reduced at intersections with exclusive pedestrian phasing compared to

intersections with concurrent pedestrian phasing or no pedestrian phase. Chen et al. (2013) examined 37 intersections where exclusive pedestrian phasing was implemented and found that pedestrian crashes decreased by 45%, a statistically significant result.

Leading pedestrian intervals are a way of operating a signal to provide the pedestrian WALK indication 3-10 seconds before providing the green signal to parallel traffic. This is intended to give the pedestrian a head start into the crossing and increase the pedestrian's visibility to drivers. Several crash-based studies have shown benefits of this timing design. King (1999) presented a crash-based analysis of the effect of leading pedestrian interval on pedestrian crashes in New York City and the results indicated decreases in crashes and injuries. These findings were incorporated in the NACTO Urban Street Design Guide as shown in Figure 3 (NACTO 2013). Fayish and Gross (2010) published a crash-based analysis of 10 intersections with leading pedestrian intervals in Pennsylvania. Their results indicated a 58.7 percent reduction in pedestrian/vehicle crashes. A review of crashes in the Lexington, KY indicated a 20 percent increase in crashes the three years following the implementation of the LPI; however, this also took place in conjunction with concerted efforts to increase pedestrian and bicycling activities within the city and no exposure estimates are available to normalize crash frequencies.

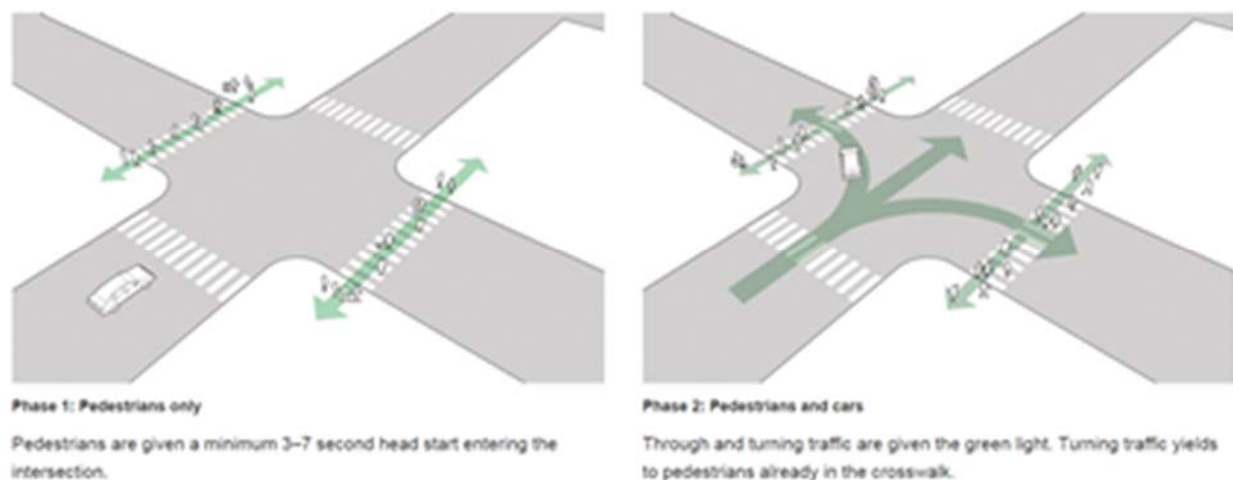


Figure 3 LPI guidance documentation (NACTO 2013)

Some non-crash based studies have also shown potential safety benefits. Van Houten et al. (2000) evaluated a signal programed to release the pedestrian signal three seconds before vehicle traffic. Results indicated that pedestrian/vehicle conflicts were reduced as well as incidences of pedestrians yielding right of way to turning traffic. Hua et al. (2009) conducted video observation and intercept surveys at four intersections in San Francisco, CA with 4-second leading pedestrian interval. Results indicated a significant reduction in percent of vehicles turning in front of pedestrians.

Longer pedestrian crossing times have been shown to be beneficial. Chen et al. (2012) investigated the effect of the length of time allocated for pedestrian crossing. They analyzed 244 intersections where pedestrian crossing time was increased and found that there was a statistically significant reduction in the rate of pedestrian crashes.

Signals that operate as permitted left turns allow drivers to choose gaps in oncoming traffic. Conversion to a protected phase controls this movement and reduces potential conflicts between vehicles and pedestrians. New York City installed left-turn phasing at 95 signals, changing the signal phasing from permitted to protected/permitted or protected-only. They found a 48 percent reduction in pedestrian crashes based on an empirical Bayes before-after study (Chen et al. 2013). The effect of permitted-protected phasing is not as conclusive. Bonneson et al. (2012) conducted a literature review to examine the issue of left-turning traffic and pedestrian safety. While it was clear that the literature indicated the potential for conflicts between pedestrians and left-turning vehicles on permitted phasing, the authors concluded that research had not established a reliable (crash-based) relationship between pedestrian safety and protected-permitted signal phasing. Other non-crash based studies have found pedestrian safety benefits from protected left-turn implementation. Pratt et al. (2012) examined the effects of implementing a leading protected left-turn signal phasing. They studied the effects on pedestrian-vehicle conflicts and determined that the leading protected left-turn phase led to a decrease in conflicts.

A primary issue in pedestrian timing has been the accommodation of pedestrian timing within coordinated timing plans, especially in the presence of split phased side streets which double pedestrian crossing requirements, extending cycle length and vehicular and pedestrian delay. There are two alternative treatments on pedestrian timings: timing based on pedestrian minimums where the required pedestrian crossing times are accommodated in the signal phase splits, and timing based on vehicle minimums where the phase splits are determined only based on vehicle demand. Tian et al. (2000) analyzed the effects of the two pedestrian treatment alternatives through a case study. It was found that although timing based on vehicle minimums can generally result in a shorter system cycle length, timing based on pedestrian minimums can normally achieve the same operational efficiency. The most significant advantage of timing based on pedestrian minimums is that the signal system will always remain in coordination. The only drawback of timing based on pedestrian minimums is the likely use of longer cycle length. It is recommended that timing based on pedestrian minimum technique should be applied when longer cycle length is required for the system, and medium to high level pedestrian crossing activities exist (Tian et al. 2000). While accommodation of pedestrians leads to longer cycle lengths, research has also shown increased delays and cycle lengths resulting from exclusive pedestrian phasing tends to cause a decrease in pedestrian compliance with the signal, resulting in crossings against the “Don’t Walk” (Kattan et al. 2009; Bechtel 2004).

Arizona (ADOT 2011) and Florida (FDOT 2012) have some guidance for split phasing. Both states use the geometry of the intersection (offset approaches), the presence of heavy left-turn and through volumes from an approach and the lack of left-turn lanes as factors in considering the use of split phasing. The Oregon DOT Traffic Signal Policy Guidelines (2013) have identified a set of potential conditions where a split phasing may be considered. These include the need for dual left-turn lanes that cannot be implemented due to site constraints, even split between left and through movements in each approach but with unbalanced total approach volumes, geometry of the intersection not allowing for clear lines of sights between the two opposing approaches, past crash experience with high numbers of sideswipes or head-on collisions, and single lane approaches.

Crash Modeling

The objective of a crash analysis is to determine if certain phasing options would lead to fewer crashes of a particular type under certain conditions. There are two broad categories of methods that can be used to make this determination: before-after studies and cross sectional studies. Before-after studies include “all techniques by which one may study the safety effect of some change that has been implemented on a group of entities (road sections, intersections, drivers, vehicles, neighborhoods, etc.)” (Hauer 2010). On the other hand, cross-sectional studies include those where “one is comparing the safety of one group of entities having some common feature (say, STOP controlled intersections) to the safety of a different group of entities not having that feature (say, YIELD controlled intersections), in order to assess the safety effect of that feature (STOP versus YIELD signs)” (Hauer 2010). In a typical before-after study, the same roadway unit is considered and therefore it is reasonable to assume that the same users in the before and after period are present and thus these factors are less likely to confound a before-after study (Elvik 2011). However, there are issues in both types of studies that need to be addressed, and these are discussed in a recent NCHRP document entitled *Recommended Protocols for Developing Crash Modification Factors* (Carter et al. 2012).

Before–after studies

With before-after studies, if treatments are installed at high crash locations, then simply comparing the crashes after the treatment to the crashes before the treatment may provide a biased estimate of the safety effectiveness of the treatment due to a phenomenon called regression to the mean (RTM) (Hauer 2010). The EB method has been proposed as one way of addressing this bias. With the EB method, the intent is to estimate the expected number of crashes in the after period (had the treatment not been implemented), and compare that with the actual crashes in the after period.

