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Safety and Operations Guidance for Using Time-of-Day Protected-Permissive Left-Turn Phasing Using Flashing Yellow Arrows

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Selection of the left-turn phasing mode is a significant decision for the safe and efficient movement of left-turning traffic at signalized intersections. Because of different safety and operational effects associated with the signal left-turn mode, the two must be evaluated concurrently and be balanced based on capacity and crash potential when protected-only, permissive-only, and protected-permissive left-turn (PPLT) phasing modes are compared. The choice between left-turn phasing modes can be made on a time-of-day basis so that changing traffic conditions are accommodated appropriately. The purpose of this study was to define guidance that field traffic engineers can use to select the appropriate left-turn mode based on prevailing traffic conditions by time of day. In particular, guidance on the use of PPLT or permissive-only with flashing yellow arrows (FYAs) to indicate permissive movements was of interest to the Virginia Department of Transportation (VDOT).

Prior to the development of time-of-day guidance, the overall safety effects of converting between left-turn phase modes and indications (or displays) needed to be explored. The study examined the impact of converting from a circular "green ball" display for the permissive portion of PPLT phasing to the FYA signal indication and converting from protected-only phasing to PPLT with FYA. To quantify these conversions, a before-after evaluation of signal conversions was performed using standard Bayesian methods to develop crash modification factors from field data for 28 intersections in Virginia. For these intersections, the expected crash reduction after conversion from PPLT to PPLT-FYA was estimated as 12 percent (total crashes), 14 percent (fatal and injury crashes), and 30 percent (angle crashes), which was consistent with results from previous studies.

In evaluating different left-turn phasing modes on a time-of-day basis, crash risk, left-turn conflicts, and capacity prediction models for permissive-only and PPLT modes were developed using simulation data. A total of 750 unique scenarios based on different combinations of intersection characteristics, traffic signal parameters, and traffic volumes were simulated in VISSIM, and trajectory files were processed using Surrogate Safety Assessment Model software to determine the number of conflicts per scenario. Based on the outputs of the simulation models, prediction models for determining left-turn capacities and the expected number of left-turn conflicts per hour per 100 left-turning vehicles were created using multiple linear regression. A final model predicting the average crash risk per hour based on the predicted number of conflicts was developed. The three models created were incorporated into a single spreadsheet tool that can be used by VDOT engineers in determining phasing mode on a time-of-day basis.

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FINAL REPORT

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ABSTRACT

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In evaluating different left-turn phasing modes on a time-of-day basis, crash risk, left-turn conflicts, and capacity prediction models for permissive-only and PPLT modes were developed using simulation data. A total of 750 unique scenarios based on different combinations of intersection characteristics, traffic signal parameters, and traffic volumes were simulated in VISSIM, and trajectory files were processed using Surrogate Safety Assessment Model software to determine the number of conflicts per scenario. Based on the outputs of the simulation models, prediction models for determining left-turn capacities and the expected number of left-turn conflicts per hour per 100 left-turning vehicles were created using multiple linear regression. A final model predicting the average crash risk per hour based on the predicted number of conflicts was developed. The three models created were incorporated into a single spreadsheet tool that can be used by VDOT engineers in determining phasing mode on a time-of-day basis.

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INTRODUCTION

As defined in the Virginia Department of Transportation's (VDOT's) *Guidance for Determination and Documentation of Left-Turn Phasing Mode,*[1] three different signal control modes are used in Virginia: protected-only, permissive-only, and protected-permissive left-turn (PPLT). With protected-only left-turn phasing, left-turning drivers are allowed to execute their turning movement only when they are given complete right of way over other opposing movements. This improves safety by separating conflicting flows but may negatively affect operations on other approaches. For the permissive-only left-turn mode, the left-turn movement is never given full right of way. Rather, left-turning vehicles may turn while yielding to opposing traffic. This mode increases the risk of crashes related to left turns, but it minimizes operational impacts to opposing movements. Finally, protected-permissive phasing uses a combination of the two aforementioned modes to provide right of way to left-turning vehicles for a portion of the signal cycle and permitted left turns during the opposing through phase.

Left-turn control mode selection at signalized intersections is an important decision that an engineer must make in signal design. If a phasing control mode that is too restrictive is selected, safety may improve at the cost of decreased capacity. If a mode that is less restrictive is selected, capacity may improve at the cost of safety. In addition, if only operations are considered when the selection is made, unintended safety consequences may be realized and vice-versa. Because of this, the engineer must carefully balance operational efficiency and driver safety when determining an appropriate phasing mode for left turns on a signal approach.

Another important consideration in left-turn phasing is the type of display used to indicate the left turn. If a driver misunderstands a signal indication and makes an incorrect action, a crash may occur. The green arrow display for protected left turns is typically well understood, but there can be some confusion associated with different permissive portion displays. Traditionally, the circular green (commonly called “green ball”) indication has been used to inform drivers that they may turn left while yielding to the opposing direction. In recent years, the flashing yellow arrow (FYA) display has started to replace the traditional green ball indication in signaling a permissive left turn, as this display has been shown to be understood better by drivers.[2-6]

Although the left-turn mode is often the same throughout the entire day, there is increasing interest in Virginia in deploying left-turn modes that can vary by time of day. As traffic volumes vary throughout the course of a day, the left-turn mode could also vary so that the optimal timing and control are given at all times. In particular, VDOT is interested in applications of the FYA signal display (for permissive-only or PPLT phasing), as the FYA has been shown to reduce the number of left-turn crashes when used in lieu of the green ball indication.[7, 8] Since its incorporation in the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD),[9] VDOT has been retrofitting intersections with the FYA display based on the results of these past studies.

This study quantified the safety implications of the permissive FYA signal display in terms of crash modification factors (CMFs); identified factors that affect left-turn capacity and conflicts for PPLT and permissive left-turn modes through microscopic traffic simulations; created prediction models for left-turn capacity and conflicts for PPLT and permissive left-turn modes; and related left-turn conflicts to left-turn crash risk. These prediction models were used to develop a spreadsheet tool to aid VDOT engineers in the decision process for left-turn control mode determination on a time-of-day basis.

PURPOSE AND SCOPE

The purpose of this study was to provide VDOT traffic engineers with a better understanding of the impacts of using the permissive FYA display on the safety and operational efficiency of signalized intersections. The specific objectives were as follows:

1. Quantify the safety effects of converting the permissive portion of PPLT from green ball to FYA and evaluate their impacts on crash type and severity.

2. Develop a left-turn phasing assessment tool for VDOT engineers to weigh the operational and safety tradeoffs of protected-only, permissive-only, and PPLT modes based on time of day.

The first objective was assessed using field data from VDOT FYA installations. The second objective, the assessment tool, was developed primarily from simulated data supplemented with some field data.

LITERATURE REVIEW

A review of the literature was conducted to identify the state of the art and the state of the practice with regard to FYA applications for PPLT phasing. Papers, journal articles, and agency guidance documents were analyzed to allow a better understanding of the effects of PPLT and FYA on intersection operations and safety and how other state agencies developed their guidelines on the use of PPLT and FYA. Transportation literature databases, such as the Transportation Research International Documentation (TRID) database, were used to identify the relevant literature.

Driver Comprehension and Behavior With Flashing Yellow Arrows

Driver Comprehension of Left-Turn Signal Displays

Noyce and Kacir evaluated different signal displays, including FYA, in 2001.[2] This study evaluated the effect of different permitted signal indications (green ball, flashing red arrow, flashing red ball, FYA, and flashing yellow ball) and other factors such as geographic location, driver demographics, and signal head arrangement on drivers' correct understanding of their right of way. In gathering data for the study, the authors presented static photographs of different intersection and signal characteristics to 2,465 drivers with 30 scenarios per driver. The study found that there was a higher level of comprehension and a lower fail critical rate with flashing permitted signal indications and that all "flashing red and yellow ball and arrow indications had significantly higher correct response rates than green ball indications."[2] In addition, the authors stated that further research into flashing permitted indications should be conducted through driver simulations and field studies.

In 2003, Brehmer et al., in NCHRP Report 493, reviewed existing literature on signal displays for PPLT phasing and evaluated driver understanding of displays, crash data, and operational data to determine the effects of different PPLT displays.[3] The major findings of this study were that the FYA display was widely understood by drivers; produced a higher fail-safe response rate over a green ball display; and eliminated the "yellow trap"—a scenario where the circular green indication turns yellow as a driver waits to make a permissive left-turn, incorrectly assumes that the opposite direction faces the same color display, and therefore attempts to complete the left turn when it may not be safe to do so. Thus, the researchers suggested that the FYA permissive indication be included in the next release of the MUTCD.

In 2005, Knodler evaluated driver understanding of different signal displays using a driver simulator.[4] In this study, driver simulators at the University of Massachusetts and the Texas A&M Transportation Institute were used to evaluate driver behavior for different scenarios of green ball and FYA signal indications. A video-based static evaluation that simulated the signal display was also performed. For the driver simulator, the percentage of correct responses varied from 90 to 92 percent, with no statistically significant differences between the different variables (indication, arrangement, through indication, and location). Average fail-critical response rates for the simulator were not statistically different between signal indications. For the static evaluation, the correct response rate was higher for FYA than for the green ball display.

The study also found that generally the correct response rate for the simulator study was higher than that of the static evaluation, indicating that drivers use contextual information rather than only the signal display indication to make their turning decisions. The study determined that the FYA left-turn display had a lower fail-critical response rate than the green ball display and that it had a high level of driver comprehension.

Because of the findings of the three studies described, the FYA display was incorporated into the 2009 MUTCD as an acceptable display for permissive portions of left-turn modes.[9] With this inclusion, more states have started to convert signals from the traditional green ball display to FYA.

Driver Behavior Studies for PPLT and FYA

In 2013, Reitgraf and Schattler evaluated driver behavior by studying real-world driver reactions to different permissive interval signal indications.[5] To do this, the researchers collected video data and extracted information such as gap size accepted by the drivers of left-turning vehicles, occurrences of adequate gap size being rejected, and comments on the actions (such as if the driver slowed down before approaching the turn). With the data, driver behavior was compared among the green ball, FYA, and flashing red arrow signal displays. Statistical comparisons of means and variances of the proportions of drivers' actions for the three display modes were completed. These comparisons yielded the percentages of drivers who completed safe actions, efficient actions, and the combination of safe and efficient actions for each signal display. These values were compared to determine if they were statistically different at the 95 percent level. The result of the analysis was that drivers made the safest and most efficient actions at intersections with FYA installed. In addition, the study found no significant difference in driver behavior between geographic areas that used multiple permissive indications and areas that used only one permissive indication.

Rescot et al. evaluated FYA installations and made recommendations for the Indiana Department of Transportation (DOT) for the widespread implementation of FYA in Indiana.[6] The study used observational analyses, crash data, and survey data to develop the recommendations for FYA. For the driver performance (observational) study, radar was used to collect acceleration and deceleration data to be compared at two intersections with PPLT-FYA and two with PPLT with a green ball display for the permissive phase. In evaluating the data, average deceleration and acceleration were determined to be the same; thus, there was no significant difference in driver performance between the indications. For the crash study, average crash rates were compared between the different display types, but there was no conclusive evidence that one was safer than the other. The researchers also conducted a driver survey wherein they collected driver responses to theoretical situations with different signal head indications and orientations. From the survey responses, the researchers determined that a majority of drivers gave correct responses to both indications, with few fail-critical responses. As a result of the study, the Indiana DOT recommended that FYA be used as an alternative to green ball indications and that proper public education be provided.

Safety Effects of PPLT and FYA

Flashing Yellow Arrows

In an attempt to illustrate safety implications of FYA installations, Pulugurtha et al. used the empirical Bayes (EB) technique to analyze crashes at six intersections in Charlotte, North Carolina, where the green ball signal indications had been converted to FYA.[10] The researchers did not specify if permissive-only or PPLT phasing was used at the study sites. In the study, the researchers developed safety performance functions (SPFs) that predicted the number of crashes based on annual average daily traffic (AADT) and skewness of the intersection. From the analysis, the researchers found that five of the six intersections studied had an odd ratio (OR) of less than 1.0. Because of the small dataset, the researchers did not conclude that the FYA installations were effective in reducing the number of crashes at intersections, but the data showed that FYA was a promising display technique.

Qi et al. (2012) evaluated the safety of FYA installations at signals with PPLT phasing at 17 intersections in Tyler, Texas, and Kennewick, Washington, using the EB method.[11] This study specifically focused on intersections that operated in PPLT mode before and after the conversion with the only change being the change in the permissive display for the signal. Four to 6 years of before data and 1 to 2 years of after data were available for analysis. Analysis techniques were similar to those in the study by Pulugurtha et al., with the exception being that the SPFs were based on the number of left-turn lanes, AADT, and posted speed. The investigation indicated that FYA did not decrease safety overall, although 3 of the 17 intersections had ORs greater than 1.0. The intersections with safety degradations were further analyzed, and the researchers found that there were side effects of the FYA installations at these sites, mostly because of higher volume-to-capacity (v/c) ratios and site-specific issues in signal timing. The two side effects of the FYA were classified as a “red trap” problem and a “yellow sneakers” problem. They described the red trap as driver confusion during the steady yellow arrow portion of the PPLT, after the protected portion—the researchers stated that drivers misinterpreted the steady yellow for a flashing yellow indication and assumed they had to yield to oncoming traffic. The yellow sneakers issue was defined as drivers executing left turns and those drivers who were in the opposing through direction speeding up to make it through the yellow indication concurrently, which was observed only when the two movements ended at the same time. As a result, the researchers suggested that the following additional changes be made when installing FYA for PPLT:

- Allow for a longer clearance interval (red time after the protected portion ends) for confused drivers to clear the intersection.

- Offset the ending times of opposing left-turn movements in lead-lag PPLT operations.

Schattler et al. examined the impacts of supplemental signage, evaluated FYA’s impact on older and younger drivers, and conducted a cost-benefit analysis for FYA installations.[7] The researchers used both the naïve before and after and EB methods to analyze crashes at 86 intersections in Illinois that underwent a conversion from PPLT to PPLT-FYA and developed CMFs and their respective confidence intervals. From the safety analysis, CMFs were determined to be 0.63, 0.61, 0.71, and 0.71 for left-turn related crashes; left-turn related crashes at intersections with supplemental signage; left-turn opposing through crashes; and left-turn opposing through crashes at intersections with supplemental signage, respectively. It should be noted that the researchers defined left-turn opposing through crashes as crashes that involved a left-turning vehicle and an opposing through direction vehicle. These results indicate that supplemental signage installed with FYA provided a slight safety improvement. In addition, the researchers determined that the FYA installations had no effect on older drivers and that FYA helped younger drivers understand the PPLT phasing. For the cost-benefit analysis, the study compared crash cost reduction benefits to the initial cost of the FYA installation with a 3 percent discount rate over the 15-year economic life of the signal. From this it was determined that there was a 19.8 to 1 benefit-to-cost ratio, indicating that the conversion was economically justifiable.

As another metric for determining the safety effectiveness of FYA deployments, Lin et al. examined gap acceptance as a short-term safety measure.[12] Since the EB method requires years of after crash data to yield accurate results, the safety implications of FYA installations cannot be immediately studied to indicate whether the deployment was effective at a particular location. Because of this, the researchers developed a method of analyzing intersections using 1 month of before and 2 months of after data. Turning-movement counts, conflicts (with the time of conflict recorded), and gap acceptance data were collected through video collection strategies. The study team concluded that a slight reduction in crash risk occurred at the study site since the crossing tolerance, defined as the "time between the moment the turning vehicle clears the gap reference point and the moment the front bumper of the opposing vehicle touches such reference point," increased. In addition, the study found that capacity improvements of up to 10 percent can be realized for moderate opposing traffic since drivers accepted shorter gaps.

Phasing Changes and FYA Installations

To quantify the effects of FYA and PPLT conversions, Srinivasan et al. determined CMFs separately for the changes from permissive-only to PPLT and for the implementation of PPLT-FYA at intersections with permissive-only and protected-only prior control modes.[13] Using the EB method for the conversion from permissive to PPLT and a modified version of the EB method for the implementation of FYA, the authors analyzed 71 sites in Toronto [Canada] and North Carolina for the change from permissive to PPLT and 51 sites in Washington State, Oregon, and North Carolina for the installation of FYA. In general, the study found that converting from permissive-only to PPLT reduced left-turn crashes by 14 percent and the addition of FYA helped reduce left-turn crashes by 36 percent. In addition, converting from protected-only to PPLT with FYA increased left-turn crashes by 124 percent because of the introduction of additional conflict points.

Simpson and Troy also developed CMFs for FYA conversions, with statistically significant results for conversions from a five-section PPLT with green ball indication to PPLT with FYA and for conversions from permissive-only with green ball indication to permissive-only with the FYA indication.[8] In addition, the study attempted to determine CMFs for the conversion from permissive-only to PPLT-FYA, protected-only to PPLT-FYA, and protected-only to PPLT-FYA with time-of-day operation, but the results showed too much variability, and the CMFs were not statistically significant. For the statistically significant CMFs, sites from

North Carolina were analyzed using a simple before-after method, using the SPFs for urban and suburban intersections in the *Highway Safety Manual* (HSM) to account for traffic volume variability. For the conversion from PPLT to PPLT-FYA, statistically significant CMFs were found for the approach level at 0.93, 0.85, 0.78, and 0.68 for total, injury, target (left turn, same roadway), and target/injury crash types, respectively, for intersections with all legs treated receiving the same treatment. The conversion from permissive-only to FYA permissive-only on an approach level revealed statistically significant CMFs of 0.69, 0.41, and 0.31 for injury, target, and target/injury crash types, respectively. A reduction in crashes was evident for the PPLT to PPLT-FYA conversion, and a more prominent reduction was evident for the permissive to permissive-FYA conversion, although these results were not based on the EB method.

Table 1 summarizes some CMFs developed in previous studies of PPLT and FYA safety.

Table 1. Summary of Crash Modification Factors (CMFs)[a]

Study	CMF	Crash Type	Conversion	Notes
Schattler et al., 2016[7]	0.62	Left-turn related	PPLT to PPLT-FYA	-
	0.71	left-turn opposing through		-
	0.59	Left-turn related		With supplemental signage
	0.71	Left-turn opposing through		
Srinivasan et al., 2012[13]	0.86	Left turn	Perm to PPLT	-
	0.75	Total	Perm to PPLT-FYA	-
	0.64	Left turn		-
	1.34	Total	Protected-only to PPLT-FYA	-
	2.24	Left turn		-
Simpson and Troy, 2015[8]	0.93	Total	PPLT to PPLT-FYA	Approach level
	0.85	Injury		
	0.78	Target		Approach level; Target = left-turn, same roadway
	0.68	Target/Injury		
	0.69	Injury	Perm to Perm-FYA	-
	0.41	Target		-
	0.31	Target/Injury		-

PPLT = protected-permissive left-turn phasing; PPLT-FYA = PPLT with flashing yellow arrow permissive indication; Perm = permissive-only left-turn phasing with green ball indication; Perm-FYA = permissive-only left-turn phasing with flashing yellow arrow indication.

[a] All CMFs were statistically significant at the 95% confidence level.

Combined Operational and Safety Effects of PPLT

A 2010 study by Qi et al. created an approach to estimate the operational benefits and safety costs associated with PPLT phasing.[14] The authors developed models that estimated left-turn delay for protected-only and PPLT phasing modes using variables such as saturation flow of permissive and protected left-turn phases, left-turn volumes, and signal timings. For the cost analysis, the number of potential conflict gaps was estimated based on Poisson arrivals. To evaluate the benefits and costs simultaneously, dollar amounts per vehicle were assigned to the delay and conflict costs. These values were multiplied by their respective delay reduction and conflict predictions and summed to determine the benefit or cost of a particular installation. According to the study, by using this method, traffic engineers could evaluate whether or not installing PPLT would provide operational and safety cost benefits. Since the study used only one city for data collection and model validation, the methodology may not be appropriate for other localities.

Existing Left-Turn Phasing Guidelines

Outside Virginia

In 1985, Agent developed recommendations for when permissive phasing, including PPLT, should not be used based on an analysis of crashes at 58 intersections in Kentucky.[15] In addition, the study evaluated the characteristics of the related crashes. Both analyses used before and after crash data, with 1 to 7 years of before data and a minimum of 1 year of after data. The study used a simple crash rate (number of crashes per year) as a metric to compare the before and after conditions following conversions from protected-only to permissive left-turn phasing. From the analyses, the study found that left-turn crashes increased with permissive-only phasing. A dramatic increase in left-turn and total crashes was found at sites with speed limits greater than 45 mph, and the overall severity of the incidents, except fatal severities, was higher than the statewide average. As a result of the study, it was recommended that any form of permissive phasing, including PPLT, should not be used under any of the following conditions:

- The speed limit is greater than 45 mph.
- The speed limit is greater than 35 mph and protected-only phasing currently exists.
- The left-turn movements must cross three or more opposing through lanes.
- There are dual left-turn lanes.
- There is not enough sight distance.
- A left-turn crash issue exists (as determined through a traffic conflicts study).