Although a properly done EB before-after analysis is considered an effective method to determine the safety effects of treatments, there are limitations to this method. In order to conduct a before-after evaluation, it is important to have accurate records on when changes

were made. Not all agencies have such records, especially, for changes involving phasing. In addition, often agencies do not apply a particular treatment in isolation, e.g., left-turn phasing may be modified at the same time that back plates are installed or signal heads are changed from incandescent to LEDs. If this happens, the ‘treatment’ is no longer just the change in left-turn phasing, but change in left-turn phasing along with these other changes. If other changes that may occur at the same time as the treatment of interest, it becomes very difficult or impossible to determine the specific safety effect of just the left-turn phasing using before-after studies. Under such circumstances, cross sectional methods could be used to determine the safety effect of specific treatments.

Another issue with respect to before-after studies is the difficulty in estimating crash modification functions. Most before-after studies develop CMFs that are just point estimates of the safety effects. There is growing consensus that CMFs do not provide sufficient information about how the safety effects may depend on site characteristics and crash modification functions are needed. In order to develop crash modification functions from before-after EB studies, an additional step is required, where the regression models are estimated with the individual CMFs from each site as a dependent variable and the site characteristics as independent variables. However, before-after studies due to their limited sample size usually do not provide reliable crash modification functions unless data from multiple studies are combined.

Cross-sectional Studies

CMFs from cross-sectional studies are developed by comparing the safety of a group of sites with a feature with the safety of a group of sites without that feature. The CMF can be derived by taking the ratio of the average crash frequency of sites with the feature to the average crash frequency of sites without the feature. For this method to work, the two groups of sites should be similar in their characteristics except for the feature. In practice, this is difficult to accomplish and multiple variable regression models are used. These cross-sectional models are also called safety performance functions (SPFs) or crash prediction models (CPMs). SPFs and CPMs are mathematical equations that relate crash frequency with

site characteristics. The coefficients of the variables from these equations are used to estimate the CMF associated with a treatment.

A primary concern with cross sectional models is whether the coefficients represent causal relationships or non-casual statistical relationships (Carter et al. 2012). The difference in safety estimated by varying the level of a factor/variable (i.e., simulating a treatment) may be due to variables other than the one of interest, which may not be controlled for in the model – this is sometimes called *confounding*. In addition, correlations among variables in a model are very likely and that can lead to incorrect effects. To address this, analyses typically consider data from untreated comparison sites (from similar road segments near the treated sites).

Traffic Simulation

A major limitation of the SPF and CMF approach is that it is based on the analysis of existing crash patterns. Crashes are known to be random events with a limited sample size. Crashes are also influenced by site specific factors, such as sight distance approach grades, etc. as well as temporal effects, such as weather, and varying traffic demand (Harkey et al. 2007). All of these influencing factors can introduce variability into crash patterns at individual sites that cannot be accounted for within the predictive models. In order to address some of the shortcomings of cross-sectional studies, safety surrogate measures have been developed to provide assessments of safety performance.

One such measure is traffic conflicts which are defined as the situation where two or more vehicles approach each other in space and time and the potential for a collision exists if no vehicle alters their movements (Hyden 1997). This approach has been extensively utilized in traffic safety to study scenarios and conditions where crashes are few. Data for studying traffic conflicts until recently have been collected through visual observations, which are time consuming and labor intensive. The recent advances in traffic simulation have increased the fidelity of simulated conditions to the real world operations and provide the capability of automatically collecting simulated traffic data and determining potential traffic conflicts.

Recently, the Surrogate Safety Assessment Model (SSAM) has been developed which is capable of extracting the information of simulated traffic conflicts from trajectory outputs from simulation tools (Gettman and Heady 2005). This development has enhanced the capability of studying traffic conflicts. Members of the UK team have extensive experience in utilizing simulation and SSAM to develop design guidance for intersection selection (Stamatiadis et al. 2012), road diet guidance (Stamatiadis and Kirk 2014) as well as development of new surrogate safety metrics (Wang and Stamatiadis 2013, 2014).

Traffic conflicts have been studied since the late 1960s, most notably documented in NCHRP Report 219, to provide a reliable and inexpensive tool to be used to “diagnose safety and operational deficiencies...within a short period of time” (Glauz and Migletz 1985). Conflict studies traditionally utilize personnel trained to identify and record conflicts observed at an intersection. SSAM was developed to automate conflict analysis with the application of simulated operational programs. SSAM models roadway facilities through a micro-simulation program, such as VISSIM, AIMSUN, Paramics and TEXAS, which use specific lane configuration and operational control strategies in conjunction with measured and/or anticipated traffic volumes. These models produce a trajectory file (TRJ), which tracks the position of each simulated vehicle with respect to simulation time. SSAM then processes the vehicle trajectories, to identify ‘conflicting’ trajectories. A conflict is a scenario where two road users may crash if one does not take alter course as shown in Figure 4.

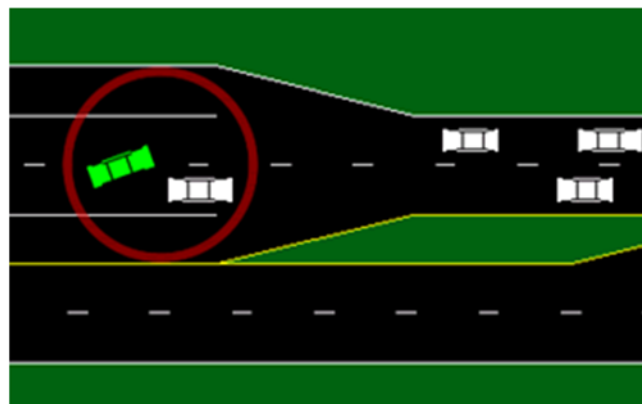


Figure 4 Conflict definition (Gettman and Shelby 2008)

The SSAM team conducted a field validation of procedures and results studying 83 four-leg signalized intersections. SSAM models were developed for the PM peak hour of operation at the site. Estimated conflicts determined from SSAM were then compared to actual crash rates at the intersections. The significant correlations between predicted conflicts and real crashes were evaluated by several statistical tests including safety ranking by total incidents and incident types, regression model tests, and identification of incident prone locations. Total conflicts and conflict types were separately used to determine intersection rankings. Two rankings based on total conflicts and conflict types were respectively compared with the rankings based on the real crashes and crash types. Regression models were developed to establish a relationship between average hourly conflict frequencies derived by SSAM and the estimated average hourly crash frequencies. Standard GLM procedures were also incorporated to establish conflict prediction models and crash prediction models. Conflicts estimated by SSAM were shown to be significantly correlated with the historical crash data. The results gave a correlation rate ($R=0.41$) between total conflicts and total crashes. The study also noted that based on the comparison between conflicts and crashes, conflict-to-collision ratios may vary by different types.

Simulation-based Safety Prediction

The current problem with using historical, empirical data is the rarity of these events and the required time needed to assess the performance of each safety treatment (Tarko 2009). Therefore, there is a need to develop alternative methodologies that can be used to predict the intersection safety performance. Current research efforts have focused on developing surrogate crash metrics that can estimate safety levels at intersections to address the small sample size of crash data (Tarko 2009, Gettman et al. 2008). For a surrogate safety measure to be useful, it must satisfy two conditions. It must be an observable non-crash event that can be physically related in a predictable and reliable way to crashes. It must also be possible to practically convert this event into a crash frequency and/or severity (Tarko 2009).

Examples of surrogate measures identified by Gettman et al. (2008) include deceleration rate distributions, required braking power distributions, gap acceptance distributions and speed variance. The most prevalent surrogate measure of safety is the traffic conflict technique which looks at all potentially dangerous traffic interactions instead of just focusing on crash events (Gettman et al. 2008, Hyden 1987, Tarko 2009). Gettman et al. (2008) defines a conflict as an observable event where two or more road users approach each other in time and space increasing their risk for collision if their movements do not change. Conflict patterns have already seen use in empirical analysis of crash data (Wang & Abdel-Aty 2008). Traffic conflicts occur much more frequently than crashes (Saleem 2012). Further, it has been shown that the proportion of conflicts that occur at an intersection is roughly the same to the proportion of collisions, meaning that the evaluation of conflicts is an appropriate substitute to examining only crashes (Sachi et al. 2013). Using these two facts, quantifiable modeling is possible with the help of microsimulation software.

Microsimulation is a popular modeling tool used in traffic engineering applications due to the ease and speed at which different safety treatments such as left turn phasing alterations may be evaluated. Not all research is in favor of the use of traffic microsimulation to evaluate safety (Tarko and Songchitruksa, 2005; Saunier and Sayed, 2007). Shahdah et al. (2014) summarizes three common criticisms introduced by these individuals. First, models are based on the fundamental rules of crash avoidance and do not explain high-risk driving behavior leading to crashes. Second, accuracy is dependent on input parameters and how these parameters reflect “real world” conditions. Lastly, safety performance is only relevant within the context of verifiable crash experience. In other words, the idea of what is deemed safe may not be solely related to conflict or crash occurrence. Sbayti and Roden (2010) point out the fact that microsimulation models require details about travel behavior at a “granular” level that is not typically available to researchers. This may reduce the accuracy and effectiveness of microsimulated, predictive models.

There are several examples of studies, however, where the predictive capabilities of microsimulation are accurate in comparison with the traditional empirical methods. Caliendo

and Guida (2012) compared recorded crashes in the field to critical conflicts identified by microsimulation software. Real world signalized intersection geometries and roadway characteristics, such as traffic volumes and phasing patterns, were replicated using the AIMSUN microsimulation software. SSAM was then used to calculate and classify conflicts. Results of this study showed a significant correlation between recorded crash data and simulated conflicts, an R-squared value of 0.967. Additionally, the conflict based model produced from this microsimulation was slightly better than the traditional empirical volume based model, an R-squared value of 0.961. Based on the verified predictability of microsimulation, it is recommended that future field measures should be made to further verify that accuracy of simulated conflicts.

Shahdah et al. (2014) conducted research to develop Crash Modification Factors (CMFs) using the VISSIM microsimulation software in conjunction with SSAM. These were then compared to CMFs developed by the traditional Empirical Bayes (EB) method. Shahdah et al. found that the simulated CMFs were consistent with the EB before-and-after study estimations. Left turn opposing conflicts from simulation were statistically similar to values obtained by the conventional method showing that CMFs are an accurate metric of estimating safety changes.

In one study, simulation software was used to create crash predictions of an intersection which were then compared to those obtained from relevant empirical models developed from traffic volumes (Saleem 2012). Additionally, a second study looked at the effects of changing the phasing from permissive to permissive/protected at signalized intersections. The empirical results were then compared to the predictions from microsimulation (Srinivasan et al. 2012, Saleem 2012). Similar to Shahdah et al (2014), VISSIM and SSAM software packages were used to complete these microsimulations. Results from Saleem (2012) indicate that the peak hour conflict models had the ability to similarly predict crashes to the volume-based models. Residuals gave statistical confidence in these results. Furthermore, the crash reductions predicted from simulated conflicts were similar to the results of Srinivasan et al (2012).

Summary

The literature review conducted here points to the wide variety of factors considered for the selection of the left-turn phase among the various agencies. There seems to be an overall agreement on the various factors to be used in determining the appropriate left-turn phase but there is little agreement on the specific values to be used.

Several agencies consider left-turn volume warrants based on the constant cross product of left-turn and opposing volumes. However, there is little agreement on the numbers to be used showing a variety between 50,000 to 225,000 as the cross product to be considered when evaluating the shift from permitted to protected phasing. Many studies also indicate that there is a need to consider a wide variety of factors in addition to the cross product. Several studies have indicated the need of considering intersection geometry. One of the issues that has been identified in the early studies, and has been addressed to a certain extent more recently, is that most of the warrants were developed based minimizing intersection delay with little consideration to intersection safety and thus minimizing potential conflicts.

Most warrants that consider intersection safety have been developed utilizing historical data of converted intersections. The major analysis in several of these studies focused on the development of a benefit and cost analysis based on before-and-after study. However, such an approach may be difficult to be implemented, since it requires knowledge of both crash history and intersection delays for both before and after periods in order to estimate the benefits and costs accurately. It should be noted here that most of the warrants and guidelines developed consider only operational efficiency or safety impacts and very few consider the combined impacts of both.

In general, almost all studies that develop left-turn volume warrants consistently applied the cross product as the main warrant. However, a limitation of this approach is the inability to allow for distinctions among different intersection geometric features and has not been evaluated for three or more opposing though lanes. Furthermore, additional research is needed to understand how other factors affect and interact with each other to provide a more

appropriate and balanced operational and safety performance. As it was noted above, there is very little work that has successfully combined safety and operational aspects and this should be addressed in the future. Table 3 provides a summary of the known criteria and the current knowledge in the decision-making process for phasing selection.

Table 3 Summary of knowledge for left-turn phasing criteria

Phase Option	Criterion	Type	Summary
Protected vs. Permitted	Cross Product	O	Most state guidelines use thresholds to determine selected phase. Limited research on the topic has resulted in developing these thresholds in the 1980's (Agent 1979; Agent 1985) and additional research has updated and expanded these values (Stamatiadis et al. 1997; Bonneson et al. 2009). An issue with this criterion is the lack of explicit consideration of intersection geometry and other aspects.
	Crashes	S	Most state guidelines use thresholds to determine the use of protected phase for a specified time period that are based on the Agent (1985) study developed based on the Critical Rate method. Research has evaluated the effect of various factors on crash occurrence resulting in revising the number of crashes in selecting phase plans (Bonneson and McCoy 1993; Stamatiadis et al. 1997). Several studies have been conducted to determine the safety of each plan (Srinivasan et al. 2012; Schultz et al. 2014) and efforts have been conducted to develop CMFs for each phase (Harwood et al. 2002; Harkey et al. 2007).
	Opposing lanes	G	Several states consider the number of opposing lanes as a criterion for phase selection. Most policies consider three opposing lanes as the threshold while Delaware, North Dakota and Texas consider four as their threshold for using protected-only. There is limited research on this topic (Bonneson et al. 2009) and the effects of this criterion are not well documented.
	Left-turn delay	O	A few state guidelines consider left-turn delay either on a per vehicle basis or total hourly delay. These values have also been based on the Agent study (1985) and there has been limited research on the determination of the accuracy of these estimates (Agent et al. 1995).
	Left-turn volume	O	A few states use a left-turn volume threshold to determine phase plan. The values used vary greatly (50 for Louisiana to 240 for Kansas) and there has been no research to document the effect of this criterion on intersection performance.

Phase Option	Criterion	Type	Summary
Leading vs. Lagging	Coordinated Phasing	O	Ozmen et al. (2009) showed operational benefits of corridor wide lead lag phasing by TOD operations for with no adverse safety impacts. Other resources including the Traffic signal timing manual, and the FHWA informational guide for Signalized intersections also promote lead/lag phasing a method to provide increased green band (Koonce, 2008 and Chandler, 2013)
	Crashes	S	No research was identified which provided quantifiable safety performance of benefits of lead lag phasing. However, Sarhan et al. (2014) identified decreased safety performance compared to split phase operations at 17 Abu Dhabi conversions.
	Turn lane length	G	Chandler (2013) identifies the limited left-turn storage as a criterion for lead lag phasing. In addition, Kikuchi et al. (2010) have evaluated variations in left-turn storage requirements based on phase selection and sequencing to quantify this impact.
Split Phase	Approach volumes	O	There has been very little research on this criterion and only Oregon (ORDOT 2013) has a policy for determining when to consider this option. The policy is general guidance without any specific volumes or values for other factors to be considered.

Legend: O: Operational; S: Safety; G: Geometric

APPROACH AND METHODOLOGY

The approach undertaken is a combination of micro-simulation with surrogate safety measures in order to develop safety prediction models. Conflicts are considered a viable surrogate to crashes due to their frequency and relatability to crash events and current micro-simulation models can be used to determine their frequency. The literature also indicated that the number of opposing lanes and length of green times and cycles are the most common variables used in prediction models but the use of cross product or individual volumes is still debated.