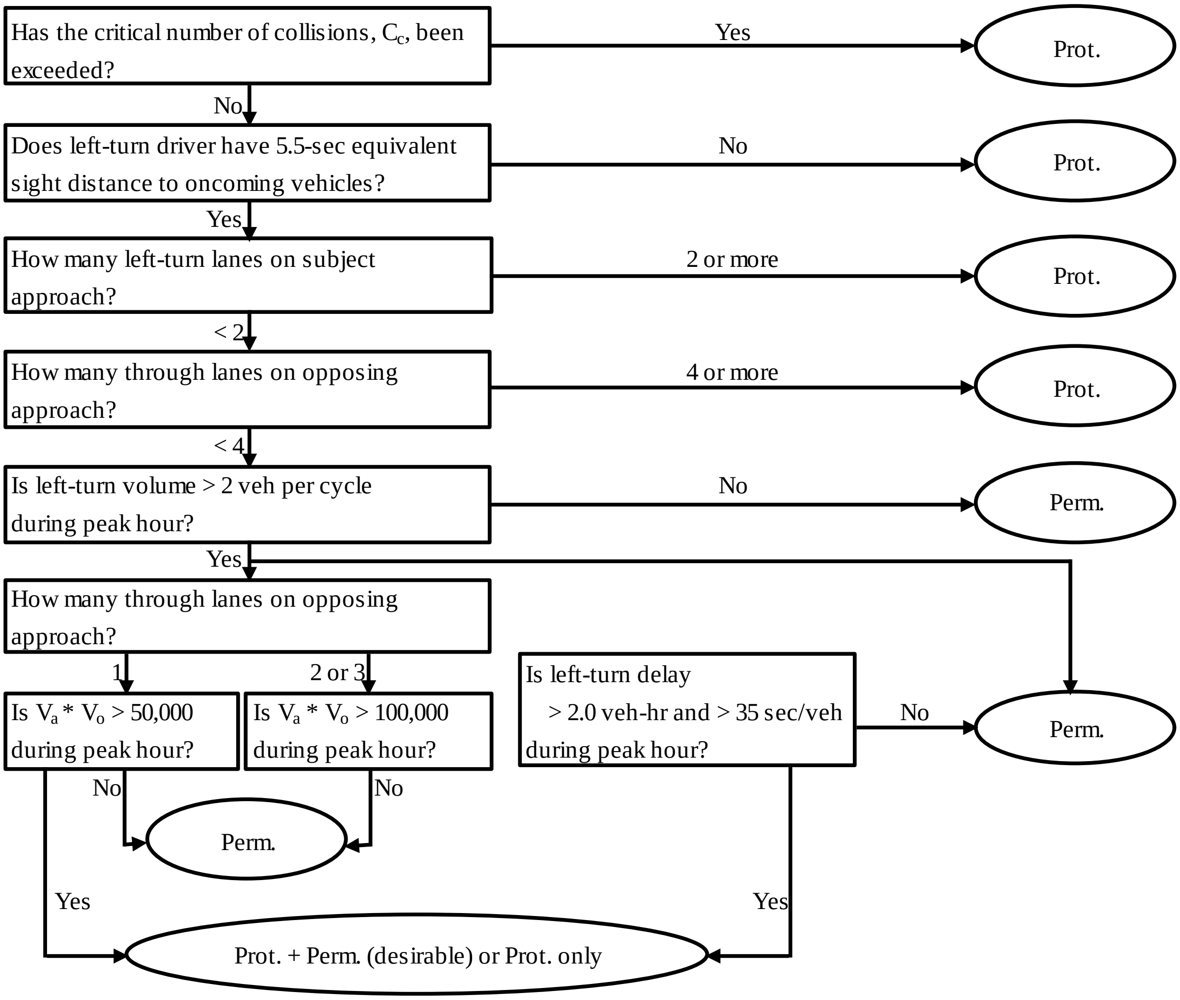
All of these guidelines applied to permissive-only and PPLT phasing modes, though the study evaluated results of only intersections converted from protected-only to permissive-only phasing. Therefore, generalization to PPLT may not be appropriate.

To address the gaps left in the 1985 study, Agent and Stamatiadis updated guidelines for determining left-turn phasing, with an emphasis on high speed areas.[16] In this study, 264 intersections in Kentucky, with a total of 518 approaches that underwent signal conversions, were evaluated using crash history, traffic conflict data, and operational characteristics. As with the previous study, the average numbers of crashes in the before and after periods were compared for each intersection with the exception that the peak hour volumes were used as a method of exposure to weigh the crashes. In addition, simulation models were used to determine left-turn delay based on different variations of left-turn volumes, opposing volumes, cross-street volumes, number of approach lanes, and left-turn phasing (protected-only, permissive, or PPLT). From the study, the researchers made a number of recommendations, the most prevalent being that PPLT phasing should be preferred over protected-only phasing for lower left-turn delay unless there is an existing or potential for a crash problem with left-turning vehicles, defined as four or more left-turn crashes in 1 year, six or more in 2 years, or eight or more in 3 years on the analysis approach. Further, if the values were higher than these thresholds, crash rates should be compared to rate tables developed in the study based on different combinations of speed limits and numbers of opposing lanes. The researchers also established that if the product of left-turning and opposing volumes for the analysis hour exceeded 100,000 on a four-lane road or 50,000 on a two-lane road, some form of protected left-turn phasing should be considered. If the product exceeded 300,000 on a four-lane street or 150,000 on a two-lane street, protected-only phasing should be considered. In addition, the researchers determined that if the left-turn movement has 2 or more vehicle hours of delay during the peak hour, protected left-turn phasing should be considered.

In 2001, Bonneson and Fontaine, in NCHRP Report 457, provided formal guidance for left-turn phasing selection.[17] The authors stated that "two-phase operation with permitted left-turn movements should be considered as a 'starting point'" and that "left-turn phasing should only be provided if it will improve operations or safety." In addition, they provided a flowchart for selection of left-turn phasing alternatives based on crash history, sight distance, site geometry, vehicular volume per cycle, and left-turn delay or cross product of volume (CPOV). The flowchart is provided in Figure 1. One major shortcoming of this guidance is that it considers only the peak period of the intersection being analyzed; i.e., whichever phasing is warranted for the peak hour should be applied for the entirety of the signal. Because of this, time-of-day phasing was not considered.

To provide additional formal guidance on the deployment of PPLT phasing and FYA signal indications, Koonce et al. included left-turn display and phasing sequence option sections in the 2008 *Traffic Signal Timing Manual.*[18] The authors stated that PPLT phasing can offer a good compromise between the safety benefits of protected-only phasing and the efficiency benefits of permissive left-turn phasing. In addition, they included guidelines for selecting left-turn phasing, including a flowchart similar to the one in NCHRP Report 457, shown in Figure 2. With regard to display, the authors suggested that the FYA permissive display be used for PPLT phasing to eliminate the "yellow trap" and allow for permissive left turns during opposing protected left turns.

Yu et al. created a comprehensive set of guidelines for the Texas DOT in 2009.[19] Safety and operational impacts of phasing mode, sequence, and display were analyzed using data for 26 intersections in Texas for the operational study and 111 pairs of intersection approaches for the safety study. For the operational impact study, GPS probe data for travel time and video traffic data were collected and used for simulation model development and validation. The models used a three-intersection roadway network to simulate intersection and network impacts. In addition, the delay and CPOV for the simulations were used as operational metrics for the intersections. In the safety impact study, data were used to develop regression models to determine left-turn crash frequency based on intersection geometrics, signal control, signal display, and traffic conditions. The authors also performed a before-after study using the EB method to determine the ORs for intersections converted from protected-only to PPLT phasing. As a result of these operational and safety studies, it was determined that the CPOV should be used as a volume-based criterion in determining phasing mode, and a phasing mode selection flowchart was created based on the literature and the developed volume-based criteria, as shown in Figure 3. In addition, the Texas DOT recommended that FYA can be used as an alternative to the green ball permissive indication for PPLT.



Critical number of collisions, C_c

On one approach, C_c = 4 left-turn collisions per 1 year or 6 left-turn collisions per 2 years.

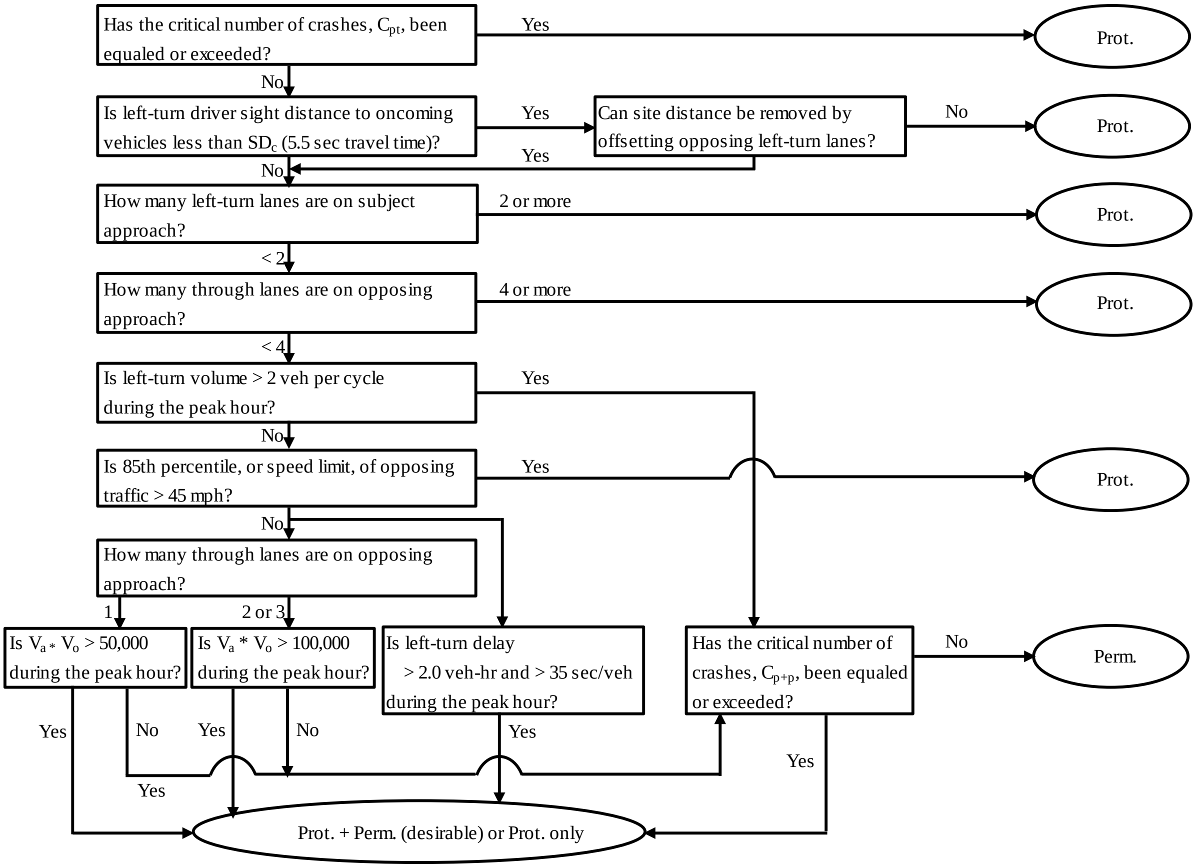
On both approaches, C_c = 6 left-turn collisions per 1 year or 10 left-turn collisions per 2 years.

Variables

V_a = left-turn volume on the subject approach, veh/hr.

V_o = through plus right-turn volume opposing the subject left-turn movement, veh/hr.

Figure 1. Left-Turn Phasing Flowchart Adapted From NCHRP Report 457 (Bonneson and Fontaine[17]). Prot. = protected left-turn phasing; Perm. = permissive left-turn phasing; veh = vehicles.



		Critical Left-Turn-Related Crash Count	
Number of Left-Turn Movements on Subject Road	Period During Which Crashes are Considered (Years)	When Considering Protected-Only, C_{pt} (Crashes/period)	When Considering Prot. + Perm., C_{p+p} (Crashes/period)
One	1	6	4
One	2	11	6
One	3	14	7
Both	1	11	6
Both	2	18	9
Both	3	26	13

Oncoming Traffic Speed Limit (mph)	Sight Distance, SD_c (ft)
25	200
30	240
35	280
40	320
45	360
50	400
55	440
60	480

Variables

V_a = left-turn volume on the subject approach, veh/hr.
V_o = through plus right-turn volume opposing the subject left-turn movement, veh/hr.
SD_c = minimum sight distance to oncoming vehicles, ft.

Figure 2. Left-Turn Phasing Flowchart Adapted From the 2008 *Traffic Signal Timing Manual* (Koonce et al.[18]). Prot. = protected left-turn phasing; veh = vehicle; Perm. = permissive left-turn phasing.

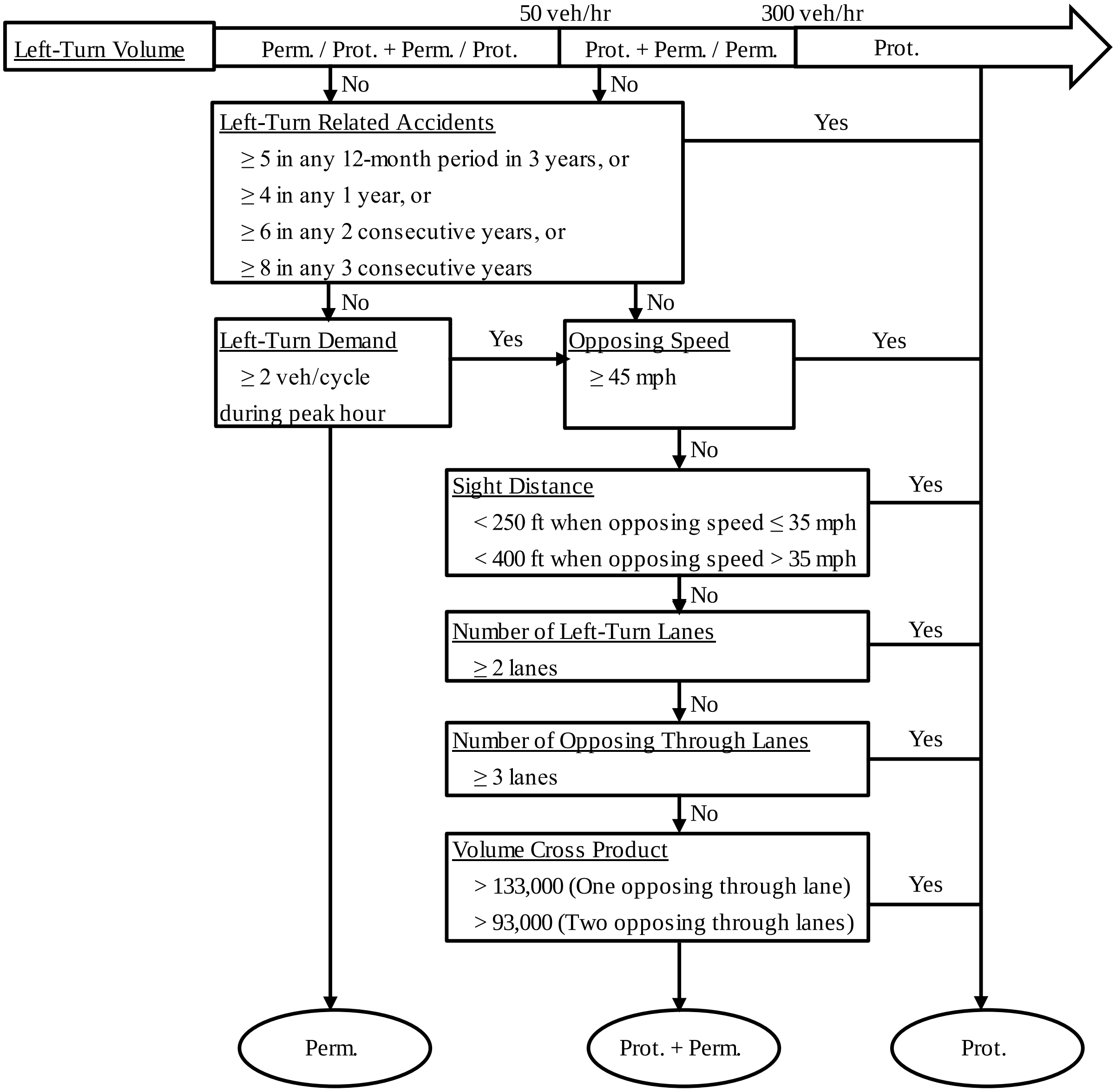


Figure 3. Left-Turn Phasing Flowchart Adapted From *Development of Left-Turn Operations Guidelines at Signalized Intersections* (Yu et al.[19]). Veh = vehicle; Prot. = protected left-turn phasing; Perm. = permissive left-turn phasing.

Two Florida studies, one in 2013 by Radwan et al.[20] and one in 2017 by Chalise et al.,[21] created a decision support system and time-of-day recommendations for the implementation of variable left-turn modes using FYA. In both studies, more than 200 hours of processed video data from intersections in Central Florida were used to develop and validate prediction models. Data collected from the video collection units included gap and volume analysis. In addition, categorical data including intersection geometry were collected to create the models. In the 2013 study, the researchers developed a decision support system based on a generalized linear model, with input variables of time of day, number of crossing lanes, speed, permitted green time, total left-turn volume, total opposing volume, criteria (urban, rural, ramp, etc.), and land use. Of these variables, total left-turn volume and total opposing volume were the most important factors, supporting the previously accepted notion that CPOV was a sufficient selection variable for left-turn phasing. The model developed by the researchers predicted the left-turn volume of the permitted portion of the phase. The system would then output the phasing recommended (either permissive or protected-only) and the number of left turns and percentage of left turns provided by the left-turn phasing by comparing the calculated permitted left-turn index (defined as permitted left-turn volume multiplied by total opposing volume divided by permitted green time in seconds) and permitted left-turn ratio (defined as the permitted left-turn volume divided by the total left-turn volume) to threshold values for one or two opposing lanes. This was done to determine if permissive phasing was feasible at a given intersection.

The 2017 study by Chalise et al. improved on the previous study by modeling delay, rather than the number of left turns made during the phase. A stepwise regression approach was used to develop two models, one to predict the delay for either PPLT or permissive-only phasing and the other to predict delay for PPLT or protected-only phasing. The researchers then proposed a threshold of 10 percent for the percent reduction in delay that was used in conjunction with the left-turn delay models to determine left-turn phasing. From both studies, decision tools were developed to aid traffic engineers in determining left-turn phasing at given intersections based on operational impacts.

Finally, Davis et al. developed guidelines for the Minnesota DOT for time-of-day use of PPLT phasing by creating a spreadsheet tool based on relative crash risk predicted by statistical models.[22] The researchers used a matched case-control technique to develop models based on geometric characteristics, crash data, and traffic volume data. Six models were developed to reflect different categories of intersections:

1. PPLT, opposing speed limit < 45 mph, no clear sight distance problem
2. PPLT, opposing speed limit < 45 mph, possible sight distance problem
3. PPLT, opposing speed limit ≥ 45 mph, possible sight distance problem
4. PPLT, opposing speed limit ≥ 45 mph, no clear sight distance problem
5. Permissive, opposing speed limit < 45 mph, possible sight distance problem
6. Permissive, opposing speed limit < 45 mph, no clear sight distance problem.

The independent variables that were model inputs were hourly left-turn and opposing through volumes. In developing the model, the researchers did not have turning movement counts for each day of the year or hourly volumes for all times and days of the years; thus, they developed methods for predicting values for days and times not gathered in the data collection. Five randomly sampled hours were selected per intersection (328 total intersections) to develop log linear models for the case-control design. The models produced were able to predict the relative risk of crashes throughout the 24-hour period selected. The models were also incorporated into a spreadsheet tool so that traffic engineers could view graphs of the relative risk and standard deviation throughout each hour of the day.

VDOT's Guidance on Left-Turn Phasing Selection

VDOT's 2015 *Guidance for Determination and Documentation of Left-Turn Phasing Mode* was meant to "equip traffic engineers in Virginia with the most appropriate tools to make informed and thoughtful decisions on left-turn phasing mode selection."[1] This guidance evaluated the literature on guidance determination and the state of the practice for state DOTs and VDOT regional guidelines throughout the state. A summary of the selection criteria for protected-only left-turn modes used by other state DOTs is included in Figure 4.