The micro-simulation used in this study is VISSIM, since it allows to coordinate the output vehicle trajectory file for each simulation with the FHWA Surrogate Safety Assessment Model package. In addition, the downstream left turning volumes and downstream opposing movements were used from the output to address the study objective of for assessing intersection safety surrounding the left turn movement during permissive phasing. Conflicts are identified with SSAM software by type utilizing the vehicle trajectories. The default SSAM values were used here, i.e., maximum time-to-collision of 1.5 seconds and maximum post-encroachment time of 5.0 seconds. SSAM identifies conflicts by type according to the angle that the trajectories of two vehicles encounter each other. In this case, vehicles with conflicts at angles less than 30 degrees are considered Rear End conflicts, with angles greater than 85 degrees are considered Crossing conflicts, and all others are Lane Change conflicts. The basic layout for the simulation was a four-leg signalized intersection with a single left turn exclusive lane to eliminate any safety related issues including intersection skew angles, poor sight distances, and multiple left turn lanes. Permissive left turn phasing is used for the left turning vehicles, since the goal of this research is to quantify conflicts attributed to the left turn movement. The variables and their ranges considered are summarized in Table 4 reflecting typical traffic conditions found at four-leg signalized intersections (Hedges 2014).

Table 4. Simulation input parameters

Values	Variables				
	Opposing Volumes	Opposing Lane	Cycle Length	Percentage Green Time	Left Turn Capacity Percentage
Range	500-3,000	1 to 3	90-210	30-70	20-100
Increments	500 vehicles	1 lane	30 seconds	10 percent	20 percent

Finally, the Statistical Package for the Social Sciences (SPSS) developed by IBM is the software used to identify explanatory variables and develop statistical, predictive models (IBM 2009).

FINDINGS; CONCLUSIONS; RECOMMENDATIONS

The first step in the analysis was to identify those variables most promising to predict left turn Crossing conflicts (Table 5, Model 1). This was achieved through a stepwise linear regression followed by variable combinations to reflect the trends observed in the stepwise analysis (Models 2 and 3). The variables of concern include the following:

- Left Turn Volume (LTLDnwn)
- Opposing Volume (OppVolOut)
- Opposing Number of Lanes (OpposingLanes)
- Cycle Length (Cycle)
- Effective Green Time Percentage (%Green)
- Cross Product (XProdOut)

Table 5. Modelling results

Model	Variable	Coefficient	Significance	R ²
1	Constant	-1.028	.000	0.372
	%Green	0.856	.000	
	LTDown	0.000	.000	
	OppVolOut	0.000	.000	
	Opposing Lanes	0.443	.000	
2	Constant	-0.181	.000	0.400
	(LTDown* OppVolOut * Opposing Lanes)/%Green	1.652E-6	.000	
3	Constant	0.144	.001	0.514
	(LTDown ² * OppVolOut * Opposing Lanes ³)/%Green ^{1/3}	4.457E-9	.000	

It should be noted here that the left turn and opposing volumes were counted downstream of the approach in order to account for processed flow and not just the design demand values in the models developed. In many scenarios, the entire input volume did not travel through the intersection due to capacity issues and therefore the downstream volumes are more accurate exposure measures.

In the initial stepwise approach, Model 1 in Table 5, all four variables were identified as significant predictors for the number of Crossing conflicts. Three of the four variables show expected relationships. Traffic volumes are expected to have a positive correlation with conflicts, since they are an exposure metric and increase volumes could result in an increased number of conflicts. Similarly, more opposing lanes could result in more Crossing conflicts, since the greater number of lanes that need to be traversed increases the risk for a crash with opposing traffic. The final variable, percent green time, shows an unexpected trend indicating that as the green time increases, the number of Crossing conflicts would also increase. This is not an expected result since the traditional belief is that as constant opposing volumes are given more green time, gaps allowing safe, permissive left turns would also increase and thus, reducing the number of Crossing conflicts. Based on the low adjusted R^2 value, the additive regression model does not have an adequate explanatory power. Therefore, a combination of variables was sought that could provide a higher predictive model power. Model 2 represents the following variable created based on the positive/negative relationships (Eq. 1) provided from Model 1 and reconsidering the effect of green time:

$$X_{Crossing} = (LTDown \times OppVolOut \times OpposingLanes)/(\%Green) \quad (1)$$

At this point, it was deemed appropriate to keep the left turn and opposing through volumes as independent variables instead of the cross product, since it was believed that there is a potential for specific contribution of each volume in the crossing conflicts (see next section for additional explanation). As also noted above, there is no agreement on this issue and thus the use of each variable was considered more appropriate. The explanatory power of the Model 2 is higher than the previous model, but may be improved by adjusting the individual powers of the root variables to reflect possible differences in their contribution to the conflict potential.

Through an iterative process, the powers of the individual root variables (Eq. 2) are adjusted within $X_{Crossing}$. The result of several iterations yield the following variable:

$$X_{Crossing} = (LTDown^2 \times OppVolOut \times OpposingLanes^3)/(\%Green^{1/3}) \quad (2)$$

Model 3 supports the notion that each volume may have a different impact on the potential for a conflict since the left turning movements have more of an influence (higher power) than the opposing through movements when predicting Crossing conflicts.

The study objective was to develop a predictive model to assist in left turn phase selection. To address this goal, Model 3 can be used to develop the point where a decision can be made as to whether protected or permissive only phasing can be implemented based on the anticipated safety levels, i.e., potential Crossing conflicts. Based on Model 3, a series of nomographs may be developed to assist in left turn phase selection representing the thresholds between permissive and protected phasing. Figures 5 and 6 are examples of such graphs and have been developed for general conditions for main street, i.e., effective green 60 percent, and for one and three opposing lanes, respectively.

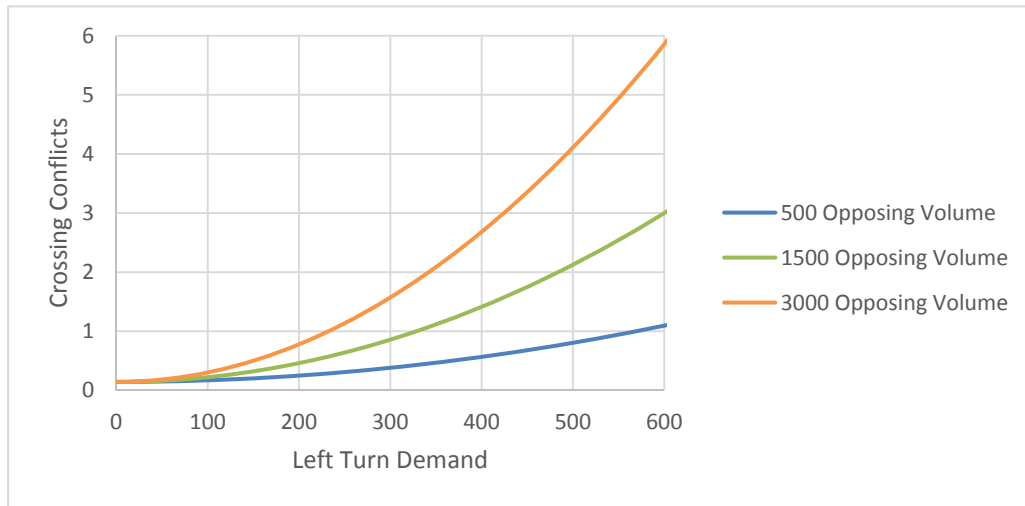


Figure 5. Left turn phasing guidance, one opposing lane.

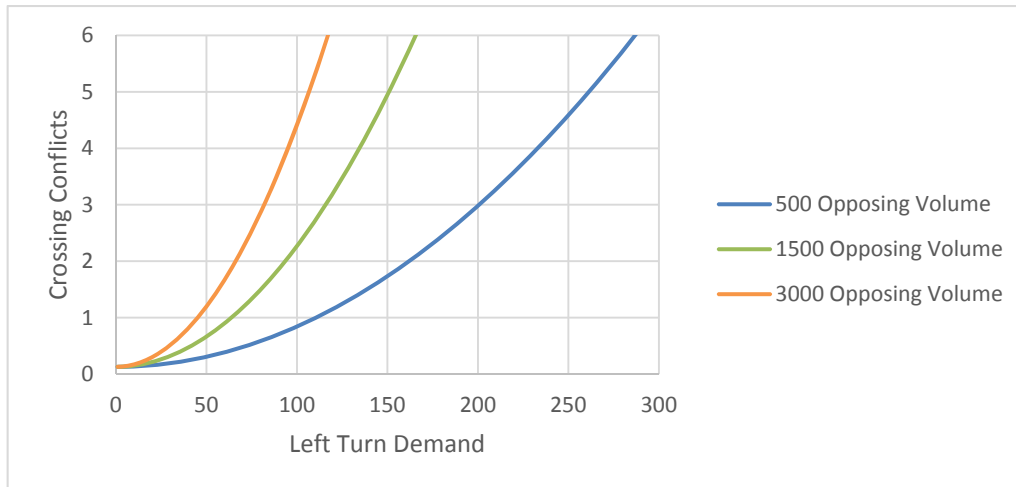


Figure 6. Left turn phasing guidance, three opposing lanes

The lines in Figures 5 and 6 represent the point of transition from permissive to protected phase, i.e., to the left of the line a permissive phase is appropriate while to the right of the line a protected phase will be more appropriate. In this case, with given the traffic volumes, percent green and number of opposing lanes, a designer can determine which phase is more appropriate for the intersection. Figures 1 and 2 illustrate the differences between one and three opposing lanes. Both plots indicate that a higher number of left turns are possible at intersections with one opposing lane than in three opposing lanes when the same number of conflicts is considered. Graphs similar to these are easily derived for any effective green percentage or lane configuration using Model 3 (Eq. 3)

$$\text{Left Turn Crossing Conflicts} = 4.45E^{-9} \times X_{\text{Crossing}} + 0.144 \quad (3)$$

Where X_{Crossing} is as defined in Equation 3.

An issue that merits attention and discussion here is the use of the traffic volumes as independent variables instead of their cross product. The reason for this is the need for differentiation between each of these volumes and their potential effects on completing the left turn movement and thus, implicitly, on safety. For example, an intersection with 500 left turning vehicles and 1,000 opposing through vehicles has the same cross product as an intersection with 1,000 left turning vehicles and 500 opposing through vehicles. It is therefore reasonable to assume that each combination would have a different safety performance and this was captured in the Crossing conflict model developed here through the inclusion of the independent variables and their relative impact, i.e., left turn volume has a power of 2 in the model. The results indicate that left turning movements have a higher correlated relationship with Crossing conflicts than the opposing through movements. As an example, the data used here produced 15 scenarios with cross products of 350,000 to 400,000 vehicles resulting in 33 Crossing conflicts. Twenty of these conflicts were attributed to higher left turn movements in the cross product and only 13 were due to higher opposing volumes in the cross product. This same relationship is true for other cross product ranges. Therefore, the model developed captures this greater influence of left turn volumes with the higher power in the variable.

Model 3 can be used to develop the nomographs and predict left turn conflicts, but also one needs to recognize its limitations. First, the research only considered a single intersection geometry design (i.e. four-leg signalized with a single left turn lane). It is therefore recommended to use it only on similar layouts and application of the model to other designs may reduce their reliability. Second, left turn capacity was derived from a microsimulation involving permissive left turns only. Application of such models to existing intersections with phasing schemes that already include a form of protection may be a questionable

practice. Third, driver behavior is always a concern when using microsimulation analysis because the software may not reflect reactive behavior in real world situations. Finally, conflict prediction models prove to be correlated with historical crash data, but better surrogate metrics may exist and need to be investigated.

This study was set out to develop a predictive safety assessment model for left turn movements at signalized intersections. The literature review indicated that conflicts are an acceptable and reliable surrogate safety measure due to a number of cases studies where a correlated relationship with real crash data was documented. Moreover, the ease of analysis with micro-simulation software packages makes this option an appealing prospect, given the long time that one may have to wait for historical crash data to determine the safety effects of the option implemented.

Future efforts will develop relationships between conflicts and crash propensity developing nomographs capable of guiding signal phasing decisions. Figure 7 demonstrates a line of equality representing a single conflict for the left turn and opposing volume combinations. Guidance such as this can be used to establish thresholds for safety performance to provide guidance on left turn phasing selection.

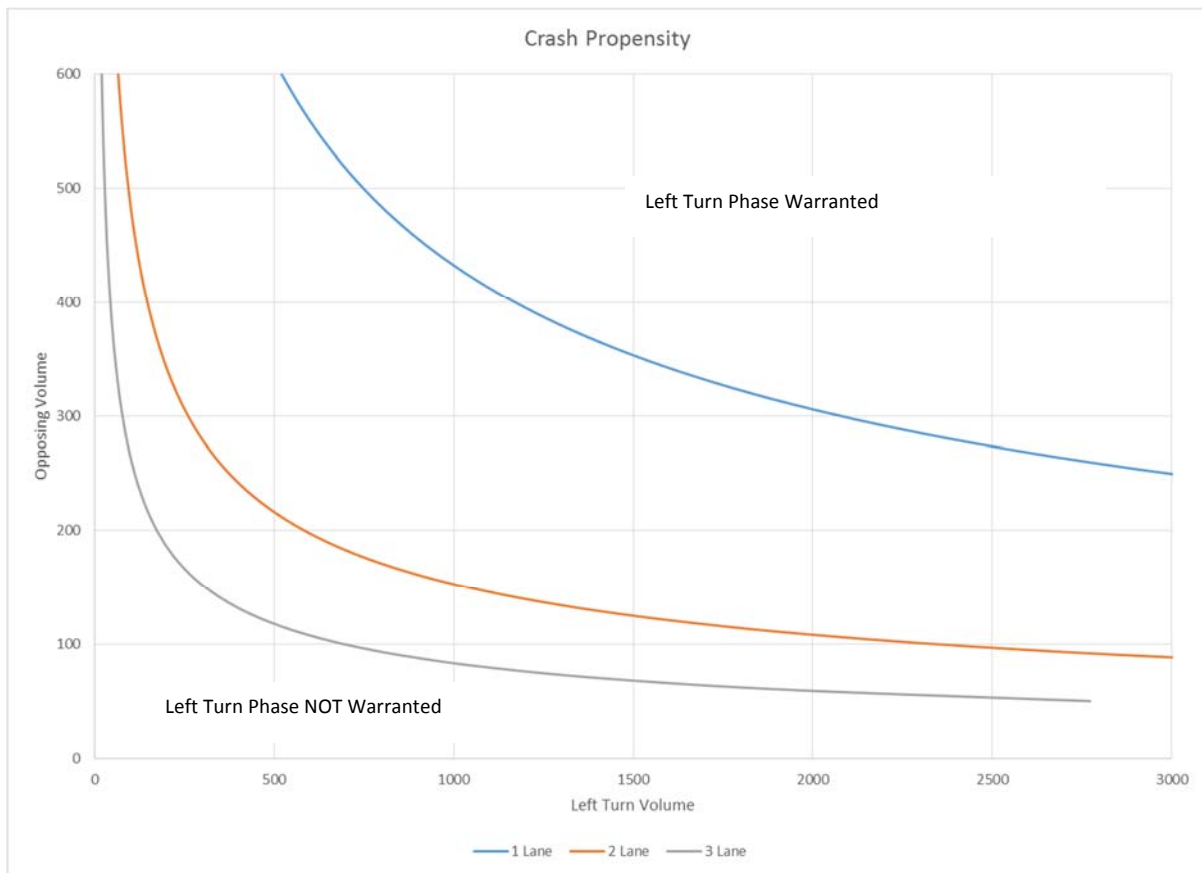


Figure 7. Left turn phasing guidance, one conflict

MUTCD recommends the use of permissive, protected or permissive/protected phasing to control left turns. Many state DOTs have developed warrants, or guidelines, for selecting the left turn phasing type for an intersection but most of them are based on operational factors such as the cross product between left turn movements and opposing through volumes. A few DOTs have safety related warrants such as the left turn related crash history. The problem associated with the current warrants is that they are based on real world historical crash data. It is a reactive method that takes a considerable amount of time to complete such an analysis. Left turn crashes are typically rare events with small sample sizes. Thus, developing safety related warrants for left turn phasing could take a long time.

The model developed here with its accompanying nomographs provides an improvement over the existing methods and warrants and allows for a systematic and quick evaluation of

the left turn phase to be selected. The model utilizes the most common variables that are already known during the design phase and can be used to determine whether a permissive or protected only phase will suit the intersection when considering safety performance. It should be pointed out that model in its current form is not capable to recommend the cases where a permissive/protected phase may be appropriate.