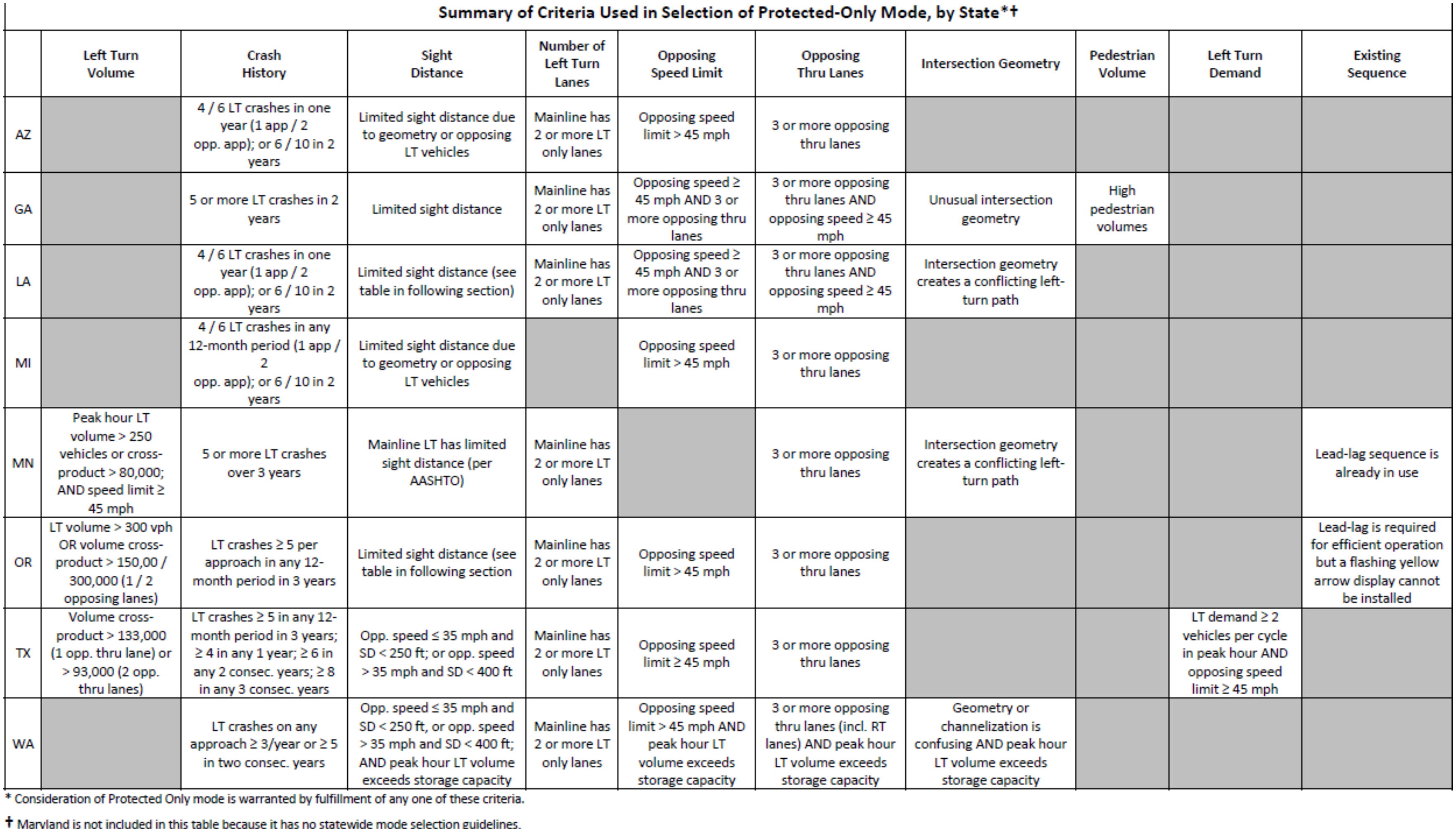
In addition, the document gave two critical evaluation questions that engineers should use when determining left-turn phasing: "from a safety perspective, can permissive left-turn movements be allowed on an approach?" and "should some level of left-turn protection (i.e., protected/permissive mode) be provided for efficiency reasons?" These questions should be constantly considered in choosing the phasing mode.

In addition, VDOT provides factors that should be considered in determining the left-turn phasing mode, including sight distance, intersection geometry, critical crossing gap, and correctable left-turn crashes. For the critical crossing gaps criteria, VDOT stated that PPLT should be considered for a CPOV greater than 50,000 for any hour, but VDOT did not establish an upper bound for PPLT using the metric, stating that PPLT can still be considered in high-CPOV conditions. In addition, VDOT stated that in evaluating correctable left-turn crashes, the EB method should be used but crash rate can also be considered with AADT to account for exposure.

In closing, the VDOT guidance stated that selection of phasing should be considered on a site-by-site basis; no fixed thresholds for certain phasing modes were provided. In addition, sight distance and critical crossing gap should be the first factors considered in reviewing intersections.

Literature Summary

The literature review showed that prior guidance on left-turn phase selection often focused on only operational or safety metrics and typically assumed the same phasing mode would be used throughout the day. Although some studies set out to examine both aspects of intersection phasing, most ultimately focused on either operations or safety.



Summary of Criteria Used in Selection of Protected-Only Mode, by State*†

	Left Turn Volume	Crash History	Sight Distance	Number of Left Turn Lanes	Opposing Speed Limit	Opposing Thru Lanes	Intersection Geometry	Pedestrian Volume	Left Turn Demand	Existing Sequence
AZ		4 / 6 LT crashes in one year (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance due to geometry or opposing LT vehicles	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph	3 or more opposing thru lanes				
GA		5 or more LT crashes in 2 years	Limited sight distance	Mainline has 2 or more LT only lanes	Opposing speed ≥ 45 mph AND 3 or more opposing thru lanes	3 or more opposing thru lanes AND opposing speed ≥ 45 mph	Unusual intersection geometry	High pedestrian volumes		
LA		4 / 6 LT crashes in one year (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance (see table in following section)	Mainline has 2 or more LT only lanes	Opposing speed ≥ 45 mph AND 3 or more opposing thru lanes	3 or more opposing thru lanes AND opposing speed ≥ 45 mph	Intersection geometry creates a conflicting left-turn path			
MI		4 / 6 LT crashes in any 12-month period (1 app / 2 opp. app); or 6 / 10 in 2 years	Limited sight distance due to geometry or opposing LT vehicles		Opposing speed limit > 45 mph	3 or more opposing thru lanes				
MN	Peak hour LT volume > 250 vehicles or cross-product > 80,000; AND speed limit ≥ 45 mph	5 or more LT crashes over 3 years	Mainline LT has limited sight distance (per AASHTO)	Mainline has 2 or more LT only lanes		3 or more opposing thru lanes	Intersection geometry creates a conflicting left-turn path			Lead-lag sequence is already in use
OR	LT volume > 300 vph OR volume cross-product > 150,00 / 300,000 (1 / 2 opposing lanes)	LT crashes ≥ 5 per approach in any 12-month period in 3 years	Limited sight distance (see table in following section	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph	3 or more opposing thru lanes				Lead-lag is required for efficient operation but a flashing yellow arrow display cannot be installed
TX	Volume cross-product > 133,000 (1 opp. thru lane) or > 93,000 (2 opp. thru lanes)	LT crashes ≥ 5 in any 12-month period in 3 years; ≥ 4 in any 1 year; ≥ 6 in any 2 consec. years; ≥ 8 in any 3 consec. years	Opp. speed ≤ 35 mph and SD < 250 ft; or opp. speed > 35 mph and SD < 400 ft	Mainline has 2 or more LT only lanes	Opposing speed limit ≥ 45 mph	3 or more opposing thru lanes			LT demand ≥ 2 vehicles per cycle in peak hour AND opposing speed limit ≥ 45 mph	
WA		LT crashes on any approach ≥ 3/year or ≥ 5 in two consec. years	Opp. speed ≤ 35 mph and SD < 250 ft, or opp. speed > 35 mph and SD < 400 ft; AND peak hour LT volume exceeds storage capacity	Mainline has 2 or more LT only lanes	Opposing speed limit > 45 mph AND peak hour LT volume exceeds storage capacity	3 or more opposing thru lanes (incl. RT lanes) AND peak hour LT volume exceeds storage capacity	Geometry or channelization is confusing AND peak hour LT volume exceeds storage capacity			

* Consideration of Protected Only mode is warranted by fulfillment of any one of these criteria.

† Maryland is not included in this table because it has no statewide mode selection guidelines.

Figure 4. Protected-Only Phasing Criteria by State. From *Guidance for Determination and Documentation of Left-Turn Phasing Mode, Version 1.0* (VDOT, 2015[1]).

METHODS

Overview

This study created guidance based on the operational and safety impacts of left-turn phasing. By using simulation runs to estimate operations and simulations and empirical CMFs to estimate safety, these outputs were combined to create specific guidance that VDOT engineers can use to assess different phasing alternatives. In addition, the study allowed for the evaluation of a left-turn signal in a time-of-day operational mode, which most previous studies had not covered. The study also developed angle-crash CMFs to provide practitioners with an easier way to evaluate target crash types. Since other forms of target crash type such as left-turn opposing through crashes require more specific data, crashes would need to be evaluated individually to determine if they involved a left-turning vehicle and another traveling in the opposing through direction; angle crashes are coded in the VDOT Roadway Network System (RNS) crash database, allowing easier access and analysis by field staff.

Six tasks were performed to achieve the study objectives:

1. Analyze before and after crash data.
2. Develop and calibrate a microsimulation model to evaluate left-turn operations.
3. Design and analyze a simulation experiment.
4. Develop capacity and conflict prediction models.
5. Develop a risk assessment model for time-of-day safety analysis.
6. Develop a spreadsheet tool for practitioners.

Analyze Before and After Crash Data

To examine the safety impacts of FYA in Virginia, a before-after study using the EB and full Bayes (FB) approaches was conducted. Both methods account for the regression-to-mean bias by combining prior information with current information. The EB method, currently the approach recommended in the HSM, allows for out-of-sample estimation of the prior information by using data from a reference group of intersections similar to the treated sites to develop an SPF that relates crash frequencies to relevant site characteristics. The SPF estimates of crash frequencies are then combined with the observed crash frequencies to obtain improved estimates of the long-term expected crash frequencies had the treatment not been implemented.

The FB approach also uses data from a reference group of intersections. However, the prior information is not estimated out of sample. Instead, data from the reference group and data from the treated sites before the treatment was applied are used in an integrated approach to obtain a distribution of likely values that are then combined with site-specific crash data to obtain estimates of the long-term expected crash frequencies. Though a relatively complex alternative to the EB approach, the FB approach is desirable because it requires less data, better accounts for uncertainty in the data, enables more detailed causal inferences, and provides more flexibility in selecting crash count distributions.[23]

For this study, intersections that underwent FYA signal indication conversions were selected based on completeness of AADT and crash data from 2008 through 2016.

Data Collection

The study used data from 28 treated intersections and a reference group of 39 signalized intersections across Virginia. Initially, 347 intersections were identified that had at least one left-turn approach with a planned or completed conversion to PPLT phasing with an FYA display for the permissive portion (PPLT-FYA) from any other left-turn phasing mode and display combination. A total of 87 of these intersections were found to have already undergone the conversion. Of these locations, 43 were determined to have complete AADT data for the analysis years. Instances for which AADT data were incomplete included when the intersection had at least one driveway as an approach (as VDOT does not maintain these segments or record their traffic count data) or when there were years of missing traffic data for an approach. The original goal was to analyze conversions to PPLT-FYA from any other left-turn phasing mode and display combination. However, each of the 43 locations had an initial left-turn phasing of either PPLT with a green ball or protected-only with a green arrow on the approaches that were converted to PPLT-FYA. Because of this, only the conversions from PPLT to PPLT-FYA and protected-only to PPLT-FYA could be considered. Upon further inspection of these 43 locations, 4 were removed since their conversion dates could not be determined, 1 was removed as it was found to be unsignalized before the FYA implementation, and 2 were removed because they had commercial driveways in close proximity. This reduced the number of intersections under consideration to 36, 28 of which converted from PPLT to PPLT-FYA and 8 of which were converted from protected-only to PPLT-FYA. The intersections that had converted from protected-only to PPLT-FYA were excluded from the analysis because of the small sample size and potential confounding effects. In particular for these intersections, any changes in crashes following PPLT-FYA conversion were likely due to the introduction of the permissive phase and not necessarily the FYA signal indication. As a consequence, the analysis focused on the 28 sites that had converted from PPLT to PPLT-FYA. The number of sites used as reference was also limited to 39 because of factors such as traffic data availability and close proximity to driveways. The reference group intersections did not have FYA signals installed at the time of the study; instead, they were under consideration by VDOT staff as candidates for future FYA installation.

Crash data and AADT data for the study intersections were retrieved from VDOT Traffic Engineering Division (TED) databases for the period from January 2008 through December 2016. In data retrieval, a crash event was assigned to an intersection if it was within 250 feet of the intersection. The major road was defined as the road with the higher AADT. The lengths of the before and after periods varied based on the date FYA was activated. Crash data were aggregated on a monthly basis, and for the FB analysis, average daily traffic (ADT) estimates for each month of the analysis period were obtained by applying appropriate monthly adjustment factors available in the VDOT TED databases to the AADT data. Data for the months in which the FYA signals were activated were not used in the analysis. A summary of some relevant characteristics of the treated intersections is provided in Figure 5.

Intersection ID	Number of Legs	Prior Left-turn Mode	Years		Main Road AADT		Minor Road AADT		Total crashes / yr	
			Before	After	Before	After	Before	After	Before	After
1	4	PPLT	7.0	1.9	19,702	22,613	7,449	7,350	10.3	7.8
2	3	PPLT	7.0	1.9	13,542	13,917	1,422	1,467	2.0	2.6
3	3	PPLT	7.0	1.9	9,940	9,357	2,119	2,090	1.4	1.0
4	4	PPLT	7.0	1.9	8,887	8,745	2,281	2,502	3.1	1.0
5	3	PPLT	6.9	2.0	9,850	9,701	2,753	2,804	1.6	2.0
6	3	PPLT	6.9	2.0	3,678	4,216	1,886	1,915	1.4	2.0
7	4	PPLT	6.9	2.0	17,924	18,052	2,832	3,198	5.9	4.0
8	3	PPLT	7.5	1.4	5,915	5,756	1,172	1,218	0.7	0.0
9	4	PPLT	7.0	1.9	8,270	7,698	546	546	1.6	2.1
10	4	PPLT	7.0	1.9	4,484	4,463	3,978	4,037	0.9	0.5
11	3	PPLT	6.8	2.2	20,830	23,882	6,273	7,035	5.0	6.0
12	3	PPLT	6.8	2.2	13,216	15,096	2,362	2,406	1.2	0.5
13	4	PPLT	6.8	2.1	7,342	8,066	3,275	3,560	0.6	1.4
14	3	PPLT	5.3	3.7	25,953	24,748	1,692	1,592	4.0	6.3
15	3	PPLT	8.2	0.8	20,540	21,716	2,814	2,685	2.9	2.7
16	4	PPLT	7.0	1.9	5,831	5,402	3,548	3,142	2.7	2.1
17	4	PPLT	7.0	1.9	13,572	12,444	3,942	3,524	3.6	3.1
18	3	PPLT	7.0	1.9	7,214	6,803	4,009	3,496	1.7	3.7
19	3	PPLT	7.0	1.9	14,305	14,988	3,894	2,968	7.1	4.7
20	4	PPLT	5.3	3.7	28,605	27,956	8,625	8,832	17.5	13.9
21	3	PPLT	6.8	2.1	14,321	13,032	5,642	5,697	2.2	3.4
22	4	PPLT	7.1	1.8	8,483	8,361	4,472	4,303	1.7	0.5
23	3	PPLT	7.2	1.8	9,798	8,627	994	948	1.7	1.1
24	4	PPLT	6.8	2.1	8,635	7,720	3,282	3,760	4.4	4.3
25	3	PPLT	7.2	1.8	9,165	8,402	1,296	894	1.1	2.3
26	3	PPLT	7.2	1.8	6,915	5,148	1,285	1,114	0.6	0.0
27	3	PPLT	5.2	3.8	10,268	10,786	4,605	5,163	5.4	4.0
28	4	PPLT	4.6	4.3	15,156	16,068	6,272	7,631	7.4	9.2
29	4	Protected	6.1	2.8	7,292	7,332	4,423	6,459	1.8	1.8
30	3	Protected	6.7	2.3	37,720	34,849	980	981	2.9	0.9
31	4	Protected	7.0	1.9	16,694	15,914	5,063	4,914	10.3	7.3
32	4	Protected	7.8	1.1	9,891	10,825	5,401	5,507	3.2	8.3
33	4	Protected	8.4	0.5	8,413	9,064	2,159	2,243	1.9	2.0
34	4	Protected	7.8	1.2	26,336	29,907	2,631	1,987	7.0	11.1
35	4	Protected	7.9	1.0	8,675	8,723	3,938	4,190	3.4	8.0
36	3	Protected	6.9	2.0	23,106	24,155	7,268	7,525	2.3	7.5
	Mean		6.9	2.0	13,346	13,459	3,516	3,602	3.7	3.9

Figure 5. Summary of Intersections Studied for Crash Modification Factor Calculations. AADT = annual average daily traffic; PPLT = protected-permissive left-turn mode. AADTs and crashes are average annual values for the before and after years.

Once necessary data were collected and the analysis sites were selected, analysis of several subsets of the sites was performed to develop specific CMFs for combinations of crash types, crash severities, and intersection types. In addition, the two conversion types were analyzed separately to illustrate the effects of the different treatments. The results of this analysis were then checked for statistical significance, and final CMF values were selected. These values were then compared to the results presented by studies mentioned earlier to determine if the CMFs were consistent. Specific tasks performed in the EB and FB analyses are described later.

EB Analysis

Safety Performance Functions for EB Analysis

When the EB method is used, SPFs are used to predict the number of crashes at a location for a specified time period, usually 1 year. Virginia-specific SPFs developed by Garber and Rivera in 2010 using generalized linear modeling with a negative binomial distribution were used in the analysis.[24] In total, there were 32 SPFs for all combinations of urban and rural locations, 3- and 4-leg intersections, total and fatal and injury crash severities, and statewide and regional locations. All of the Virginia-specific SPFs used the same model form, with major and minor street AADTs as predictor variables. Base conditions for the SPFs were the same as those in the HSM.[25] For each intersection in the current study, the corresponding SPF for the region, location type, and intersection geometry was used. Of the 32 available Virginia intersection SPFs, 18 were used in this study, corresponding to the different intersection types and locations of the dataset. The parameters of these SPFs are shown in Table 2. The equation form for the Virginia-specific SPFs is shown in Equation 1.

$$N_{prd} = e^{\propto} * (MajAADT)^{\beta_1} * (MinAADT)^{\beta_2} \qquad \text{[Eq. 1]}$$

where

N_{prd} = predicted number of crashes per year
$MajAADT$ = AADT on major roadway
$MinAADT$ = AADT on minor roadway
α, β_1, β_2 = regression coefficients.

Table 2. Parameters for Safety Performance Functions (SPFs) Used[24]

Region	Crash Severity	Urban/Rural	No. of Intersection Legs	SPF Coefficients			k^a
				α	β_1	β_2	
Northern	All	Urban	3	-4.999	0.5555	0.1554	0.393
			4	-8.3067	0.7522	0.328	0.2119
		Rural	4	-1.604	0.2284	0.1514	0.3211
	Fatal and Injury	Urban	3	-7.3982	0.6496	0.2088	0.4152
			4	-9.6546	0.7603	0.3597	0.2056
		Rural	4	-3.3285	0.3601	0.0597	0.2505
Western	All	Urban	3	-9.6143	0.8677	0.3297	0.3719
			4	-12.3913	1.0631	0.4567	0.1624
		Rural	3	-6.4368	0.544	0.2863	0.4112
			4	-6.3951	0.5508	0.3106	0.1525
	Fatal and Injury	Urban	3	-11.0104	0.908	0.3226	0.5043
			4	-11.4284	0.8662	0.4412	0.1492
		Rural	3	-8.8607	0.7059	0.2809	0.392
			4	-8.0583	0.6809	0.2557	0.2285
Eastern	All	Urban	3	-6.7518	0.6157	0.2969	0.3343
			4	-8.8553	0.7825	0.3706	0.1346
	Fatal and Injury	Urban	3	-7.266	0.5508	0.3107	0.2975
			4	-9.9582	0.7484	0.4017	0.1269

[a] *k*, the overdispersion parameter, is used in calculating the number of expected crashes.

Site Characteristics for Base CMF Development

Site characteristics for the study locations were also collected so that they could be checked against the base conditions for the Virginia-specific SPFs. In situations where conditions at the evaluation sites differed from the base conditions, the SPF predictions were adjusted to site-specific conditions by use of appropriate CMFs determined from other sources, such as the HSM. To check if the conditions were met or if adjustment CMFs had to be determined, the site characteristics listed in Table 3 were found for each site.