The findings of this study also point to some future research to improve understanding of the left turn phasing implications. The first recommendation is to develop better design criteria when conducting microsimulation analysis. This research uses theoretical values that are deemed “typical” for real world conditions. Based on the findings, the observed microsimulation traffic conditions may be sometimes oversaturated, allowing for too few left turning movements and thus, less interactions between left turns and opposing through movements. Another recommendation is to further investigate the effectiveness of surrogate safety measures and more specifically, those used by SSAM. TTC and PET are utilized by SSAM, but as Wang (34) determined, these measures may not reflect actual driver behavior due to the difficulty of mimicking unpredictable human reaction with computer software. Furthermore, Kirk (2013) suggests in his research to adjust the default parameters SSAM uses for TTC and PET. Kirk uses 2.0 and 5.0 seconds, respectively, for these values. The default parameters for TTC and PET in SSAM were not adjusted for the research proposed in this report. Finally, the use of historical crash data could be beneficial in validating the model developed here and increase its predictive power.

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APPENDIX A

Refereed Paper

Forthcoming in the Advances of Transportation Studies (March 2016)

Left Turn Guidance Based on Crossing Conflict Analysis

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Abstract

Left turn movements at an intersection are considered the most critical due to their implications on safety and operational performance. This is more critical for signalized intersections due to the need for balancing operational efficiency with safety. Signal phasing schemes are implemented to control such movements and improve the safety of the intersection. However, providing the left turn movement with its own phase often reduces the intersection operational efficiency. Warrants have been developed to decide between phasing schemes, but those involving safety require years of study to evaluate. There is a need for a preliminary design tool to assist in left turn phasing decisions. The research proposes a quantitative safety assessment tool that predicts left turn related conflicts as the deciding measure between different phasing schemes. VISSIM micro-simulation software in conjunction with the Surrogate Safety Assessment Model were used to develop the model.

Keywords – Left turns, Safety, Micro-simulation

1. Advances in Transportation Studies, an International Journal

The left turning movement at signalized intersections is probably the most critical given that it often requires driver judgment to complete it. The need to balance both operational efficiency and safety complicates the choice of phasing type. Phasing strategies are employed to offset any negative safety impacts of such movements. An intersection serves as a point of convergence for traffic flows and proper designs aim to optimize the capacity of the movements through a combination of design and operational techniques.

The left turn movement at signalized intersections is critical because of its impact on both system capacity and safety. Given the interaction between left turn vehicles and opposing traffic, precautionary measures are used to accommodate these movements. The primary strategy to control left turns at intersections is traffic signal phasing. According to the Manual on Uniform Traffic Control Devices (MUTCD) there are four potential design alternatives for the left turn movement at signalized intersections: *permissive only*, *protected only*, *protected/permissive*, and *variable left turn mode* [1]. In general, protected only phasing, which gives the right of way to left turning vehicles, is considered a safer option than permissive only phasing due to separation of conflicting movements. Protected/Permissive could be considered as a compromised balance between intersection safety and operational efficiency.

The selection of appropriate left turn phasing is typically based on a combination of various factors including intersection capacity, geometric features, and historical crash data. Many state departments of transportation (DOTs) use operational characteristics, such as the cross product between the left turn volume and the opposing through volume, as the primary metric for selecting phasing schemes. However, a review of 24 state policies regarding their protected only left turn policy indicated that 17 state DOTs included some consideration of crash history [2]. Although some warrants that consider sight distance and geometric features are related to intersection safety, there is a need for a metric to estimate left turn crash potential without having to wait to collect historical crash data.

The Intersection Design Aid Tool (IDAT) is a tool that could assist in selecting appropriate intersection configurations considering operational and safety issues [3]. Conflicts were used as a surrogate measure to crash events and micro-simulation software helped to develop models for left turn, right turn angle, rear end, and sideswipe (lane change) conflicts [3, 4]. The scope of this research, however, did not specifically examine left turn movements at intersections but rather global intersection performance. In related research, empirical before-and-after studies have been conducted to assess left turn phasing treatments (i.e. converting a protected only left turn intersection to protected/permmissive), but require years of time to complete because of the rarity of crash events [5]. Such studies do not provide predictive information, but only assess left turn treatments based on historical crash data. Furthermore, there is a need for the identification of significant contributing factors that may influence the safety of left turns at intersections. Current safety research does not clearly identify the factors a designer should give priority when selecting appropriate left turn phasing schemes.

The purpose of this research is to develop a quantitative safety assessment tool that would predict left turn related conflicts and aid traffic engineers in selecting the appropriate left turn phase at signalized intersections. The goal of the research is to provide a predictive measure for planners and designers to enhance safety considerations when selecting left turn phasing options. This has the potential to eliminate the current timely and reactive method used for left turn phasing decisions when considering historical crash data.

2. Literature review

Current safety criteria used by state DOTs includes insufficient sight distance and high left turn crash rates due to existing phasing schemes (i.e. permmissive only or protected/permmissive) [2]. Of the 24 state policies that were reviewed, 23 cited insufficient sight distance as a safety criteria and 17 included crash history as a determining factor. The values noted for the crash history warrants varied from 4 crashes over a one-year period to 7 crashes over a three-year period. Historically, left turn studies have focused on utilizing safety indicators to develop these safety warrants [6, 7, 8, 9]. These studies use either a comparison of control and test sites or historical crash records with changes in left turn treatment.

The results of these empirical studies indicate that an intersection with a protected left turn phase is in general safer than one without [10, 11]. This is true in highly urbanized environments [12] and in locations with high speed uncongested flow [13]. However, some research found that around a certain threshold, 45 mph, permittted/protected phasing does not affect safety [14]. An overall agreement exists that there is a relationship between levels of safety and different left turn phasing treatments. However, the exact nature of this relationship is not agreed upon. Protected only phasing is safer than permmissive [1, 11], but there is not a consensus upon the effects of split

phasing. Split protected/permissive phasing can be more dangerous than permissive only [15], or the comparative level of safety can depend on leading versus lagging design [16].

The rarity of crashes is a concern for using historical, left turn crash data [5]. Therefore, there is a need to develop alternative methods that can be used to predict the intersection safety performance. Current research efforts have focused on developing surrogate crash metrics that can estimate safety levels at intersections to address the small sample size of crash data [5, 18]. Surrogate safety measures must be an observable non-crash event that can be physically related in a predictable and reliable way to crashes and it should be convertible into a crash frequency and/or severity [5].

Examples of surrogate measures identified by Gettman et al. [17] include deceleration rate distributions, required braking power distributions, gap acceptance distributions and speed variance. The most prevalent surrogate measure of safety is the traffic conflict technique which looks at all potentially dangerous traffic interactions instead of just focusing on crash events [5, 17]. Gettman et al. [17] define a conflict as an observable event where two or more road users approach each other in time and space increasing their risk for collision if their movements do not change. Conflict patterns have already been used in empirical analysis of crash data [18]. Further, it has been shown that the proportion of conflicts that occur at an intersection is roughly the same to the proportion of collisions, meaning that the evaluation of conflicts is an appropriate substitute to examining only crashes [19]. It is therefore possible to develop quantifiable modeling with the help of microsimulation software.

The ease and speed of microsimulation has made it a popular modeling tool for traffic engineering applications. However, not all research is in favor of the use of traffic microsimulation to evaluate safety [20, 21]. Shahdah et al. [22] summarizes three common criticisms introduced in prior research: 1) models are based on the fundamental rules of crash avoidance and do not explain high-risk driving behavior leading to crashes; 2) accuracy is dependent on input parameters and how these parameters reflect "real world" conditions; and 3) safety performance is only relevant within the context of verifiable crash experience. In other words, the idea of what is deemed safe may not be solely related to conflict or crash occurrence.

There are several examples of studies, however, where the predictive capabilities of microsimulation are accurate [22, 23, 24] in comparison with the traditional empirical methods. Microsimulation software packages, such as AIMSUN or VISSIM, were used in these studies in conjunction with the Surrogate Safety Assessment Model (SSAM) to identify, classify, and evaluate conflicts. The Federal Highway Administration (FHWA) conducted a study in 2008 to validate the use of SSAM when predicting traffic conflicts [25]. First, simulations only included morning peak-hour volumes. The correlation between total conflicts predicted by SSAM and the total crashes in the field had an R^2 value of 0.41. This means that the SSAM model could explain 41 percent of the variability in the historical crash data. Second, crash prediction models based on yearly average 24-hr traffic volumes correlated with an R^2 value of 0.68 with actual crash data. FHWA recommends the use of micro-simulation research efforts with SSAM due to the speed and ease at which assessment may be completed. Caliendo and Guida [23] demonstrated that there is a significant correlation between recorded crash data and simulated conflicts when they compared recorded crashes in the field to critical conflicts identified by micro-simulation software at signalized intersections. Shahdah et al. [22] concluded that the simulated CMFs were consistent with the EB before-and-after study estimations produced by Srinivasan et al. [26].