With these characteristics, CMF values were determined for each location using values from the HSM.[25] To find site characteristics, Google Maps and Google Street View were used to view imagery of the locations. It should be noted that whether a site was rural or urban was based on VDOT's functional classification of the roads at the intersection. Base CMFs for left-turn phasing were accounted for only in the PPLT to PPLT-FYA conversion cases, as the final CMFs that were calculated for the protected-only to PPLT-FYA conversion cases accounted for the phasing change. It should also be noted that the geometry change of one urban intersection changed concurrently with the signal conversion, which added two left-turn lanes, one in each direction, on the mainline roadway. This was accounted for in the before and after CMFs for this intersection. No other intersections in the analysis had changes in base conditions between the before and after periods.

Table 3. Site Characteristics for Development of Base Crash Modification Factor

	Characteristic	**Values**
Urban/Rural	Location type	Urban, Rural
Both	No. of legs	3, 4
	Roadway lighting	Yes, No
	No. of legs with left-turn lanes	0, 1, 2, 3, 4
	No. of legs with right-turn lanes	0, 1, 2, 3, 4
Urban	No. of legs with left-turn phasing	0, 1, 2, 3, 4
	No. of legs with right turn on red prohibited	0, 1, 2, 3, 4
	Left-turn phasing (for each approach)	Permissive, protected, PPLT

PPLT = protected-permissive left-turn phasing.

Angle Crashes

In addition to all crash type CMF calculations, angle crashes were analyzed, since these should have been the crash type most affected by the conversion from PPLT or protected-only to PPLT-FYA that are also readily accessible to VDOT engineers. The Virginia SPFs used for the analysis were developed for total crashes and fatal and injury crashes; they do not explicitly model angle crashes or other crash types. To correct for only angle crash types, the number of observed crashes for each year counted only angle crashes, and the numbers of predicted crashes for both the before and after periods were multiplied by the percentage of angle crashes to total crashes before the conversion, as recommended in the HSM.[25] The percentages of angle crashes used in the calculations are listed in Table 4.

Table 4. Percentage of Angle Crashes in the Before Period at Study Sites

Conversion Type	Intersection Geometry	% Angle Crashes	
		All Crash Severities	**Fatal and Injury Crash Severities**
PPLT to PPLT-FYA	All	49%	56%
	3	43%	50%
	4	53%	61%
Protected-only to PPLT-FYA	All	29%	28%

PPLT = protected-permissive phasing (with green ball for the permissive portion); PPLT-FYA = protected-permissive phasing with FYA for the permissive portion.

Full-Year Data vs. Partial-Year Data

Traditionally, data from the installation year of the treatment would not be used for CMF development. This would constrain the data analysis to include only sites installed before 2016, i.e., a total of 27 sites. To allow for a larger sample size and potentially more accurate results than those obtained by analyzing only sites with full-year data, sites with partial-year data were included in CMF development. This process allowed for an additional site in CMF development.

To complete this analysis, partial-year data were accounted for by multiplying the number of predicted crashes in both the before and after periods by the number of months before or after and dividing by 12. For example, for a site that was installed in March 2016, the number of predicted crashes for 2016 in the before period was multiplied by 2/12 and the number of predicted crashes for 2016 in the after period was multiplied by 9/12. From this it should also be noted that the installation month data were not considered in the analysis; therefore, in the example, only January and February were used in the before period and April through December were used in the after period for 2016.

CMF Calculations

The predicted number of crashes summed across all years in the before period was determined using the Virginia SPFs and then multiplying by the corresponding CMFs determined for that intersection to determine the predicted crashes for the before period. This process was repeated for the after period using the after period CMFs to calculate the number of predicted crashes in the after years. The number of expected crashes was determined by applying a weighting factor, as calculated using the appropriate overdispersion factor, *k*, for the intersection, to the observed and predicted number of crashes. The weighting factor, *w*, determines what percentage of predicted crashes should be used and what remaining percentage $(1 - w)$ of observed crashes should be used in deciding the expected crashes in the before period. The equation for calculating the weighting factor is shown in Equation 2, and the equation for calculating the number of expected crashes in the before period is shown in Equation 3.[25]

$$w = \frac{1}{1+k\sum_{all\ before\ years} N_{prd}} \qquad \text{[Eq. 2]}$$

where

w = weighting factor (decimal)
k = overdispersion factor from SPF (decimal)

N_{prd} = SPF-predicted crashes per year.

$$N_{xpt} = wN_{prd} + (1 - w)N_{obs} \tag{Eq. 3}$$

where

N_{xpt} = number of expected crashes in the before period
N_{obs} = number of field-observed crashes in the before period.

The number of expected crashes, along with the ratio of the predicted number of crashes in the after period to the predicted number of crashes in the before period, was then used to calculate the number of expected crashes in the after period. From there, this value was compared to the observed number of crashes at each site to find an OR. The overall OR was then calculated using the summation of all observed crashes at all locations and dividing that by the summation of all predicted crashes at all locations. Finally, a correction was applied to this value to formulate the final CMF value for the analysis, the equation for which is found in Equation 4.

$$OR = \frac{OR'}{1 + \frac{\sum_{All\ sites} r_i^2 N_{xpt,B}(1 - w_i)}{(\sum_{All\ sites} N_{xpt,A})^2}} \tag{Eq. 4}$$

where

OR = unbiased, final odds ratio (CMF)
OR' = unadjusted odds ratio
r_i = adjustment factor (ratio of predicted crashes before to after).

CMFs and their corresponding standard errors and significance levels were computed for the following:

- total crashes (all types and severities)
- fatal and injury crashes (all types)
- angle crashes (all severities).

FB Analysis

Two basic model forms that account for overdispersion in crash counts were considered for the FB analysis: the Poisson-Gamma model and the Poisson-Lognormal model. These models can be expressed as indicated in Equation 5[23, 26]:

$$y_{it} \sim Pois(\varepsilon_i \lambda_{it}) \tag{Eq. 5}$$

where

y_{it} = observed number of crashes at intersection i in month t

ε_i = nonnegative multiplicative random effect term for intersection *i* (to model individual heterogeneity).

For the Poisson-Gamma model:

$\varepsilon_i \sim Gamma(\phi, 1/\phi)$ with mean 1, variance $1/\phi$ and dispersion parameter ϕ
$\varepsilon_i \sim Gamma(1,1)$.

For the Poisson-Lognormal model:

$\varepsilon_i \sim LogN(0, \sigma^2)$ with mean $e^{\sigma^2/2}$ and variance $e^{\sigma^2}(e^{\sigma^2} - 1)$
$\sigma^2 \sim Inverse\,Gamma(0.001, 0.001)$
λ_{it} = expected number of crashes at intersection *i* in month *t*.

The expected number of crashes (λ_{it}) was modeled as a function of entering ADTs on the major and the minor roads. Three functional forms of the regression model were tested; they are shown in Equations 6 through 8. Equation 7 includes a time trend term to account for time effects, and Equations 6 and 8 do not. Equation 8 also includes time-varying coefficients to account for temporal variations in traffic environment, driver behavior, weather, etc.[23]

$$\lambda_{it} = d_{3i}\beta_{30} + d_{4i}\beta_{40} + (d_{3i}\beta_{31} + d_{4i}\beta_{41})\ln\left(\frac{ADTm_{it}}{1000}\right) + (d_{3i}\beta_{32} + d_{4i}\beta_{42})\ln\left(\frac{ADTc_{it}}{1000}\right) \qquad \text{[Eq. 6]}$$

$$\lambda_{it} = d_{3i}\beta_{30} + d_{4i}\beta_{40} + (d_{3i}\beta_{31} + d_{4i}\beta_{41})\ln\left(\frac{ADTm_{it}}{1000}\right) + (d_{3i}\beta_{32} + d_{4i}\beta_{42})\ln\left(\frac{ADTc_{it}}{1000}\right) + \beta_3 t \qquad \text{[Eq. 7]}$$

$$\lambda_{it} = d_{3i}\beta_{t30} + d_{4i}\beta_{t40} + (d_{3i}\beta_{31} + d_{4i}\beta_{41})\ln\left(\frac{ADTm_{it}}{1000}\right) + (d_{3i}\beta_{32} + d_{4i}\beta_{42})\ln\left(\frac{ADTc_{it}}{1000}\right) \qquad \text{[Eq. 8]}$$

where

β_{kj} (k = 3, 4; j = 0, 1, 2), β_{t30}, β_{t40}, and β_3 are regression coefficients

d_{ki} (k = 3, 4) are dummy variables such that d_{ki} = 1 if intersection *i* is *k*-leg and 0 otherwise

$ADTm_{it}$ = main road entering ADT for intersection *i* and month *t*

$ADTc_{it}$ = minor road entering ADT for intersection *i* and month *t*.

Markov chain Monte Carlo methods were used to calibrate posterior distributions for the model parameters and functions of model parameters using WinBUGS software.[27] The calibration was done using data from the period before treatment occurred at the treated sites and data from the entire before and after periods for the reference sites. Prior distributions for all regression coefficients were assumed to be normal with a mean of zero and a large variance (10^3) to reflect complete ignorance about their values a priori. The calibrated parameters were used to obtain estimates of the total number of crashes expected ($\varepsilon_i\lambda_{it}$) at the treated sites in the after periods had the treatment not been implemented. The expected crash reduction rate (R) following FYA installation was then calculated, using Equation 9, as the percentage difference between the expected total number of crashes and the actual number of crashes in the after period.

$$R = 1 - \frac{\sum_{i\in I}\sum_{t>T_{0i}} y_{it}}{\sum_{i\in I}\sum_{t>T_{0i}} \varepsilon_i \lambda_{it}} \qquad \text{[Eq. 9]}$$

where

T_{0i} = month in which FYA was activated at intersection I
I = set of treated intersections
y_{it} = observed number of crashes at intersection i in month t.

Two parallel Markov chains were run for 130,000 iterations to obtain posterior distributions of the model parameters and the crash reduction rates. Convergence was monitored using the Brooks-Gelman-Rubin diagnostic,[27] which showed that model parameters converged after approximately 30,000 iterations. As a consequence, the first 30,000 iterations of each chain were discarded as burn-in runs. In addition, the chains were thinned using a factor of 20 (i.e., results were collected on model parameters at every 20th iteration only) so as to minimize the effects of serial correlations; thus, inferences were based on samples of size 10,000 for every model parameter. The deviance information criterion, a goodness-of-fit measure similar to Akaike's information criterion, was used as the primary criterion for comparing the different FB models. In comparing two models, the model with the lower deviance information criterion is generally preferable.[27] As a consequence, the Poisson-Gamma model with a regression function for the expected number of crashes that includes a time trend term to allow for estimating and accounting for time effects was selected because it had relatively low deviance information criterion values and the 90 percent posterior credible interval for the trend effect did not include zero. As with the EB approach, separate models were calibrated based on data for the following:

- total crashes (all types and severities)
- fatal and injury crashes (all types)
- angle crashes (all severities).

Develop and Calibrate a Microsimulation Model to Evaluate Left-Turn Operations

After the safety effects of the left-turn phasing mode and displays were determined, models were created to predict left-turn capacities and the number of crossing conflicts based on simulation data for permissive-only and PPLT phasing modes. Since the results from CMF development focused on static phasing mode choice, models developed in this section were critical in the evaluation of time-of-day operations of signals, as they take into consideration intersection parameters that change throughout the day, affecting operations and safety dynamically. To evaluate the impacts of signal parameters, traffic characteristics, and geometric conditions on the operations and safety of permissive-only and PPLT phasing control modes, simulations were run in PTV's VISSIM 8. Simulation modeling was chosen so that variables could be controlled and hundreds of combinations of input variables could be tested with relative ease. VISSIM was used as the simulation software for the research since it had the ability to be run via a script to automate scenario creation so that the inputs of hundreds of scenarios did not have to be entered manually. In addition, VISSIM supported the tracking of the paths of individual vehicles through trajectory (TRJ) files that could be later analyzed for conflicts in the Surrogate Safety Assessment Model (SSAM) software.

Model Development

A base model was first created so that it could be calibrated to ensure accurate results. The base model was a standard non-skewed, four-legged intersection on a zero-percent grade. Left turns were from a single exclusive lane and across one, two, or three opposing through traffic lanes. A detector was positioned on the receiving end of the turn, just past the final opposing lane that the turning traffic had to cross, and it counted each vehicle that passed over it for the duration of the simulation.

A schematic diagram of the configuration with one opposing though lane is shown in Figure 6. Since the focus of the study was on left-turning traffic and potential conflicts with opposing through traffic, only the subject left-turn lane and the opposing through lanes were loaded with traffic in the simulations.

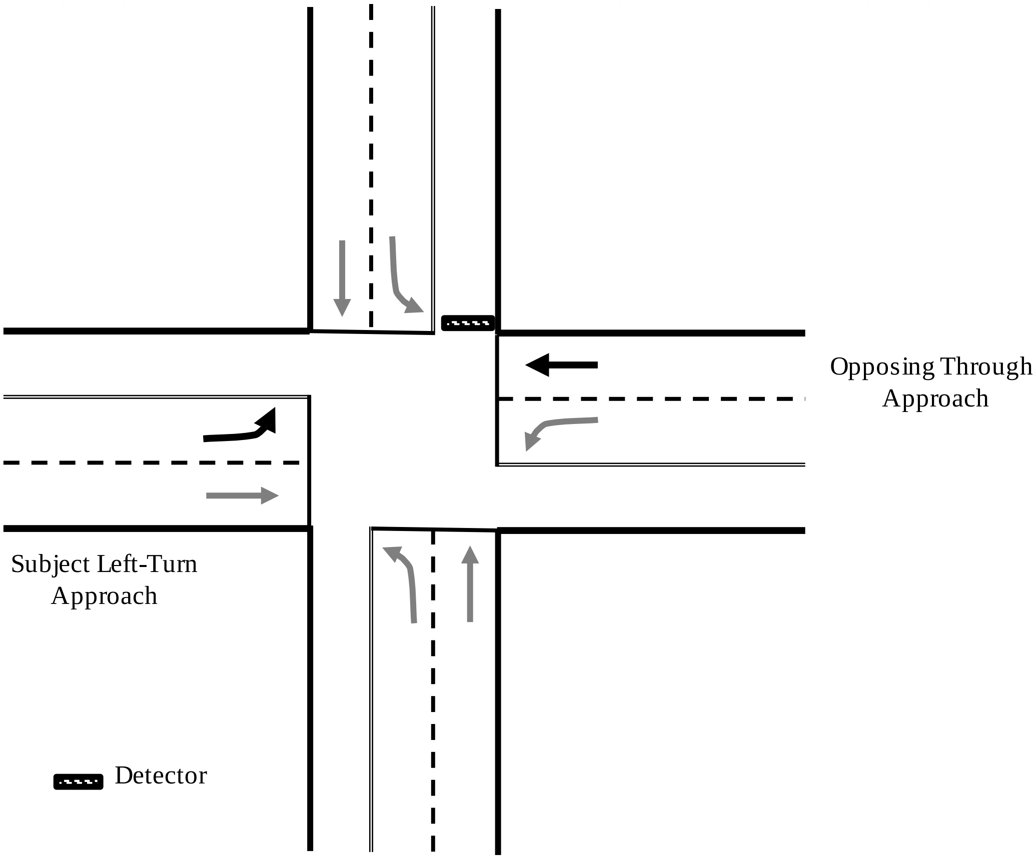


Figure 6. VISSIM Base Model. Only movements indicated by dark arrows had traffic input in the simulations. Left turns were from a single lane and across one, two, or three opposing lanes.

Model Calibration

In creating a model that accurately represents theoretical conditions, calibration was performed to achieve two objectives:

1. Ensure that the saturation flow rates for the urban and rural cases are consistent with values provided in the HCM.[28]

2. Ensure that the model produces accurate capacity estimates.

For the first calibration, the Wiedemann 74 car following models used in VISSIM were calibrated to produce the appropriate saturation flow rates. Five simulations were run for 13 different combinations of the multiplicative and additive part of desired safety distance factors to determine headways for vehicles in the left-turn and opposing through directions separately. The cycle used for the discharge rate evaluations was 120 seconds with 30 seconds of green time for the subject left-turn phase and 45 seconds of green for the opposing through phase. All left-turn phases operated in the protected-only mode. No traffic was loaded on the other approaches, but their signal phases turned green, thus allowing vehicles to move up to the stop bar before the start of green. Headway values for the 5th through 10th vehicles were averaged across the five runs and for the 2nd through 29th signal cycles (a total of 840 values).

The second stage of the calibration process involved adjusting relevant VISSIM parameters such that simulated capacities for permissive left turns reflected theoretical values calculated in accordance with HCM procedures. To achieve this, 336 scenarios were developed and run using the base model to compare the simulated capacities to HCM-calculated capacities. The calibration involved altering the behavior of left-turning drivers when they approached conflict areas. The front and rear gap parameters of the VISSIM conflict areas attribute for the turning vehicles were varied to determine values that would produce more accurate capacities. These values, as defined in the VISSIM user manual, are the “time that a vehicle waits before entering the conflict area, after the vehicle with the right of way has left it.”[29] By shortening or lengthening the time the driver of a left-turning vehicle waits to execute his or her turn, the number of vehicles served by each scenario can be changed. In addition, the stopping position of yielding left-turn vehicles was set back by adjusting the additional stopping distance parameter of the conflict areas attribute such that there was an average of two sneakers per cycle. In each scenario, two opposing lanes, a 45 mph speed limit for opposing vehicles, and permissive-only left-turn phasing were held constant. Permissive-only phasing was used since the capacities could be easily determined from HCM equations and the calibration results could be applied to the PPLT mode.

The variable parameters used for calibration were area type, cycle length, proportion of the cycle time available to the subject street phases (split ratio), and opposing volume, as these could be used in the HCM capacity calculations. All combinations of rural and urban area types, cycle lengths of 90 seconds and 120 seconds, split ratios of 0.6 and 0.8, and opposing volumes of 100, 200, 400, 600, 800, 1,000, and 1,200 vehicles per hour per lane (veh/hr/ln) were used. For simplicity, the front and rear gaps were assumed to be equal in each scenario with values of 0.3, 0.4, 0.5, 0.6, 0.7, and 0.8 being tested, for a total of 336 simulation scenarios.

Theoretical capacities for the permissive scenarios were calculated using Equation 10, from the HCM:

$$c_p = \frac{g_u}{C} + Sneakers \qquad \text{[Eq. 10]}$$

where

c_p = capacity of the permissive left-turn phasing (veh/hr)
g_u = duration of permissive left-turn green that is not blocked by an opposing queue (sec)
C = cycle length (sec)
s_p = saturation flow rate of the permissive movement (veh/hr/ln).

Effectively, Equation 10 determines the number of vehicles that are able to execute the permissive left turn after the opposing queue clears and the number of vehicles in 1 hour that are sneakers, based on an average of two sneakers per cycle. The duration of the permissive left-turn phasing that is not blocked by the opposing queue (the unblocked green time) was calculated by deriving information from the queue polygon in the HCM that represented protected movements. In Figure 7, the amount of time that the opposing queue took to dissipate is represented by the variable g_s.[28] To determine this value for each scenario, the initial queue had to be divided by the rate at which the queue dissipated, as shown in Equation 11.

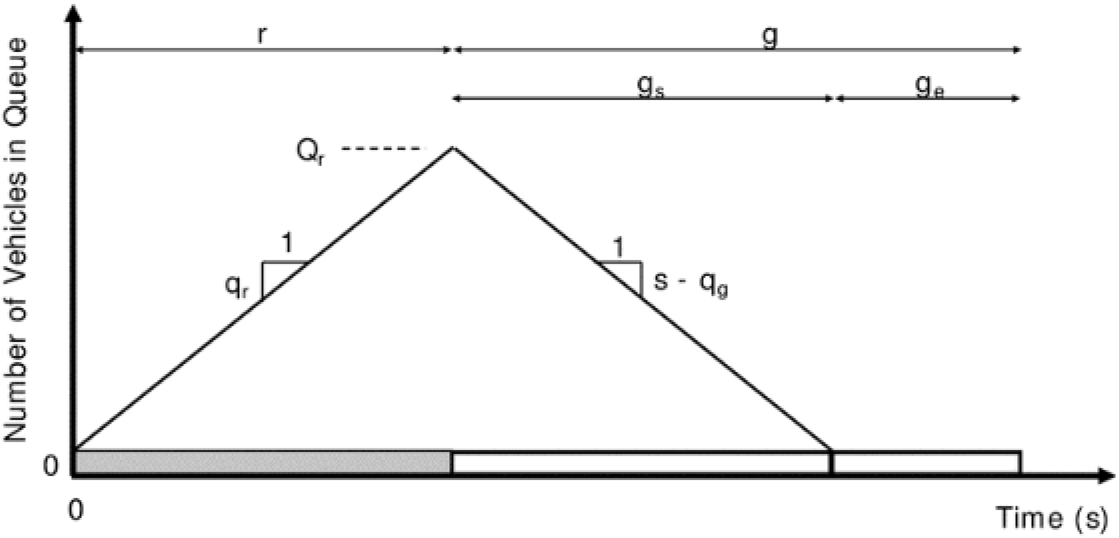


Figure 7. Queue Accumulation Polygon for Protected Movements

$$g_b = g_s = \frac{Q_r}{s-q_g} = \frac{q_r r}{s-q_g} \qquad \text{[Eq. 11]}$$

where

g_s = queue service time (sec) or g_b = duration of permissive left-turn green time that is not blocked by an opposing queue (sec)
Q_r = queue size at the end of the effective red time = $q_r r$ (veh)
q_r = arrival flow rate during the effective red time = opposing volume (veh/hr/ln)
r = effective red time = $C - g$ (sec)
g = effective green time = $C(G/C) - l$ (sec)
G/C = subject street green ratio
l = loss time, 5 sec (assumed)
s = ideal saturation flow rate: 1,900 for urban and 1,750 for rural (veh/hr/ln)
q_g = arrival flow rate during the effective green time = opposing volume (veh/hr/ln).

Once the blocked green time is determined, it can be subtracted from the effective green time for the subject street to calculate the unblocked green time, g_u. The saturation flow rate of the permissive left-turn approach, s_p, is determined from Equation 12, from the HCM:

$$s_p = \frac{v_0 e^{-v_0 t_c/3600}}{1-v_0 e^{-v_0 t_f/3600}} \qquad \text{[Eq. 12]}$$

where

v_0 = opposing volume (veh/hr)
t_c = critical headway = 4.5 sec
t_f = follow-up headway = 2.5 sec (for exclusive lane).

Finally, the number of sneakers per hour is calculated, as shown in Equation 13, by multiplying the HCM default of 2 sneakers per cycle by the number of cycles in an hour:

$$Sneakers = \frac{3600}{C} * 2 \qquad \text{[Eq. 13]}$$

where C = cycle length.

Design and Analyze Simulation Experiment

Simulation Parameters

The first step in creating simulation models for time-of-day analyses of FYA was to select the parameters that would be used in the simulations. It was also important to decide which parameters would be constant in each model and which would vary from model to model. Ultimately, eight variables were chosen to be simulated, shown in Table 5. Each variable is discussed separately in subsequent sections.

Table 5. Simulation Parameters Evaluated

Parameter	Values/Range
Area Type	Rural, urban
No. of Opposing Lanes	1, 2, 3 lanes
Left-Turn Mode	Permissive-only, PPLT-lead
Protected Left-Turn (PPLT) Ratio	0.10, 0.15, 0.20, 0.25
Cycle Length	80-240 seconds
Split Ratio	0.3-0.8
Opposing Volume	200-1,200 veh/hr/ln
Average Opposing Speed	35-55 mph

PPLT-lead = protected-permissive left-turn phasing with leading left turns.

Area Type

Urban and rural area types were chosen to be modeled to distinguish between results with different saturation flow rates. As defined by the HCM,[28] the defining traffic characteristic between the two areas is the ideal saturation flow rate. For urban areas, a value of 1,900 veh/hr/ln was assumed, and for rural areas, a value of 1,750 veh/hr/ln was assumed.

Number of Opposing Lanes

Since previous studies have shown that the number of opposing through lanes has a significant effect on operations and the safety of left turns,[1, 7, 11, 15–22] this was included as a variable in the simulations. One, two, and three opposing lanes were used as the levels of this variable since less restrictive left-turn phasing modes such as permissive-only and PPLT are uncommon at intersections with more than three opposing through lanes in Virginia.

Left-Turn Phasing Mode

Permissive-only and PPLT control modes were selected as the two left-turn phasing modes for simulation. The protected-only mode was not simulated since left-turn capacities could easily be determined for this mode analytically and the safety of this mode is generally well understood. Further, since VISSIM simulates fundamentally safe driving behavior, few if any left-turn conflicts should be generated from protected-only phasing. If protected-only phasing was modeled, the number of unique scenarios would increase by 50 percent, making running and processing the simulations take far longer. It should also be noted that for all PPLT scenarios, the protected portion of the phase was always the leading portion.

Cycle Length

The length of the signal cycle was also accounted for as a variable in the simulations. Cycle lengths from 80 to 240 seconds were tested to capture the most common values used in Virginia for traffic signals. This simulation parameter, along with the subsequent three parameters, was used as a continuous variable in determining the simulation scenarios.

Protected Left-Turn Ratio

The ratio of the protected left-turn phase of PPLT to the cycle length was used as another simulation parameter. It should be noted that the numerator of the ratio includes yellow and all-red times. For example, a protected left ratio of 0.1 and cycle length of 90 seconds would have 0.1*90 seconds = 9 seconds of combined green, yellow, and all-red times. Four levels of the protected left ratio were used in the simulation models: 0.10, 0.15, 0.20, and 0.25. Ultimately, this was reflected in the left-turn mode parameter as one permissive-only left-turn mode (0% protected) and the four levels of PPLT. These levels were selected in consultation with a panel of VDOT traffic engineers as being representative of common PPLT protected portions in Virginia.

Subject Street Split Ratio

Similar to the protected left ratio, the subject street split ratio, or simply split ratio, was calculated as the ratio of the subject street phase duration (the sum of the subject left-turn and opposing through phases) to the cycle length. This number determined the proportion of the cycle length given to the subject street and the remaining time given to the cross street. For example, if the split ratio was 0.6, the subject street would get 60 percent of the cycle and the cross street would get 40 percent of the cycle. It should also be noted that the simulations were set up in a manner that only one approach was identified as the subject left-turn approach and only one approach was identified as the opposing through approach, both of which are on the subject street. The value of split ratios used in the simulation ranged from 0.3 to 0.8. This was deemed to be realistic based on guidance from a panel of VDOT traffic engineers. The split ratio was also a continuous simulation parameter.

Opposing Volume

Opposing through volume, in units of vehicles per hour per lane, is widely accepted as one of the most influential factors with regard to left-turn capacity and safety for permissive left-turn phasing since it determines the number of gaps available to execute left turns. As such, the opposing volume was included in the simulations as a continuous variable from 200 to 1,200 veh/hr/ln. The range of opposing volumes was considered to be appropriate, as opposing volumes less than 200 veh/hr/ln would provide enough safe gaps for permissive left-turning vehicles. Volumes higher than 1,200 veh/hr/ln would likely have few safe gaps; thus, protected-only phasing would be recommended over this value. This parameter was represented in the VISSIM models by changing the "Volume" field in the vehicle inputs attribute for the opposing through lanes link. Since this value was input as vehicles per hour (veh/hr), the desired volumes in vehicles per hour per lane were multiplied by the number of lanes for the scenario before the value was entered.

Average Speed for Opposing Vehicles

The final continuous variable, the speed for opposing through vehicles, ranged from 35 to 55 mph. This parameter was accounted for in the simulations by using it to determine the desired speed distributions. Speeds were modeled as approximately normal with a standard deviation of 5 mph and the minimum and maximum values being the average speed ±10 mph, respectively. The speed was used as a simulation variable since speed limit was determined by other studies to affect permissive left-turn modes.[11, 15, 16, 18–22]

Constants

The percentage of trucks was set to 0.001 in VISSIM to reflect roughly 0 percent trucks, as VISSIM does not allow the value to be exactly zero. This parameter did not vary in the simulations since adjustment factors for different percentages of trucks can be applied after the capacities for an intersection are determined, using factors from the HCM.

Another factor that was held constant throughout the simulations was the percent grade of the approaching roadways. This parameter was not studied as a part of the simulation modeling as the effect of roadway grade on the operations and safety of an intersection is generally understood. Therefore, this parameter can be accounted for by engineers after they receive predictions from the models developed in this study.

Finally, the yellow and all-red clearance times were held constant throughout the scenarios at values of 4 seconds and 1 second, respectively. In the case of PPLT switching from the protected to the permitted portion of the phase, the all-red clearance time was considered the PPLT clearance time, as the red indication was shown only to the left-turn approach rather than to all approaches. This value also was 1 second; thus, when the protected portion of the PPLT phase ended, 4 seconds of yellow and 1 second of red was shown to the left-turn approach before the permitted portion of the phase began.

Experimental Design

Since a full-factorial experimental design would produce millions of simulation scenarios, a sliced Latin Hypercube Design (LHD) was used to determine the combinations of model parameters to simulate. An LHD with N variables produces M random samples from M equally probable intervals for each N. In doing so, exactly one point is selected from each interval of each variable. These values were then permuted to ensure random combinations of the variables, rather than each variable following the same trend (i.e., as Variable A increases, so does Variable B).

LHDs require all variables to be continuous; therefore, a sliced LHD had to be used in developing the simulation scenarios since there were three discrete variables that needed to be modeled (area type, number of opposing lanes, and left-turn mode). In a sliced LHD, a Latin hypercube is created for each combination of discrete variables, considered a slice. For the purpose of the study, 30 slices were created (2 levels of area type × 3 levels of opposing lanes × 5 levels of left-turn mode). In each slice, 25 combinations of the continuous variables were determined using the aforementioned procedure for LHDs. A value of 25 combinations was considered to be sufficient for the purpose of the simulations as it provided the required degree of freedom for a quadratic response surface and provided an acceptable number of observations per dimension.[30] As a result, 750 unique combinations of the seven simulation parameters were used in VISSIM.

VISSIM Model Execution

Once the VISSIM model was calibrated and simulation parameter combinations were selected, simulation runs could be executed. A VISSIM vehicle actuated programming (VAP) file for determining signal timing was created. Since the signal timing variables used in the simulations were tested to determine their impact on left-turn capacity and conflicts, a fixed-time signal plan was used in the VAP file. In running each scenario in the simulations, the VAP file was automatically updated to reflect the combination of phasing mode, protected left-turn ratio, cycle length, and subject street's split ratio variables being simulated through a Perl script. These parameters determined the display sequence and green times given to each intersection approach. In each of the simulation runs for PPLT phasing, the subject street's left-turn approaches started first with the protected portion of their phase. Once this portion's time elapsed, the through movements' green time would start, with the left-turn approaches having permissive time. Once that time elapsed, all of one side street's approaches would go, followed by the all of other side street's approaches, as the side street was set up as split phasing. For the permissive-only runs, a similar sequence would occur, with the exception that the subject street's left-turn approaches were not given any protected green time. Therefore, the subject street's green time consisted of only the two through approaches, with permissive time for the left turns occurring at the same time.

Each of the 750 scenarios was run 10 times in VISSIM using a Perl script to automate the process. The researchers decided that 10 runs would be sufficient, as during the calibration process the minimum sample size for each of the scenarios to which the model was calibrated was calculated at a 95 percent confidence level using the average and standard deviation of the results of 20 runs. As the model runs completed, capacity results were compiled in a spreadsheet for each of the 7,500 simulation runs. To determine the capacity of the simulated left-turn capacity, the left-turn link demand volumes were set to 2,000 veh/hr in the "Vehicle Inputs" asset for the road link to ensure that the lane was oversaturated. By doing this, the counts collected by the data collector for the link were considered to be left-turn capacities, as they were the maximum number of vehicles that could be served by the particular simulation run. All simulation runs lasted for 75 minutes, with 60 minutes of data collection. Data collection did not occur during the first 15 minutes to ensure that the traffic volumes reached equilibrium values. In doing this, accurate simulation runs were produced, and the capacity numbers from the simulations were in units of vehicles per hour. In addition, TRJ files were produced by VISSIM for each run and saved to be analyzed for conflicts in SSAM.

SSAM Conflict Analysis

Since VISSIM models safe driving behavior, traditional measures of safety could not be used to evaluate the models. Therefore, the surrogate safety measures time to collision (TTC) and post encroachment time (PET) were used. TTC is defined as the time remaining until two vehicles would come in contact with each other, based on their trajectories, if they did not alter their paths. PET is the time that elapsed between one vehicle crossing a reference point and the second vehicle crossing that same point. Both of these values help indicate potential conflicts between vehicles.

To determine the number of vehicles that encountered potential conflicts in each simulation run, SSAM was used to process TRJ files from VISSIM. Using the TRJ files, SSAM models each vehicle's trajectory throughout the simulation to determine minimum TTC and PET values for each vehicle's interactions with other vehicles. In doing so, SSAM classifies conflicts into three types based on conflict angles: crossing, rear end, and lane change.[31] When evaluating the TRJ files, SSAM classifies conflicts based on user-defined thresholds. Maximum TTC, maximum PET, rear end conflict angle, and crossing conflict angle were set at 2, 5, 30, and 80, respectively, as these were the default values suggested by the software. Once SSAM processes all of the vehicle trajectories and determines conflicts, the results can be exported as a comma-separated values (CSV) file. This file lists conflicts as separate rows, with the columns indicating information about each conflict such as the TRJ file name, minimum TTC, minimum PET, conflict type, lane information, etc.

Develop Capacity and Conflict Prediction Models

Multiple regression analysis was performed to create models to predict capacity and conflicts based on the simulation results. Separate models were developed for capacity and conflicts for both permissive-only and PPLT control modes using IBM's SPSS Statistics software package and SAS. The following sections describe how the models were created and validated.

Data

The data for each left-turn mode (PPLT and permissive-only) were separated into two subsets of data: cases with non-zero permissive capacities and cases with no permissive capacity (i.e., sneakers only for permissive-only phasing). This was done to separate cases that produced zero conflicts from those that produced non-zero conflicts so that models would fit the data better. In addition, with zero vehicles turning during the permissive portion of PPLT or as non-sneakers for the permissive-only portion, no conflicts were expected; therefore, zero conflicts could be assumed with zero-permissive capacity, yet the conflicts for the other cases still had to be modeled.

Thresholds were determined separately for permissive-only and PPLT phasing modes to determine to which case a simulation scenario belonged. The determination as to whether a scenario produced only sneakers was made by classifying any scenario with greater than a certain “threshold” percentage of its capacity coming from sneakers as a sneakers-only case. This threshold was determined based on the existence of a clear break point in the percent sneaker capacity data. In addition, the average number of conflicts per scenario for each of the TTC and PET thresholds was evaluated to determine which threshold conformed to the fact that zero conflicts should occur when zero vehicles are able to execute a permissive left turn.

Characteristics of the sneakers-only cases were then analyzed to determine combinations of values of the simulation parameters that set these cases apart from the non-sneakers–only cases. Since opposing volume was a continuous variable and is accepted as one of the most influential factors in determining permissive capacities, it was used as a threshold value for different combinations of other variables.

Model Development

After datasets were created for the combinations of permissive-only phasing and PPLT phasing with zero-permissive capacities, and non-zero permissive capacities, more accurate prediction models could be created than for the permissive-only and PPLT models with one set of data each. In addition, it should be noted that the conflict prediction models used normalized conflicts, with the scenario’s left-turn capacity as the method of exposure, to produce the number of conflicts per 100 turning vehicles. With the models predicting number of conflicts per 100 left-turning vehicles, the number of conflicts for a particular scenario can be calculated by multiplying the prediction by the left-turn demand divided by 100. Standard statistical methods including analysis of variance (ANOVA) and stepwise regression were used.

Model Validation

For each of the sets of data, 70 to 80 percent of the data were randomly selected as the training dataset and the remaining data comprised the validation set. The validation was completed by calculating the respective predicted capacities or number of conflicts per 100 left-turning vehicles for each model using the entire dataset (including the training and validation datasets). These predictions were then compared to the actual simulated capacities or number of conflicts and aggregated based on the dataset: build or validation data. Statistics such as mean square prediction error, mean absolute error, mean absolute percent error, and mean bias were compared across the training and validation datasets to ensure each produced a similar result.

Develop Risk Assessment Model for Time-of-Day Safety Analysis

The number of conflicts is not a commonly used safety metric by practitioners. Therefore, a model to assess crash risk based on conflicts was created. In addition, time-of-day safety analysis measures are not currently available to engineers; thus, a risk assessment model based on varying conflicts should be developed. Six intersections in the Southwest region of Virginia were selected to build the risk assessment model, based on availability of complete signal timing and hourly volume data. The number of conflicts, along with SPF-predicted hourly crash rates, was determined using the prediction models created in this study and Virginia-specific SPFs. A model was then developed to relate predicted crash frequencies to conflicts using the data from the intersections. Finally, the model was validated with data that were initially set aside from the model construction dataset.

Data Compilation

The model for assessing crash risk based on number of predicted conflicts was based on data from six intersection sites in the Southwest region of Virginia. These intersections were identified as analysis sites since hourly turning movement counts and signal timing plans were readily available and provided by VDOT traffic engineers. Available data included the workbooks used for the signal studies that were conducted by VDOT, turning movement counts, Synchro file outputs, and other files. Information needed to predict conflicts and crashes needed to be extracted from these files to gather data for model development. Because of a lack of full-day timing plans, PM peak hour timing plans for each intersection were assumed to represent average signal parameters needed for the conflict models throughout the analysis day. Signal timing information needed for the conflict prediction models such as split ratios and cycle lengths were extracted from the Synchro output files for the proposed timing plans for each intersection approach. Left-turn phasing modes for each approach were then determined from the signal study workbooks. Site characteristics, such as speed limits and lane geometries, were also obtained from the files provided. Finally, hourly turning movement counts for all vehicles over a 24-hour period were copied into a spreadsheet. Once information pertinent to each intersection and approach was compiled into one workbook, calculations could be performed to predict conflicts and crashes. A summary of the intersections is provided in Table 6, and specific parameters for the approaches of each intersection are listed in Table 7. With the exception of Intersection F, which was a 3-leg intersection and had PPLT-FYA operations on the southbound leg, all other intersections were 4-leg intersections with protected-only phasing for all left-turn movements. These intersections were under review for FYA implementation (as of May 2016) and the proposed left-turn phasing modes are summarized in Table 6.

Table 6. Characteristics of Intersections Used for Modeling Crash Risk

Site	Intersection[a]	Locality	No. of Legs	Proposed Approach Phasing Modes	Average Cycle Length
A	Main Street and Industrial Park Drive	Montgomery County	4	4 PPLT-FYA	107.5 seconds
B	Main Street and Professional Park Drive	Montgomery County	4	4 PPLT-FYA	88 seconds
C	Route 220 and Route 1290	Roanoke County	4	2 PPLT-FYA, 2 PO	153.1 seconds
D	Route 220 and Route 862	Roanoke County	4	2 PPLT-FYA, 2 PO	162.8 seconds
E	Route 221 and Route 687	Roanoke County	4	3 PPLT-FYA, 1 PO	131.9 seconds
F	Route 220 and Route 789	Roanoke County	3	1 PPLT-FYA	155.7 seconds

PPLT-FYA = protected-permissive left turn with flashing yellow arrow (FYA) for the permissive portion; PO = protected-only.

[a] All intersections are of the urban area type and are located in VDOT's Southwest region. For Intersections A-E, phasing modes are proposed treatments as of May 2016. The recommended treatment at Intersection A was later changed to 2 PPLT-FYA, 2 PO because of limited sight distance on 2 approaches (M. McPherson, unpublished data).

Table 7. Approach-Level Characteristics at Intersections Used for Crash Risk Modeling

Site	Approach	Protected Ratio	Green Ratio	No. of Opposing Lanes	Speed
A	Northbound	0.147	0.612	2	45 mph
	Southbound	0.099			
	Eastbound	0.127	0.388	1	35 mph[a]
	Westbound	0.145			
B	Northbound	0.130	0.698	2	45 mph
	Southbound	0.116			
	Eastbound	0.099	0.302	1	35 mph[a]
	Westbound	0.153			
C	Northbound	0.075[a]	0.736	2	45 mph
	Southbound	0.115			
	Eastbound	-	-	-	-
	Westbound	-			
D	Northbound	0.100	0.790	2	45 mph
	Southbound	0.090			
	Eastbound	-	-	-	-
	Westbound	-			
E	Northbound	0.160	0.510	2	45 mph
	Southbound	0.130			
	Eastbound	0.127	0.490	1	35 mph[a]
	Westbound	-			
F	Northbound	-	0.8[a]	2	45 mph
	Southbound	0.110			
	Eastbound	-	-	-	-
	Westbound	-			

- = Not applicable.

[a] Value was adjusted to fit the model restrictions (e.g., some average speeds were adjusted from 25 mph to 35 mph).

Conflict Calculations

Using the models developed, predicted conflicts were calculated for each hour of the six selected intersections on a left-turn approach level. The conflict prediction model that was used for each hour and each approach was determined by first evaluating whether or not permissive capacity could be provided for the particular phasing mode. If it was determined that no permissive capacity could be provided or the approach operated in protected-only mode, zero conflicts per 100 left-turning vehicles were assumed for that hour; otherwise the appropriate prediction model was used. In addition, if for a particular hour the opposing volumes were outside the range of the 200 to 1,200 veh/hr/ln used in developing the conflict and capacity models, that hour was not used in further development of the models. Predictions of conflicts per 100 left-turning vehicles were then multiplied by the left-turn demands for each hour divided by 100 to find the number of conflicts for that hour. Finally, conflicts were summed across each left-turn approach for the intersection-level conflicts to be used in the crash prediction model development.