The typical explanatory variables in crash modeling are those describing operational, geometric, and traffic characteristics. For traffic, some use the total intersection volume as an explanatory variable [26] while others say it should be approach specific [27]. For the approach specific methodology, the left-turning volume and the opposing through volume are solely considered [16]. These flows are treated as explanatory variables in different forms, with some using the cross-product of flow and others using each as independent variables in multivariate models. For geometric variables, the number of lanes entering and exiting, the angle of intersection, sight distance, and the presence and length of turning bays have been used as explanatory variables [26, 28]. Operational characteristics such as speed limits, delay, and complexity of the phases have also been suggested as explanatory [9, 29, 30]. Kirk [4] showed correlation between variables such as cycle length and effective green time percentage and simulated conflicts. These explanatory variables could be useful for predictive left turn safety analysis completed in this research.

The literature review indicated that micro-simulation combined with surrogate safety measures is becoming a widely accepted method for evaluating safety and developing safety prediction models. Surrogate measures of safety are emerging as replacement of dependence on historical crash data. Conflicts are identified as the viable surrogate to crashes due to their frequency and reliability to crash events. There is also a consensus on the explanatory variables that can be used to predict the safety performance of left turn phasing. These include number of opposing lanes and length of green times and cycles. However, there is still discussion on whether the cross product or the left turn and opposing volumes should be used as separate predictor variables.

3. Methodology

The first step in the development of the models was the identification of the variables to be considered and their ranges for the simulation. A four-leg, signalized intersection with a single left turn exclusive lane is chosen as the geometry to control for any safety related issues including intersection skew angles, poor sight distances, and multiple left turn lanes. Permissive left turn phasing is used for the left turning vehicles, since the goal of this research is to quantify conflicts attributed to the left turn movement. Table 1 shows the different design parameters are used to reflect typical traffic conditions found at four-leg signalized intersections including variable opposing volumes, number of opposing lanes, cycle lengths, percentage of the cycle length allowed for green movements, and percentage of total left turn capacity that were also used in the development of the operational component of the left-turn phasing selection [31].

Tab. 1- Simulation input parameters

	Opposing Volumes	Opposing Lanes	Cycle Length	Percentage of Green Time	Left Turn Capacity Percentage
Range	500 - 3000	1 to 3	90 to 210	30 to 70	20 to 100
Increments	500 vehicles	1 lane	30 seconds	10 percent	20 percent

The PTV VISSIM is used as the micro-simulation software [32]. VISSIM produces a variety of output from its simulations including downstream volumes for through and turning movements, average delay and queue length experienced, vehicular emissions measurements, and vehicular

speed. Since the objective of this research is to assess intersection safety surrounding the left turn movement during permissive phasing, the two output parameters of most use for model development are downstream left turning volumes and downstream opposing movements. Finally, VISSIM also produces a vehicle trajectory file for each simulation that is used for conflict analysis in the FHWA Surrogate Safety Assessment Model package.

Conflicts are identified with SSAM software by type. For the purpose of this research, the default thresholds for SSAM are used in the conflict analysis. The maximum time-to-collision is 1.5 seconds and the maximum post-encroachment time is 5.0 seconds. SSAM identifies conflicts by type according to the angle that the trajectories of two vehicles encounter each other. Vehicle trajectories that interact at angles less than 30 degrees are considered Rear End conflicts, an interaction angle greater than 85 degrees is determined to be a Crossing conflict, and all interactions between these two values are to be Lane Change conflicts.

The Statistical Package for the Social Sciences (SPSS) developed by IBM is the software used to identify explanatory variables and develop statistical, predictive models [33].

4. Results and analysis

Initial step-wise linear regression used the following explanatory variables as SPSS input to predict left turn Crossing conflicts:

- Left Turn Volume (LTDown)
- Opposing Volume (OppVolOut)
- Opposing Number of Lanes (Opposing Lanes)
- Cycle Length (Cycle)
- Effective Green Time Percentage (%Green)
- Cross Product (XProdOut)

One important note is that the left turn and opposing volumes represent the downstream quantities so that models created would reflect processed flow and not just the design demand values. In many scenarios, the entire input volume did not travel through the intersection due to capacity issues so downstream quantities reflect more appropriate real world traffic exposure.

Table 2 provides the output for the model development process. Included in the table is a list of the variables used, the coefficients generated by SPSS, the statistical significance of each variable based on an alpha level of 0.05, and the respective coefficient of determination, or R^2 value, for each model.

Tab. 2 – SPSS Model Development

Model	Variable	Coefficient	Significance	R ²
1	Constant	-1.028	.000	0.372
	%Green	.856	.000	
	LTDown	.000	.000	
	OppVolOut	.000	.000	
	Opposing Lanes	.443	.000	
2	Constant	-.181	.000	0.400
	(LTDown * OppVolOut * Opposing Lanes)/%Green	1.652E-6	.000	
3	Constant	.144	.001	0.514
	(LTDown ² * OppVolOut * Opposing Lanes ³)/%Green ^{1/3}	4.457E-9	.000	

Model 1 represents the identification of significant root variables by step-wise linear regression. Table 2 indicates that all four variables are positively correlated with the number of Crossing conflicts. This result leads to both expected and unexpected relationships. First, the left turning and opposing through volumes are expected to have a positive correlation with conflicts. These two variables are a direct measure of potential conflict exposure, therefore, one would expect that as the number of vehicle interactions increases the number of Crossing conflicts would also increase. Additionally, the analysis indicates that an increase in the number of opposing lanes is positively correlated with Crossing conflicts. This is also reasonable: as the number of lanes that a turning vehicle would need to traverse increases the risk for a crash with opposing traffic also increase. Counterintuitively, the analysis indicates that as the green time increases, the number of Crossing conflicts would also increase. This is not an expected result since the traditional belief is that as constant opposing volumes are given more green time, gaps allowing safe, permissive left turns would also increase and thus, reducing the number of Crossing conflicts. Based on the low adjusted R² value, the additive regression model does not have an adequate explanatory power. Therefore, a combination of variables was sought that could provide a higher predictive model power.

Model 2 represents the following variable created based on the positive/negative relationships provided from Model 1 and reconsidering the effect of green time:

$$X_{\text{Crossing}} = \frac{\text{Left Turns} \times \text{Opposing Throughs} \times \text{Opposing Lanes}}{\text{Green Time Percentage}} \quad (1)$$

It should be noted that the left turn and opposing through volumes were used here, since there is a potential for specific contribution of each volume in the crossing conflicts, as it will be explained in the next section. Moreover, the literature review identified a disagreement on whether to treat the cross product as a single term or to consider the left turn and opposing through volumes separately. Due to this disagreement, it was determined to use them separately. Additionally, despite the results from the step-wise regression, the percentage of green time was moved to the denominator to reflect traditional engineering judgment. The explanatory power of the Model 2 is

higher than the previous model, but may be improved by adjusting the individual powers of the root variables to reflect possible differences in their contribution to the conflict potential.

Through an iterative process, the powers of the individual root variables are adjusted within $X_{Crossing}$. The result of several iterations yield the following variable:

$$X_{Crossing, power} = \frac{Left\ Turns^2 \times Opposing\ Throughs \times Opposing\ Lanes^3}{Green\ Time\ Percentage^{1/3}} \quad (2)$$

Model 3 represents the results of the linear regression of $X_{Crossing, power}$ (Table 2). The model supports the notion that each volume may have a different impact on the potential for a conflict since the left turning movements have more of an influence (higher power) than the opposing through movements when predicting Crossing conflicts.

5. Discussion & Conclusions

The primary measure to control left turns is the implementation of a variety of signal phasing schemes including permissive only, protected only, or a combination of permissive and protected left turns. Many state DOTs have developed warrants, or guidelines, for selecting the left turn phasing type for an intersection. Warrants are often based on operational factors such as the cross product between left turn movements and opposing through volumes, or warrants may be safety related such as the left turn related crash history. The problem associated with the current warrants is that they are based on real world historical crash data. It is a reactive method that takes a considerable amount of time to complete such an analysis. Left turn crashes are typically rare events with small sample sizes. Thus, developing safety related warrants for left turn phasing could take a long time.