Crash Frequency Calculations

Average annual crash frequencies were calculated on an hourly basis for each intersection for comparison with the predicted conflicts. Although a model for predicting these frequencies on an hourly basis does not currently exist, these were estimated using the Virginia-specific SPFs used in the CMF development described previously. To do this, turning movement counts were summed across streets and multiplied by 24 to estimate an equivalent daily volume for each hour. Next, annual crashes were predicted using turning movement counts for the entire 24-hour period, representing estimated AADT values, and were used in calculating crash frequencies for a "true" prediction of daily crashes. The previously calculated hourly crash frequencies were then normalized by multiplying them by the true crash frequency for the day divided by the sum of the hourly crash frequencies over the 24 hours. In doing so, the sum of the normalized crash counts across the 24 hours was equal to the annual crash count based on the daily traffic. These counts represented the number of crashes that would be expected in that hour if the characteristics of that hour were the same throughout the course of a year. Although this is not a perfect estimate of traffic safety, it does provide a scalable metric that can be used to assess relative safety based on volume.

Similar to the approach used in developing CMFs, base conditions were adjusted for by calculating base CMFs for the site-specific characteristics defined in the HSM, including left-turn phasing. Once the SPF-predicted crash rates were calculated for each hour, the base CMFs were applied. In addition, the percentages of angle crashes found during CMF development were multiplied by the predictions to determine the predicted number of angle crashes, the target crash type to be compared to left-turn conflicts. Values of 43% for 3-leg intersections and 53% for 4-leg intersections were assumed based on data from the CMF development phase of the study.

Model Development and Validation

A model to predict the number of yearly crashes for a particular hour at an intersection based on that hour’s conflict predictions was developed in SPSS and SAS using a similar process as in the development of the conflict and capacity models described previously. Three main steps were taken: transformations of the conflicts variable, model selection, and model validation. Data used in the models consisted of each hour’s conflicts and estimated crashes for all sites for which conflicts were able to be calculated for each approach as the independent and dependent variables, respectively.

An additional check was completed to determine the difference in the SPF-predicted crashes and the model-predicted crashes aggregated within the sites. In addition, the model was compared with a previously computed model developed by Gettman et al.[31]

Develop Spreadsheet Tool for Practitioners

With models to predict left-turn capacities, conflicts, and crash risk for permissive-only and PPLT left-turn phasing modes having been developed, a spreadsheet tool was created to assist traffic engineers in using the models for intersections they want to analyze. The tool requires users to input static input parameters, timing variables, and volume counts for each analysis hour. Then, the spreadsheet calculates the left-turn capacities, v/c ratios, number of conflicts per 100 left-turning vehicles, and crash risk using the appropriate models, assumptions, and calculations determined previously. Finally, capacities and crash risk are plotted for each analysis hour in separate graphs for a visual representation of the operational and safety variations across a typical day. This spreadsheet tool is intended to aid field engineers in their decisions regarding left-turn mode choices rather than to define strict guidelines.

Predictions

Left-Turn Capacity

Capacities for the left-turn movements were calculated for each analysis hour for three different phasing modes: PPLT, permissive-only, and protected-only. For PPLT and permissive-only cases, appropriate model equations were used to complete these calculations. If for a particular hour the opposing volume was outside the range of 200 to 1,200 veh/hr/ln established in model development, the capacities for that hour for PPLT and permissive-only modes were left blank. Protected-only capacities were calculated using Equation 14, derived from the HCM, with the 1.05 term representing a left-turn factor for saturation flow rate.

$$c_{protected-only}=\left(\frac{G}{C_{prot}}-\frac{l}{C}\right)\frac{s}{1.05} \qquad \text{[Eq. 14]}$$

where

$\frac{G}{C_{prot}}$ = protected green ratio (decimal)
l = loss time (yellow and all red time + 2 s) (s)

C = cycle length (s)
s = ideal saturation flow rate: 1,900 for urban and 1,750 for rural (veh/hr/ln).

Volume-to-Capacity Ratio

For easy identification of the percentage of capacity being used by the demand left-turn volume for each hour and each phasing mode, v/c ratios were calculated. This was done by dividing the demand left-turn volume by the capacities produced previously. In cases where PPLT and permissive-only capacities were not calculated because of the opposing volumes being outside the appropriate range, the v/c ratio for that hour was left blank for these two modes. In addition, conditional formatting was set in the Excel spreadsheet tool such that v/c ratios greater than 1.0 were automatically highlighted in red to identify cases where the phasing mode could not provide enough capacity to process all vehicles in that hour.

Conflicts per 100 Left-Turning Vehicles

Using the models developed in this study, the number of conflicts per 100 left-turning vehicles was calculated for each hour for the PPLT and permissive-only phasing control modes. As the study did not simulate protected-only scenarios and conflict prediction models are not currently available for this mode, predictions were not made for protected-only phasing. Left-turn conflicts are expected to be minimal for protected phasing, though. Using these values, the number of conflicts in an hour can be determined by multiplying the prediction by the left-turn demand volume divided by 100. As with the capacity and v/c ratio calculations, hours with opposing volumes outside the modeled range were left blank for the calculation of conflicts per 100 left-turning vehicles.

Crash Risk

The average number of annual angle crashes was calculated for each set of conditions to illustrate the relative risk of permissive-only and PPLT modes over the course of a typical day with changing conditions. This was done by using the crash risk assessment model, described in the previous section, with the number of conflicts generated by the left-turn conflict prediction model as input. Again, hours with opposing volumes less than 200 veh/hr/ln or greater than 1,200 veh/hr/ln were left blank for these predictions. In addition, it should be noted that these predictions represent the number of crashes predicted for a year if the same conditions existed for the entire year; therefore, the relative magnitude of these predictions when compared across control mode and hour is more important than the values themselves. Because of this, the outputs from this model should be used in evaluating relative risk rather than in predicting crashes.

Graphs

The final step in developing the spreadsheet tool was to create scatterplots that illustrated how left-turn capacities and angle crash risk varied throughout the analysis period. In both graphs, the x-axis represented the hour of the day, from 0 to 23, representing midnight to 11 PM. The y-axis for the capacity graph represented the predicted left-turn capacity, in vehicles per hour, and for the crash frequency graph represented the average annual angle crash frequency, in crashes per year. In the capacity plot, predicted capacities for each of the three left-turn phasing control modes, as well as the left-turn demand for each hour, were shown. For the crash frequency graph, predicted angle crash frequencies for PPLT and permissive-only modes were plotted.

RESULTS AND DISCUSSION

Before-After FYA Safety Analysis

EB Analysis and Results

The results of the EB analysis are summarized in Table 8. As shown, the PPLT to PPLT-FYA conversion created a 19 percent reduction in angle crashes (all severities), which was statistically significant at the 90 percent confidence level. The changes were not statistically significant.

Table 8. Summary of Results of Empirical Bayes Analysis

Crash Type	Crash Reduction Rate (*R*)	Crash Modification Factor (CMF)	Standard Error
Total crashes	0.00	1.00	0.079
Fatal and injury crashes	-0.07	1.07	0.135
Angle crashes	0.19	0.81*	0.101

*Indicates CMF is statistically significant at the 90% confidence level.

FB Analysis and Results

The results of the FB analysis are summarized in Table 9. The results indicated a fairly high reduction of 30 percent in angle crashes and relatively modest reductions in total crashes (12%) and fatal and injury crashes (14%).

Although the average reduction in fatal and injury crashes was fairly substantial, the researchers did not rule out potential increases in fatal and injury crashes following conversion from PPLT to PPLT-FYA as the 95 percent credible interval for the fatal and injury crash reduction rate included zero (no safety effects) and negative values (increased crashes).

Table 9. Crash Reduction Rates for Full Bayes Analysis

Crash Type	Mean	Standard Error	Median	95% Credible Interval	
				2.50%	97.50%
Total crashes	0.119	0.053	0.122	0.010	0.216
Fatal and injury crashes	0.137	0.079	0.140	-0.032	0.283
Angle crashes	0.301	0.066	0.304	0.162	0.421

Discussion

A reliable CMF was calculated using the EB method for angle crashes (all severities); CMF estimates for total crashes (all types and severities) and fatal and injury crashes (all types) were not statistically significant. Using the FB approach, reliable CMFs were obtained for total crashes and angle crashes (all severities). The CMF for fatal and injury crashes (all types) was

0.86, which is similar to the CMF of 0.85 obtained by Simpson and Troy.[8] However, the central 95 percent credible interval did not rule out the possibility of CMFs greater than one (increased crashes).

The results also indicated that the FB approach can provide similar results to the EB approach; the statistically significant angle crash reduction rate estimated by the EB approach was within the central 95 percent credible set of the corresponding FB estimate. In addition, even with the relatively small sample of conversion sites, the 95 percent credible sets for expected crash reduction rates estimated with the FB method are relatively narrow as compared to the EB results, suggesting that CMFs are estimated with a good degree of confidence. This is consistent with the thought that the FB can have an advantage over the EB when the sample size is restricted because of cost and other practical limitations.[23, 32]

When the results of this study and the CMFs developed by Srinivasan et al.[13] and Simpson and Troy[8] were compared, it was seen that the estimated 12 percent (1% to 22%) reduction in total crashes for the PPLT to PPLT-FYA conversion was consistent with the 12 percent and 6 percent estimates by Srinivasan et al.[13] and Simpson and Troy,[8] respectively. Srinivasan et al.[13] also reported a 19 percent decrease in left-turn crashes following conversion from PPLT to PPLT-FYA. Left-turn crashes were not studied; instead, angle crashes were analyzed because information on angle crashes is more readily accessible by VDOT engineers. It is worth noting that the expected decrease in left-turn crashes of 19 percent obtained by Srinivasan et al.[13] and the expected decrease in target crashes (crashes involving left-turning vehicles and opposing through vehicles) of 22 percent reported by Simpson and Troy[8] are both consistent with the 30 percent (16% to 42%) expected decrease in angle crashes obtained in this study. The expected reduction in fatal and injury crashes of 14 percent (-3% to 28%) following FYA conversion is also consistent with the 15 percent reduction reported by Simpson and Troy.[8]

VISSIM Model Calibration and Simulation Output

Model Calibration

To ensure that the saturation flow rates for the urban and rural cases were consistent with values provided in the HCM, the reciprocals of the average simulated headways (saturation flow rates) for both the left-turn movement and through traffic were compared to their HCM equivalents. It was found that a value of 4.00 for the multiplicative part of desired safety distance and a value of 3.25 for the additive part of desired safety distance were optimal for urban saturation flow rates and that values of 4.75 and 3.75, respectively, were optimal for rural saturation flow rates.

To ensure that the simulation model produced accurate capacity estimates, the HCM-calculated permissive capacity corresponding to each scenario was determined and the values were compared to the outputs of one simulation run per scenario. Based on these comparisons, front gap–rear gaps of 0.6 for opposing volumes of 400 veh/hr/ln or less and 0.3 for opposing volumes higher than 400 veh/hr/ln were considered optimal. Simulations were run 19 more times per scenario with the optimal front gap–rear gap values to ensure consistent results. This produced average HCM and simulated permissive left-turn capacities and percent errors, shown in Table 10.

Table 10. Final Capacity Calibration Results

Opposing Volume	Rural			Urban		
	HCM	**Simulation**	**% Error**	**HCM**	**Simulation**	**% Error**
100	827	877	6%	829	925	12%
200	677	689	2%	681	715	5%
400	448	413	-8%	456	419	-8%
600	292	287	-2%	302	289	-4%
800	186	173	-7%	198	172	-13%
1,000	116	107	-8%	128	106	-17%
1,200	85	74	-14%	94	79	-16%

HCM = *Highway Capacity Manual*.[28]

Capacity and Conflict Results

Once the TRJ files were processed with SSAM, roughly 2 million to 3 million conflicts were obtained. Since the target conflict type for left turns was the crossing conflict type, rear end and lane change conflicts had to be removed from the files. To do this, an executable Java program was developed to scan through each CSV file and remove lines that corresponded to non-crossing conflict types. As a result, roughly 860,000 crossing conflicts were found, although more than 90 percent had TTC or PET values of 0, that would be considered “crashes.” Since crashes cannot occur in VISSIM, Gettman et al. indicated that these values are errors in SSAM processing and should be removed.[31] In addition, it was observed in the current study that in many instances, vehicle identifications were found in more than one conflict. Since only one conflict record should exist per turning vehicle, duplicates were removed. After data filtering, a total of 64,000 conflicts were identified across the 7,500 simulation runs.

A final Excel workbook was created that included capacity and conflict data from VISSIM and SSAM at two levels: a simulation run level (7,500 runs), and an aggregate scenario level (750 scenarios). Data in both spreadsheets included VISSIM simulation parameters, capacities, and counts of conflicts with TTC less than or equal to 0.5, 1, 1.5, and 2 and counts of conflicts with PET less than or equal to 2.5, 3, 3.5, 4, and 4.5. For the simulation run level, there were 7,500 rows of data corresponding to each of the 10 runs for the 750 scenarios. The scenario-level sheet had 750 rows of data corresponding to average values of the number of conflicts and capacities for the 10 runs of each scenario. Ultimately, the aggregate data across each of the simulation iterations for separate scenarios were used for further analysis.

Left-Turn Capacity and Conflict Models

Separation of Datasets

Scenarios with greater than 90 percent of their capacity coming from sneakers were categorized as sneakers-only cases. This threshold was defined because of a clear break in the data (i.e., there were many scenarios with 90 percent and one scenario with 80 to 90 percent; the rest of the data had less than 80 percent). In addition, it was determined that the case where TTC was less than or equal to 2 seconds matched the assumption that when there was zero-permissive capacity, zero conflicts should occur. Because of this, the average number of conflicts with TTC less than or equal to 2 was selected as the average number of conflicts per scenario for all of the models.

Combinations of subject street green ratio and opposing volume were examined to identify thresholds above which only sneakers were present. These thresholds are shown in Table 11. They established the maximum opposing volumes, inclusive of the value, to which non-zero permissive capacities can be realized based on the subject street's percentage of the signal cycle. The set of thresholds for PPLT that produced the most accurate result with the fewest combinations of parameters was the combination of protected green ratio and subject street green ratio. As with the permissive-only dataset, the thresholds established maximum opposing volumes, inclusive of the value, to which non-zero permissive capacities are found based on the subject street's and the subject left-turn's protected portion percentage of the signal cycle. These thresholds are provided in Table 12.

Table 11. Sneakers-Only Thresholds for Permissive-Only Phasing

Subject Street Green Ratio	Opposing Volume (veh/hr/ln)
0.3	450
0.4	625
0.5	875
0.6	900
0.7	1,000
0.8	1,100

Table 12. Zero-Permissive Capacity Thresholds for Protected-Permissive Phasing

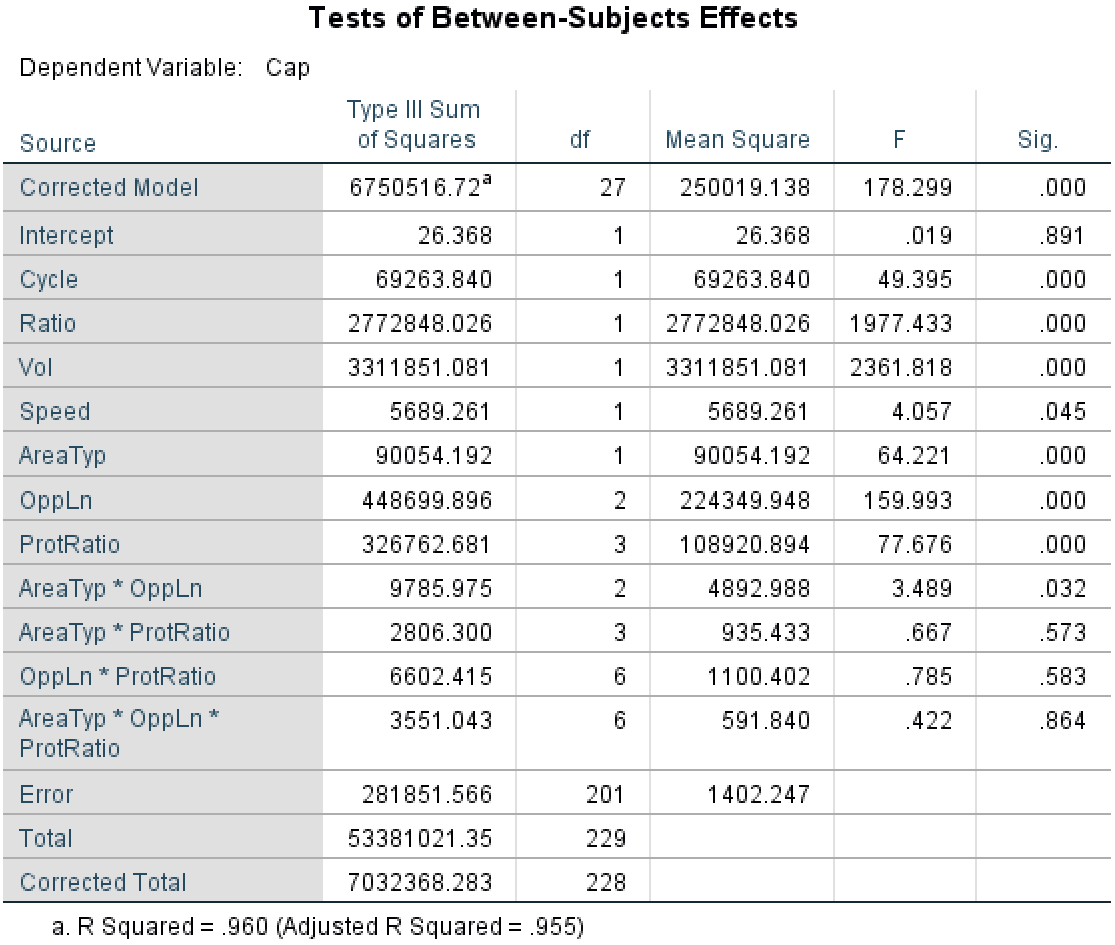
Protected Green Ratio	Subject Street Green Ratio	Opposing Volume (veh/hr/ln)
0.1	0.3	250
	0.4	450
	0.5	625
	0.6	825
	0.7	975
	0.8	975
0.15	0.3	0
	0.4	300
	0.5	550
	0.6	700
	0.7	925
	0.8	975
0.2	0.3	0
	0.4	0
	0.5	475
	0.6	625
	0.7	700
	0.8	900
0.25	0.3	0
	0.4	0
	0.5	400
	0.6	525
	0.7	600
	0.8	900

Left-Turn Capacity Models

Three left-turn capacity prediction models were created using SPSS corresponding to non-zero permissive capacity cases of PPLT, zero-permissive capacity cases of PPLT, and non-zero permissive capacity cases of permissive-only phasing. The zero-permissive capacity cases (sneakers-only cases) for permissive-only phasing were not modeled, as capacities for these cases could be calculated using Equation 13. In each case, regressions assumptions were checked for the best fit models and the models were validated.

PPLT Capacity Model for Non-Zero Permissive Capacities

As shown in Figure 8, ANOVA results indicated that area type, opposing lanes, protected green ratio, cycle length, green ratio, opposing volume, and speed had a statistically significant impact on capacity, as they had significance values less than 0.05.



Tests of Between-Subjects Effects

Dependent Variable: Cap

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	6750516.72[a]	27	250019.138	178.299	.000
Intercept	26.368	1	26.368	.019	.891
Cycle	69263.840	1	69263.840	49.395	.000
Ratio	2772848.026	1	2772848.026	1977.433	.000
Vol	3311851.081	1	3311851.081	2361.818	.000
Speed	5689.261	1	5689.261	4.057	.045
AreaTyp	90054.192	1	90054.192	64.221	.000
OppLn	448699.896	2	224349.948	159.993	.000
ProtRatio	326762.681	3	108920.894	77.676	.000
AreaTyp * OppLn	9785.975	2	4892.988	3.489	.032
AreaTyp * ProtRatio	2806.300	3	935.433	.667	.573
OppLn * ProtRatio	6602.415	6	1100.402	.785	.583
AreaTyp * OppLn * ProtRatio	3551.043	6	591.840	.422	.864
Error	281851.566	201	1402.247		
Total	53381021.35	229			
Corrected Total	7032368.283	228			

a. R Squared = .960 (Adjusted R Squared = .955)

Figure 8. ANOVA Results for PPLT Capacity Model for Non-Zero Permissive Capacities

After ANOVA, models for predicting capacity were developed. Although speed was a variable found to be statistically significant in ANOVA, it was later removed from the model, as it did not add predictive value when stepwise regression was performed. The final model that provided the best fit for the data is shown in Equation 15. An adjusted R^2 value of 0.956 resulted from this model form, indicating a good fit.

$$\begin{aligned} c = 128.5 + (39.6 * URB) + (120.2 * LN1) + (54.0 * LN2) - (109.8 * PP10) \\ - (66.21 * PP15) - (33.51 * PP20) - \left(\frac{10540}{C}\right) + \left(1119 * \frac{G}{C}\right) \\ - (0.7103 * q) \end{aligned} \qquad \text{[Eq. 15]}$$

where

c = left-turn capacity (veh/hr)
URB = area type dummy variable (1 for urban)
LN_1 = one opposing lane dummy variable (1 for one opposing lane)
LN_2 = two opposing lanes dummy variable (1 for two opposing lanes)
PP_{10} = PPLT with 0.10 protected ratio dummy variable
PP_{15} = PPLT with 0.15 protected ratio dummy variable
PP_{20} = PPLT with 0.20 protected ratio dummy variable
C = cycle length (sec)
G/C = subject street green ratio
q = opposing volume (veh/hr/ln).