The purpose of this research is to create a predictive safety assessment model for left turn movements at signalized intersections. From the literature review, conflicts are determined to be the best surrogate safety measure due to a studied correlated relationship with real crash data and the ease of analysis with micro-simulation software packages.

An important area of discussion is variable selection and the combination of such variables, particularly the cross product between opposing through movements and left turn maneuvers. For example, an intersection with 500 left turning vehicles and 1,000 opposing through vehicles has the same cross product as an intersection with 1,000 left turning vehicles and 500 opposing through vehicles. It is therefore reasonable to assume that each combination would have a different safety performance and this was captured in the Crossing conflict model developed here though the inclusion of the separate values and their relative impact, i.e., left turn volume has a power of 2 in the model. Based on the results, it is determined that left turning movements have a higher correlated relationship with Crossing conflicts than the opposing through movements. After reviewing the data, for example, for cross products of 350,000 to 400,000 there were 15 scenarios. Within these scenarios, 33 Crossing conflicts were calculated by SSAM. Of the 33 conflicts, 20 were attributed to higher left turn movements in the cross product while only 13 were due to higher opposing volumes in the cross product. This same relationship is true for other cross product ranges. When developing the model for Crossing conflicts, a higher power was given to the left turn movement parameter indicating the greater influence of left turns on crossing conflicts.

The Crossing conflict predictive model developed in this research is as follows:

$$\text{Left Turn Crossing Conflicts} = 4.45E^{-9} \times X_{\text{CrossingNew}} + 0.144 \quad (3)$$

$$\text{where } X_{\text{Crossing, power}} = \frac{\text{Left Turns}^2 \times \text{Opposing Throughs} \times \text{Opposing Lanes}^3}{\text{Green Time Percentage}^{1/3}}$$

The model shows predictive ability with correlation to left turn conflicts, but also includes some limitations. First, the research only considered a single intersection geometry design (i.e. four-leg signalized with a single left turn lane). Application of such models to alternative designs may reduce their reliability. Second, left turn capacity was derived from a microsimulation involving permissive left turns only. Application of such models to existing intersections with phasing schemes that already include a form of protection may be a questionable practice. Third, driver behavior is always a concern when using microsimulation analysis because the software may not reflect reactive behavior in real world situations. Finally, conflict prediction models prove to be correlated with historical crash data, but better surrogate metrics may exist and need to be investigated.

The purpose of the research is to develop a predictive tool for left turn conflicts. Based on the model for Crossing conflicts, a series of nomographs may be developed to assist in left turn phase selection representing the thresholds between permissive and protected phasing. Figures 1 and 2 are examples of such graphs and have been developed for general conditions for main street, i.e., effective green 60 percent, and for one and three opposing lanes, respectively.

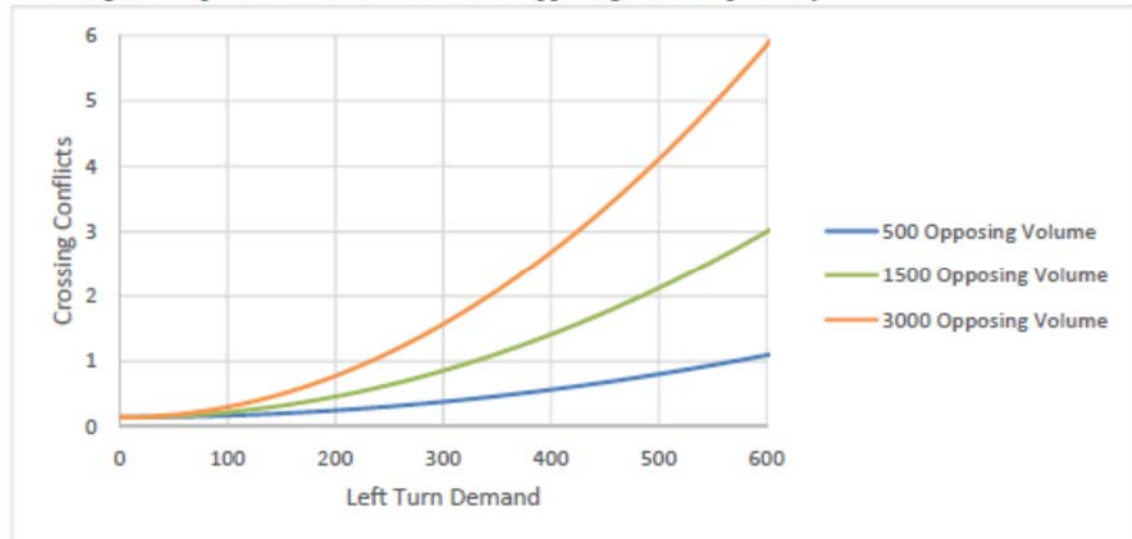


Fig.1 - Left turn phasing guidance, one opposing lane

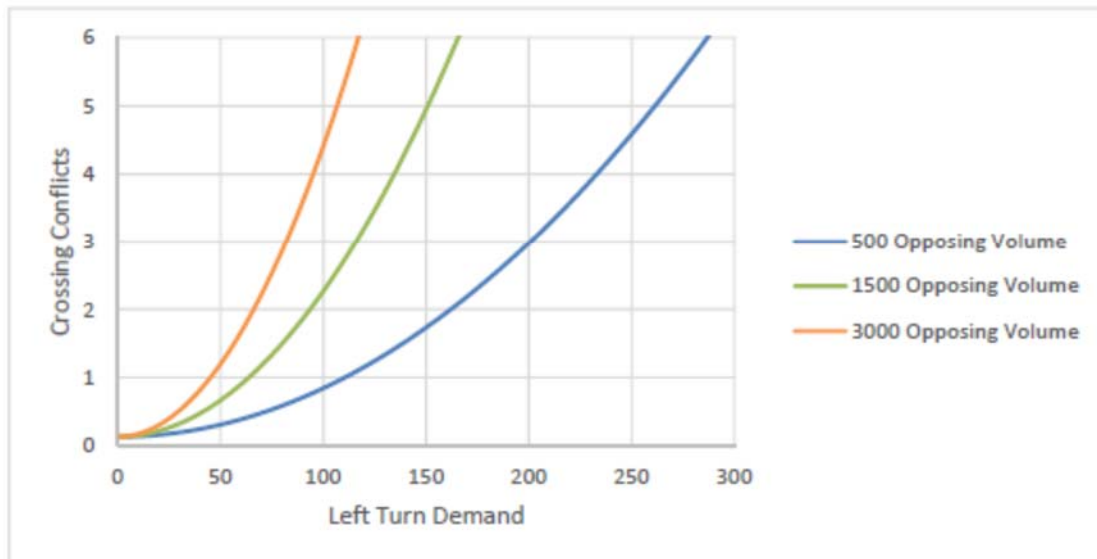


Fig. 2 - Left turn phasing guidance, three opposing lanes

Figures 1 and 2 are references that could be used to assist in signal phasing decisions. Simply knowing the typical left turn demand, opposing through volume, lane configuration, and an assumed effective green time percentage, designers are able to determine the predicted number of conflicts for any given scenario. Based on engineering judgment, conflict thresholds would then be determined as a distinction between permissive and some form of protected phasing. Figures 1 and 2 illustrate the differences between one and three opposing lanes. Both plots indicate that a higher number of left turns are possible at intersections with one opposing lane than in three opposing lanes when the same number of conflicts is considered. Graphs similar to these are easily derived for any effective green percentage or lane configuration.

The findings of this study also point to some future research to improve understanding of the left turn phasing implications. The first recommendation is to develop better design criteria when conducting micro-simulation analysis. This research uses theoretical values that are deemed "typical" for real world conditions. Based on the findings, the observed micro-simulation traffic conditions may be oversaturated, allowing for too few left turning movements and thus, less interactions between left turns and opposing through movements. Another recommendation is to further investigate the effectiveness of surrogate safety measures and more specifically, those used by SSAM. TTC and PET are utilized by SSAM, but as Wang [34] determined, these measures may not reflect actual driver behavior due to the difficulty of mimicking unpredictable human reaction with computer software. Furthermore, Kirk [4] suggests in his research to adjust the default parameters SSAM uses for TTC and PET. Kirk uses 2.0 and 5.0 seconds, respectively, for these values. The default parameters for TTC and PET in SSAM were not adjusted for the research proposed in this report. Finally, the use of historical crash data could be beneficial in validating the model developed here and increase its predictive power.

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APPENDIX B

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