For the validation phase of this model, mean square prediction error (MSPE), mean absolute error (MAE), mean absolute percent error (MAPE), and mean bias were calculated for both the training and validation datasets and are shown in Table 13. The model validation showed acceptable results, with similar and reasonable error levels.

Table 13. Validation Results for Protected-Permissive Left-Turn Capacity Models for Non-Zero Permissive Capacities

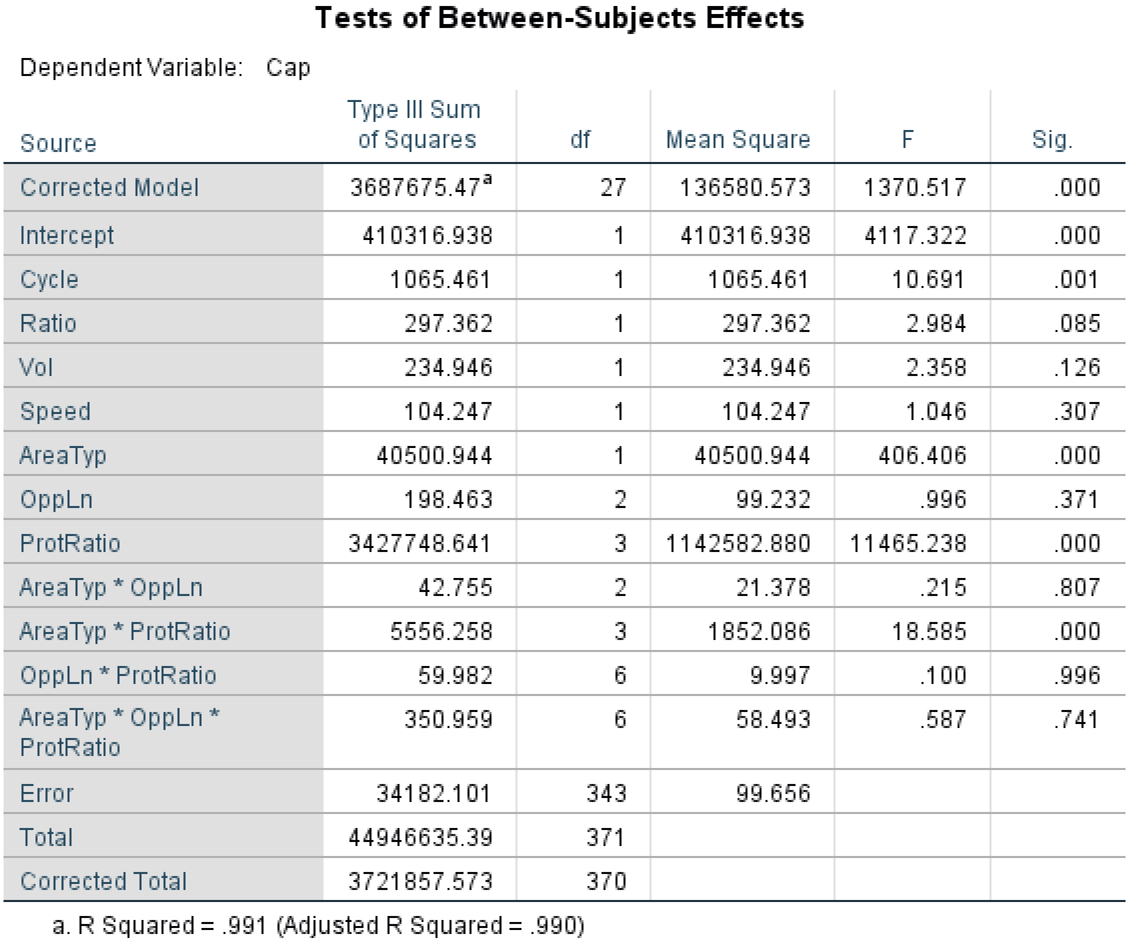
Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	182	1316.1	27.33	6.02%	0.00
Validation	47	1385.6	30.42	6.98%	1.23

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

PPLT Capacity Model for Zero-Permissive Capacities

The ANOVA results for the PPLT model when permitted capacity is zero are shown in Figure 9. Area type, protected green ratio, and cycle length had a statistically significant effect on capacity.

The results of the stepwise regression for the capacity model are shown in Equation 16. This model form produced a 0.990 adjusted R^2 value. Table 14 lists the results from validating the model for this dataset. Validation results again showed good performance, as the error statistics for the validation and build datasets were reasonably close to one another.



Tests of Between-Subjects Effects

Dependent Variable: Cap

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	3687675.47^a	27	136580.573	1370.517	.000
Intercept	410316.938	1	410316.938	4117.322	.000
Cycle	1065.461	1	1065.461	10.691	.001
Ratio	297.362	1	297.362	2.984	.085
Vol	234.946	1	234.946	2.358	.126
Speed	104.247	1	104.247	1.046	.307
AreaTyp	40500.944	1	40500.944	406.406	.000
OppLn	198.463	2	99.232	.996	.371
ProtRatio	3427748.641	3	1142582.880	11465.238	.000
AreaTyp * OppLn	42.755	2	21.378	.215	.807
AreaTyp * ProtRatio	5556.258	3	1852.086	18.585	.000
OppLn * ProtRatio	59.982	6	9.997	.100	.996
AreaTyp * OppLn * ProtRatio	350.959	6	58.493	.587	.741
Error	34182.101	343	99.656		
Total	44946635.39	371			
Corrected Total	3721857.573	370			

a. R Squared = .991 (Adjusted R Squared = .990)

Figure 9. ANOVA Results for Protected-Permissive Left-Turn Capacity Model for Zero-Permissive Capacities

$$c = 406.5 + (22.10 * URB) - (275.0 * PP10) - (179.6 * PP15) - (89.09 * PP20) + (0.5015 * C) - (0.00166 * C^2) \quad \text{[Eq. 16]}$$

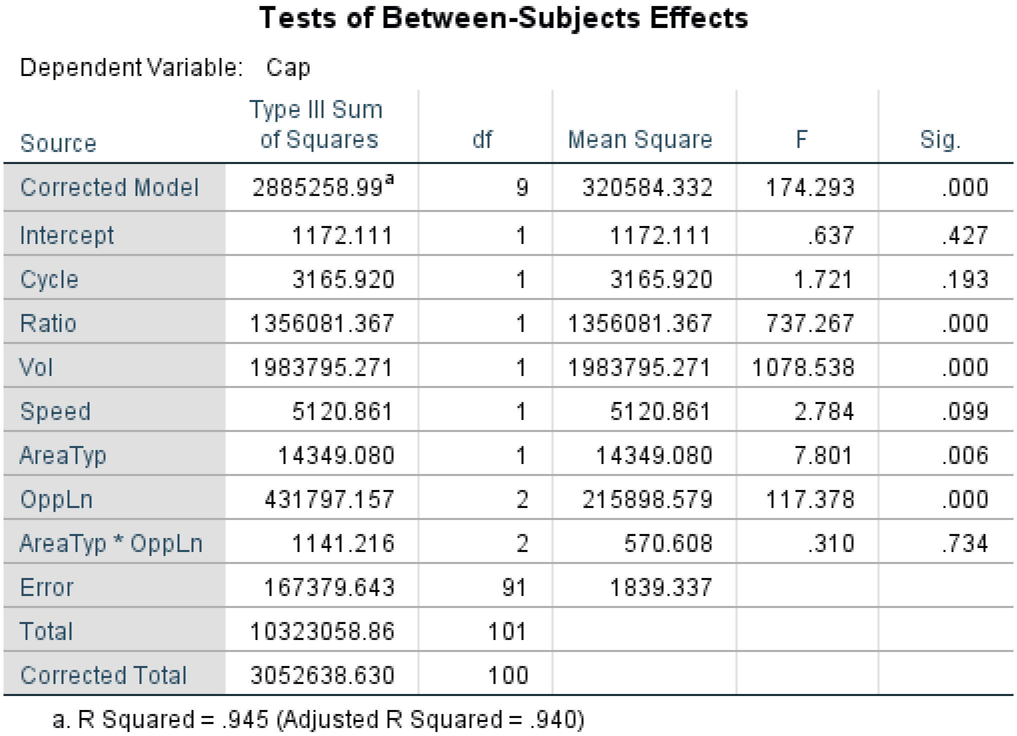
Table 14. Validation Results for Protected-Permissive Left-Turn Capacity Models for Zero-Permissive Capacities

Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	290	97.8	7.68	2.33%	-0.01
Validation	81	109.9	8.01	2.33%	0.28

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

Permissive-Only Capacity Model for Non-Zero Permissive Capacities

The ANOVA results for permitted phasing where the permitted capacity is greater than zero are shown in Figure 10. Area type, opposing lanes, green ratio, and opposing volume had statistically significant impacts on mean capacity.



Tests of Between-Subjects Effects

Dependent Variable: Cap

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	2885258.99[a]	9	320584.332	174.293	.000
Intercept	1172.111	1	1172.111	.637	.427
Cycle	3165.920	1	3165.920	1.721	.193
Ratio	1356081.367	1	1356081.367	737.267	.000
Vol	1983795.271	1	1983795.271	1078.538	.000
Speed	5120.861	1	5120.861	2.784	.099
AreaTyp	14349.080	1	14349.080	7.801	.006
OppLn	431797.157	2	215898.579	117.378	.000
AreaTyp * OppLn	1141.216	2	570.608	.310	.734
Error	167379.643	91	1839.337		
Total	10323058.86	101			
Corrected Total	3052638.630	100			

a. R Squared = .945 (Adjusted R Squared = .940)

Figure 10. ANOVA Results for Permissive-Only Capacity Model for Non-Zero Permissive Capacities

The final model that provided the best fit for this dataset is in Equation 17. The model had an adjusted R^2 value of 0.926; the validation results are shown in Table 15. Validation results were within 13 percent, and the validation dataset proved to fit the models better in all categories except for mean bias, which showed a 16-vehicle underprediction overall.

$$c = 246.2 + (26.05 * URB) + (161.8 * LN1) + (64.77 * LN2) + \left(844.4 * (\frac{G}{C})^2\right) - (0.6788 * q) \qquad \text{[Eq. 17]}$$

Table 1. Validation Results for Permissive-Only Capacity Models for Non-Zero Permissive Capacities

Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	80	1903.0	34.47	12.95%	0.00
Validation	21	1892.4	30.77	11.15%	-15.62

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

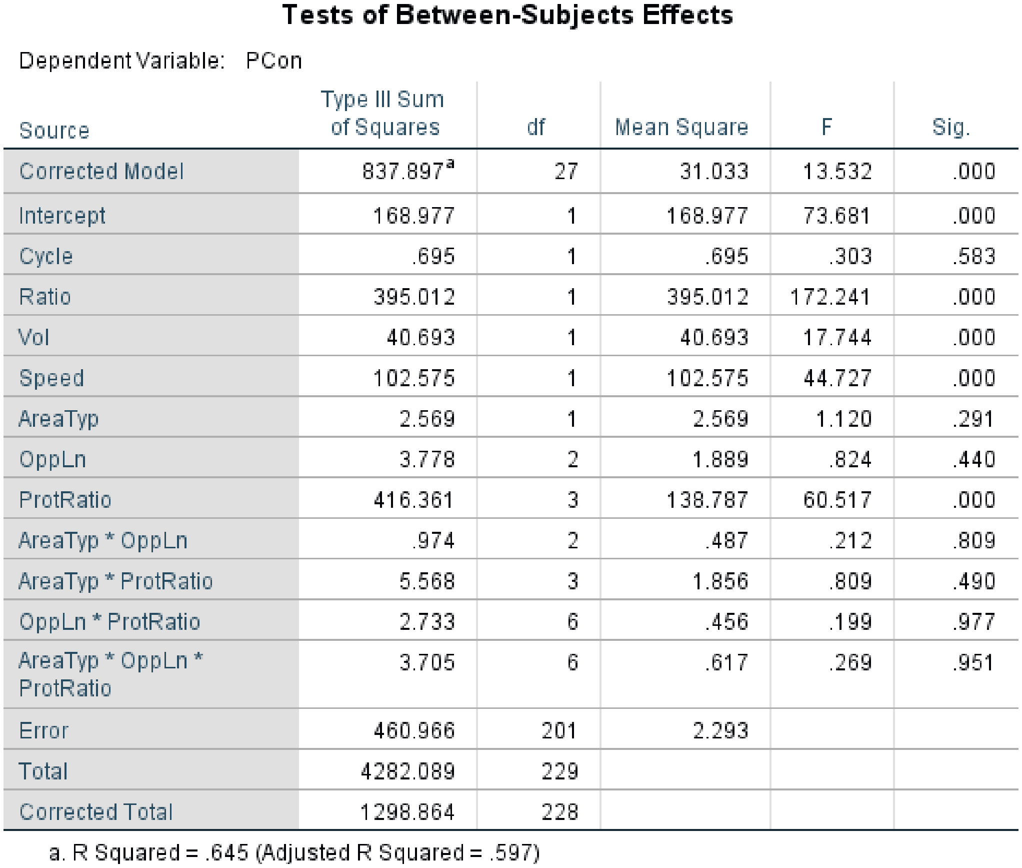
Left-Turn Conflict Models

Two left-turn conflict prediction models were created using SPSS and SAS corresponding to non-zero permissive capacity cases of PPLT and non-zero permissive capacity cases of permissive-only phasing. The zero-permissive capacity cases for permissive-only and PPLT phasing modes were not modeled, as conflicts for these cases were assumed to be zero. For both models, model fits were not as good as with the capacity models (in terms of MAPE), but they still produced acceptable results. In addition, regression assumptions were met, and validation was performed.

PPLT Left-Turn Conflict Model for Non-Zero Permissive Capacities

Figure 11 shows the ANOVA results for PPLT conflicts when the permitted capacity is greater than zero. Protected green ratio, subject street green ratio, opposing volume, and speed had statistically significant effects on conflicts.

Equation 18 shows the conflict prediction model that was produced from Poisson regression using SAS. The model had deviance-to–degrees of freedom and Pearson Chi Square–to-degrees of freedom ratios that did not deviate too far from 1 (1.146 and 1.039, respectively), indicating a good fit.[33] Although validation results (see Table 16) were relatively worse for conflict prediction models than for capacity models, the large percentage errors are attributable to the small magnitudes of conflicts. In addition, the build and validation datasets closely matched in terms of the statistics calculated, indicating the model fit each dataset similarly.



Tests of Between-Subjects Effects

Dependent Variable: PCon

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	837.897[a]	27	31.033	13.532	.000
Intercept	168.977	1	168.977	73.681	.000
Cycle	.695	1	.695	.303	.583
Ratio	395.012	1	395.012	172.241	.000
Vol	40.693	1	40.693	17.744	.000
Speed	102.575	1	102.575	44.727	.000
AreaTyp	2.569	1	2.569	1.120	.291
OppLn	3.778	2	1.889	.824	.440
ProtRatio	416.361	3	138.787	60.517	.000
AreaTyp * OppLn	.974	2	.487	.212	.809
AreaTyp * ProtRatio	5.568	3	1.856	.809	.490
OppLn * ProtRatio	2.733	6	.456	.199	.977
AreaTyp * OppLn * ProtRatio	3.705	6	.617	.269	.951
Error	460.966	201	2.293		
Total	4282.089	229			
Corrected Total	1298.864	228			

a. R Squared = .645 (Adjusted R Squared = .597)

Figure 11. ANOVA Results for PPLT Conflict Model for Non-Zero Permissive Capacities

$$
\begin{aligned}
con_{100} = \exp\Bigg(& 1.091 - (0.08925 * LN1) - (0.3662 * PP15) + (0.7329 * PP20) \\
& - (0.9970 * PP25) + \left(5.828 * \left[\frac{G}{C} - 0.5\right]\right) \\
& - (1.984x10^{-3} * [q - 500]) + (0.03347 * [S - 45]) \\
& - \left(4.616 * \left[\frac{G}{C} - 0.5\right]^2\right) - (6.386x10^{-3} * [q - 500]^2) \\
& + \left(9.622x10^{-3} * [q - 500] * \left[\frac{G}{C} - 0.5\right]\right)\Bigg)
\end{aligned}
\qquad \text{[Eq. 18]}
$$

where

con_{100} = number of conflicts per 100 left-turning vehicles
S = average opposing speed.

Table 16. Validation Results for Protected-Permissive Left-Turn Conflict Models for Non-Zero Permissive Capacities

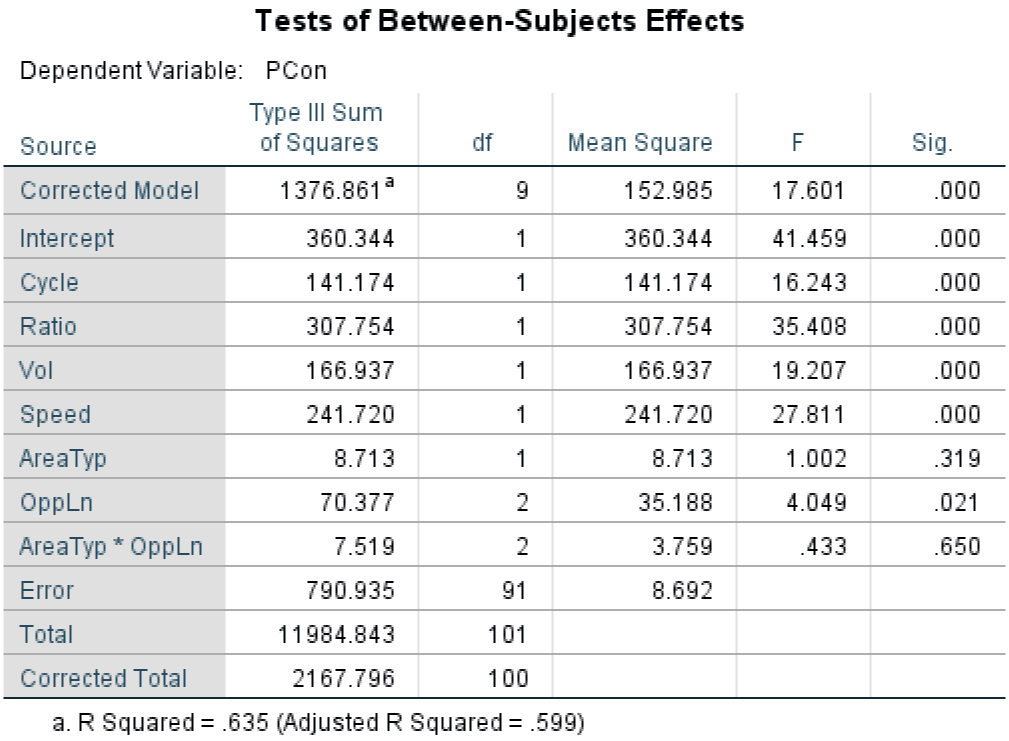
Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	183	0.9	0.70	19.54%	-0.01
Validation	46	1.0	0.71	19.10%	0.14

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

Permissive-Only Left-Turn Conflict Model for Non-Zero Permissive Capacities

Figure 12 shows the ANOVA results for conflicts for permitted phasing with a non-zero permitted capacity. Number of opposing lanes, cycle length, green ratio, opposing volume, and speed had statistically significant effects on left-turn conflicts.

Next, Poisson regression was used to create a model to predict conflicts when capacities are not zero. The final model for conflicts per 100 left-turning vehicles is shown in Equation 19. This model had deviance-to–degrees of freedom and Pearson Chi Square–to-degrees of freedom ratios equal to 0.682 and 0.650, respectively, indicating a relatively good fit. The results from model validation are shown in Table 17. Again, large percent errors can be attributed to the small magnitudes of conflicts. In addition, the validation dataset appeared to have fit the model about as well as the build dataset, indicating a consistent performance of the model.



Tests of Between-Subjects Effects

Dependent Variable: PCon

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1376.861[a]	9	152.985	17.601	.000
Intercept	360.344	1	360.344	41.459	.000
Cycle	141.174	1	141.174	16.243	.000
Ratio	307.754	1	307.754	35.408	.000
Vol	166.937	1	166.937	19.207	.000
Speed	241.720	1	241.720	27.811	.000
AreaTyp	8.713	1	8.713	1.002	.319
OppLn	70.377	2	35.188	4.049	.021
AreaTyp * OppLn	7.519	2	3.759	.433	.650
Error	790.935	91	8.692		
Total	11984.843	101			
Corrected Total	2167.796	100			

a. R Squared = .635 (Adjusted R Squared = .599)

Figure 12. ANOVA Results for Permissive-Only Conflict Model for Non-Zero Permissive Capacities

$$
\begin{aligned}
con_{100} = exp\Bigg(& 2.244 - (0.2979 * LN1) + (1.335x10^{-3} * [C - 90]) \\
&+ \left(1.119 * \left[\frac{G}{C} - 0.5\right]\right) + (1.427x10^{-3} * [q - 500]) \\
&+ (0.02094 * [S - 45]) - (3.978x10^{-6} * [q - 500]^{2}) \\
&+ \left(2.673x10^{-3} * [q - 500] * \left[\frac{G}{C} - 0.5\right]\right)\Bigg)
\end{aligned}
\qquad \text{[Eq. 19]}
$$

Table 17. Validation Results for Permissive-Only Conflict Models for Non-Zero Permissive Capacities

Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	72	5.2	1.51	15.67%	0.24
Validation	28	4.3	1.58	14.52%	0.15

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

Summary

Three capacity and two conflict models were created in this portion of the study, representing capacity models for non-zero permissive capacities for PPLT, zero-permissive capacities for PPLT, and non-zero permissive capacities for permissive-only phasing, as well as conflict models for non-zero permissive capacities for both PPLT and permissive-only phasing. Coefficients were reasonable in magnitude and sign for each of the models. In addition, all regression assumptions were checked and found to be unviolated.

The three remaining phasing mode predictions were derived from assumptions, rather than modeled using regression. For developed scenarios over the thresholds for the permissive-only mode, a capacity consisting of only sneakers was assumed (two sneakers per cycle), as these were defined as zero-permissive capacity cases in determining the thresholds. For cases with zero-permissive capacities for PPLT and permissive-only phasing, it can also be assumed that zero conflicts will occur. Though these cases were determined from the simulations to have zero conflicts, this does not indicate that these situations are safe for left-turning drivers. As mentioned earlier in this section, cases with zero-permissive capacity are not necessarily safe because of driver habits, such as being impatient or misjudging gaps in opposing traffic; therefore, traffic engineers should carefully evaluate these cases to determine if permissive phasing of any type is appropriate.

Risk Assessment Model for Time-of-Day Safety Analysis

A model to predict the number of yearly crashes for a particular hour at an intersection based on that hour's conflict predictions was developed in SAS. Data used in the models consisted of each hour's conflicts and estimated crashes for all sites for which conflicts were able to be calculated for each approach (81 total hours) as the independent and dependent variables, respectively. Further, hours for which the estimated crashes exceeded the number of conflicts were excluded from model development. This process reduced the total number of hours of data to 42 (including 9 for Site B, 16 for Site C, 15 for Site D, 2 for Site E, and none for Sites A and F). Approximately 75 percent of the data were used to build the model, and the rest of the data were used as hold-back data for validation.

In determining the best model for predicting annual crash frequencies based on the number of conflicts, a final nonlinear model was found and is shown in Equation 20. The results from model validation, which include statistics from the build and validation datasets, are shown in Table 18. An adjusted R^2 value for this model was determined to be 0.785, and errors calculated were 23 percent and 19 percent for the build and validation data, respectively. Model validation provided similar results for the two datasets.

It is also important to note that a prediction from this model represents an annual crash rate that would result from a constant level of conflicts over the course of an entire year for the corresponding hour of the day; therefore, these results should be used mostly as a relative risk measure rather than as an estimate of annual crash rates.

$$Annual\ crashes\ per\ hour = e^{-0.2545} * (Number\ of\ conflicts\ per\ hour)^{0.7345} \quad \text{[Eq. 20]}$$

Table 18. Validation Results for Crash Model

Dataset	N	MSPE	MAE	MAPE	Mean Bias
Build	32	1.3	0.85	22.67%	-0.07
Validation	10	1.1	0.85	18.91%	0.02

MSPE = mean square prediction error; MAE = mean absolute error;
MAPE = mean absolute percent error.

In addition to the standard model validation process, the crash predictions produced by the risk assessment model were compared across the sites used to build the model (see Table 19). As with the mean bias shown previously, the percent difference across all sites was 1 percent, meaning the overpredictions for some sites mostly matched the underpredictions for others. Sites B through D performed similarly, with Site E proving to be different. This difference may be explained by the number of approaches with PPLT-FYA, as this site had an odd number of legs treated. However, only 2 hours of usable data were available for this site, so further investigation may be needed. From these results, 4-leg intersections with all legs treated (Site B) performed the best with the model created and the 4-leg intersections with two legs treated (Sites C and D) had absolute percent errors similar to those for the entire dataset, so they had acceptable performance. All crash predictions were within 3 crashes/year of what was predicted by the SPF.

The model developed in this study was compared to the crash prediction model developed by Gettman et al.[31] shown by Equation 21. Predictions using the conflict data in this portion of the study were made using this model and divided by 24 to compare with the prediction model developed in this study. Results from these calculations were compared across the individual sites and on an aggregate level, as with the calculations from the study-developed model. These results are shown in Table 20 and indicate poor performance when compared to the study-developed model.

Although a model already existed for predicting annual crash frequencies based on number of conflicts, developed by Gettman et al.,[31] the existing model did not perform nearly as well as the model developed in this study for Virginia intersection data. This was evident when the two prediction models were compared: SSAM predicted far fewer crashes than the state-specific model. Because of this, the model created in this study should be used for Virginia intersections and for left-turn conflicts.

Table 19. Crash Predictions Across Separate Sites

Site	Predicted Crashes		% Error	Absolute % Error
	SPF	Model		
B	18.30	18.45	0.9%	0.9%
C	67.26	76.97	14.4%	14.4%
D	69.19	61.51	-11.1%	11.1%
E	9.75	5.66	-41.9%	41.9%
Average			-9.4%	17.1%

SPF = safety performance function.

$$Annual\ crashes = 0.119^{Number\ of\ conflicts * 1.419} \qquad \text{[Eq. 21]}$$

Table 20. SSAM Crash Predictions Across Separate Sites

Site	Predicted Crashes		% Error	Absolute % Error
	SPF	SSAM		
B	18.30	0.31	-98%	98%
C	67.26	3.10	-95%	95%
D	69.19	2.04	-97%	97%
E	9.75	0.12	-99%	99%
Average			-97%	97%

SPF = safety performance function; SSAM = Surrogate Safety Assessment Model.[31]

Spreadsheet Tool for Practitioners

A spreadsheet tool was created that provided an output table of predictions for the different phasing modes and two graphs illustrating how operations and safety varied throughout the course of a 24-hour analysis period.

It should be noted that the crash prediction for each hour represents an equivalent yearly value assuming the same conditions for the subject hour existed for an entire year; therefore, the relative magnitude of these predictions when compared across control mode and hour is more important than the values themselves. Because of this, the outputs from this model should be used in evaluating relative risk, rather than in predicting crashes.

Inputs

For the tool to work properly, input parameters and traffic counts must be specified by the engineer for the intersection being analyzed. These parameters were the predictor variables required for the prediction models discussed in previous sections of this report and are used for calculations in the spreadsheet. Cells in the spreadsheet that require information from the engineer were colored green to indicate inputs. Since some parameters do not change throughout the course of a day and some are variable across each hour, two sets of parameters were required: constant parameters and hourly inputs, outlined here.

Constant Parameters

Area type, number of opposing lanes, and speed limit of opposing lanes were the three constant parameters required for the spreadsheet, as these are site characteristics and do not vary by time of day. For these parameters, a table was provided at the top-left corner of the spreadsheet, with separate cells for the individual parameters. For area type, a dropdown menu with options of “Urban” and “Rural” was provided. Number of lanes was also given a dropdown menu, with options of one, two, or three opposing lanes. Finally, the speed limit of opposing lanes (which was used as the average speed of opposing lanes predictor variable in the model calculations) required the value to be any value between 35 and 55 mph.

Hourly Inputs

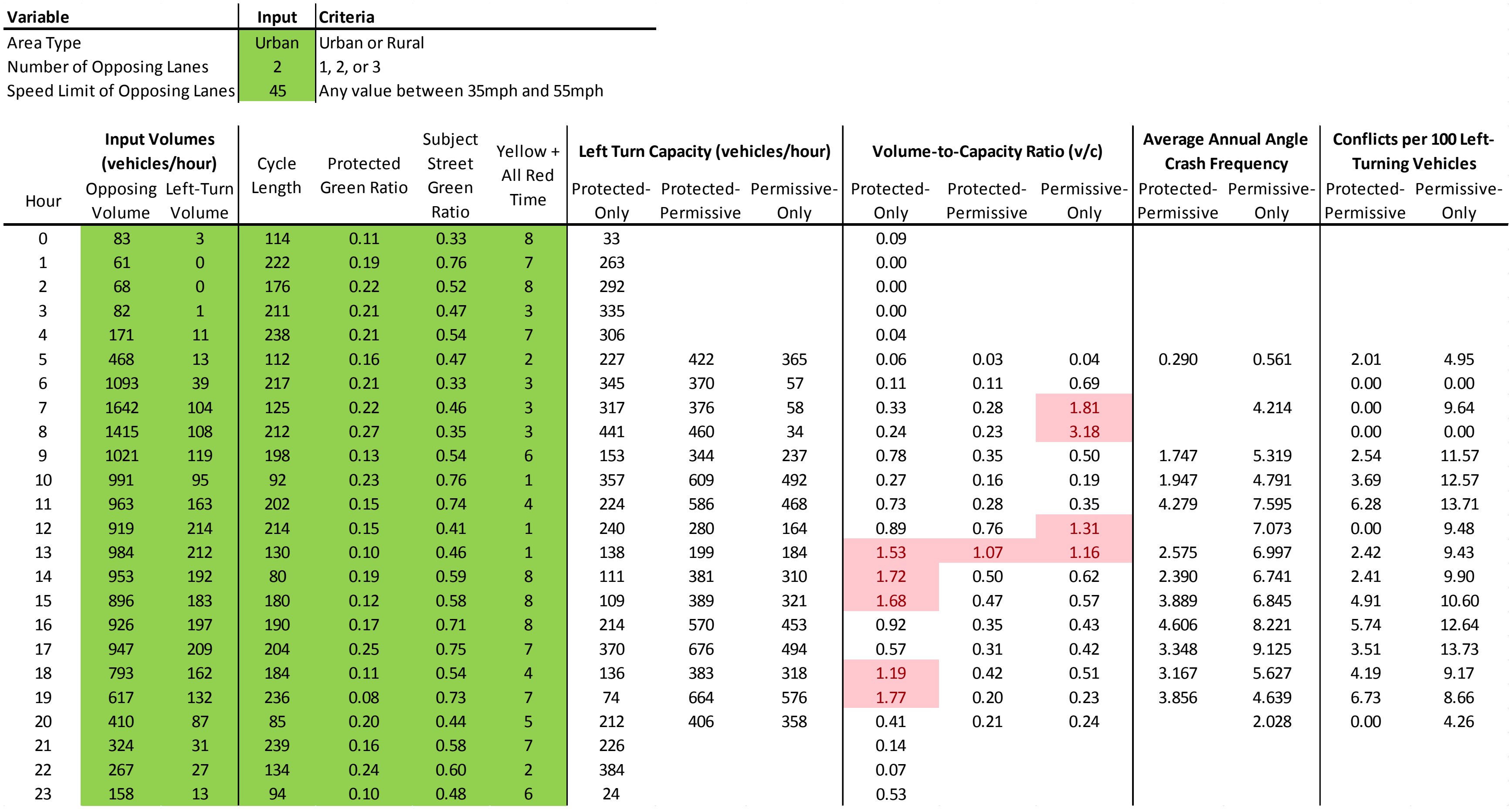
For each hour of the analysis period, hourly inputs must be specified to achieve results from the spreadsheet tool. Cycle length, protected green ratio, subject street green ratio, yellow plus all red duration, opposing volumes, and left-turn volumes were indicated as parameters that can vary throughout the course of a day, as they pertain to timing parameters and traffic volumes. Similar to the constants, parameters associated with signal timing were restricted to ranges that corresponded to the predictor variable ranges for the capacity and conflict models; cycle length could be any value between 80 and 240 seconds; protected green ratios could be between 0.075 and 0.274 (as these are rounded to the nearest 0.05 in the calculations); subject street green ratios could be any value between 0.3 and 0.8; and the yellow plus all red time parameter could be any value between 0 and the cycle length multiplied by the protected green ratio. Restrictions were not set for the opposing and left-turn volume inputs, as these are field-reported values that should not be altered, though the spreadsheet could not make predictions if opposing volumes were outside the acceptable range. In addition, it should be noted that input volumes were required in units of vehicles per hour so that the engineer could insert data directly from turning movement counts without having to make any calculations.

Examples

Examples of the input and output data are provided in Figures 13 through 15. These were created using input volumes from the southbound left-turn approach of the intersection of Route 220 and Route 1290 in Roanoke County, area type, number of opposing lanes, and speed limit information for this intersection. Cycle lengths, protected green ratios, subject street green ratios, and yellow plus all red times were randomized between their appropriate values to generate different timing parameter scenarios.

With a tool for automatically calculating predictions for left-turn capacities, v/c ratios, angle conflicts, average annual angle crash frequency based on signal parameters, site characteristics, and traffic counts, engineers will have a better way to analyze left-turn phasing control modes. In addition, the spreadsheet will allow engineers to inspect visually and compare (1) predicted capacities and demands across hours of a day and (2) predicted angle crash frequencies across hours of a day. Currently, there are no known methods to evaluate left-turn modes for safety and operations concurrently with regard to time of day; therefore, this tool can be a useful technique for engineers to evaluate the time-of-day implementation of left-turn phasing.

Although the spreadsheet tool does not suggest the left-turn mode that should be used in a particular hour of the day, practitioners will be able to make a more informed decision using their own judgment regarding locational conditions and motives for the evaluation of the turn phasing (e.g., more capacity is desired; therefore, turn phasing that provides additional capacity is being explored). In addition, as this tool is intended for use by VDOT traffic engineers, phasing mode choice should not be, and is not, prescriptive from the spreadsheet tool, since it is the intent of VDOT's TED to provide information to engineers to allow flexibility in left-turn mode determination.



Variable	Input	Criteria
Area Type	Urban	Urban or Rural
Number of Opposing Lanes	2	1, 2, or 3
Speed Limit of Opposing Lanes	45	Any value between 35mph and 55mph

Hour	Input Volumes (vehicles/hour)		Cycle Length	Protected Green Ratio	Subject Street Green Ratio	Yellow + All Red Time	Left Turn Capacity (vehicles/hour)			Volume-to-Capacity Ratio (v/c)			Average Annual Angle Crash Frequency		Conflicts per 100 Left-Turning Vehicles	
	Opposing Volume	Left-Turn Volume					Protected-Only	Protected-Permissive	Permissive-Only	Protected-Only	Protected-Permissive	Permissive-Only	Protected-Permissive	Permissive-Only	Protected-Permissive	Permissive-Only
0	83	3	114	0.11	0.33	8	33			0.09						
1	61	0	222	0.19	0.76	7	263			0.00						
2	68	0	176	0.22	0.52	8	292			0.00						
3	82	1	211	0.21	0.47	3	335			0.00						
4	171	11	238	0.21	0.54	7	306			0.04						
5	468	13	112	0.16	0.47	2	227	422	365	0.06	0.03	0.04	0.290	0.561	2.01	4.95
6	1093	39	217	0.21	0.33	3	345	370	57	0.11	0.11	0.69			0.00	0.00
7	1642	104	125	0.22	0.46	3	317	376	58	0.33	0.28	1.81		4.214	0.00	9.64
8	1415	108	212	0.27	0.35	3	441	460	34	0.24	0.23	3.18			0.00	0.00
9	1021	119	198	0.13	0.54	6	153	344	237	0.78	0.35	0.50	1.747	5.319	2.54	11.57
10	991	95	92	0.23	0.76	1	357	609	492	0.27	0.16	0.19	1.947	4.791	3.69	12.57
11	963	163	202	0.15	0.74	4	224	586	468	0.73	0.28	0.35	4.279	7.595	6.28	13.71
12	919	214	214	0.15	0.41	1	240	280	164	0.89	0.76	1.31		7.073	0.00	9.48
13	984	212	130	0.10	0.46	1	138	199	184	1.53	1.07	1.16	2.575	6.997	2.42	9.43
14	953	192	80	0.19	0.59	8	111	381	310	1.72	0.50	0.62	2.390	6.741	2.41	9.90
15	896	183	180	0.12	0.58	8	109	389	321	1.68	0.47	0.57	3.889	6.845	4.91	10.60
16	926	197	190	0.17	0.71	8	214	570	453	0.92	0.35	0.43	4.606	8.221	5.74	12.64
17	947	209	204	0.25	0.75	7	370	676	494	0.57	0.31	0.42	3.348	9.125	3.51	13.73
18	793	162	184	0.11	0.54	4	136	383	318	1.19	0.42	0.51	3.167	5.627	4.19	9.17
19	617	132	236	0.08	0.73	7	74	664	576	1.77	0.20	0.23	3.856	4.639	6.73	8.66
20	410	87	85	0.20	0.44	5	212	406	358	0.41	0.21	0.24		2.028	0.00	4.26
21	324	31	239	0.16	0.58	7	226			0.14						
22	267	27	134	0.24	0.60	2	384			0.07						
23	158	13	94	0.10	0.48	6	24			0.53						

Figure 13. Sample Table for Spreadsheet Tool. Crash predictions represent equivalent yearly values assuming the same conditions for the subject hour existed for an entire year; therefore, the relative magnitude of these predictions when compared across control mode and hour is more important than the values themselves. The outputs from this model should be used in evaluating relative risk, rather than predicting crashes.

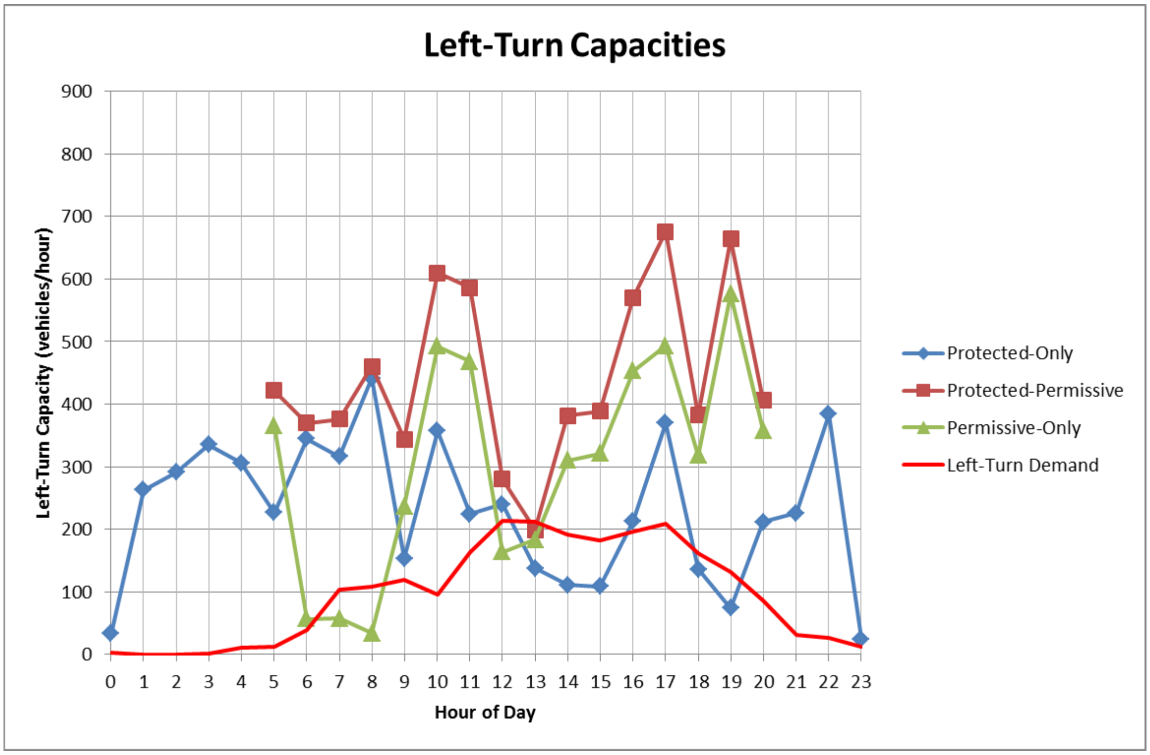


Figure 14. Sample Capacity Plot for Spreadsheet Tool

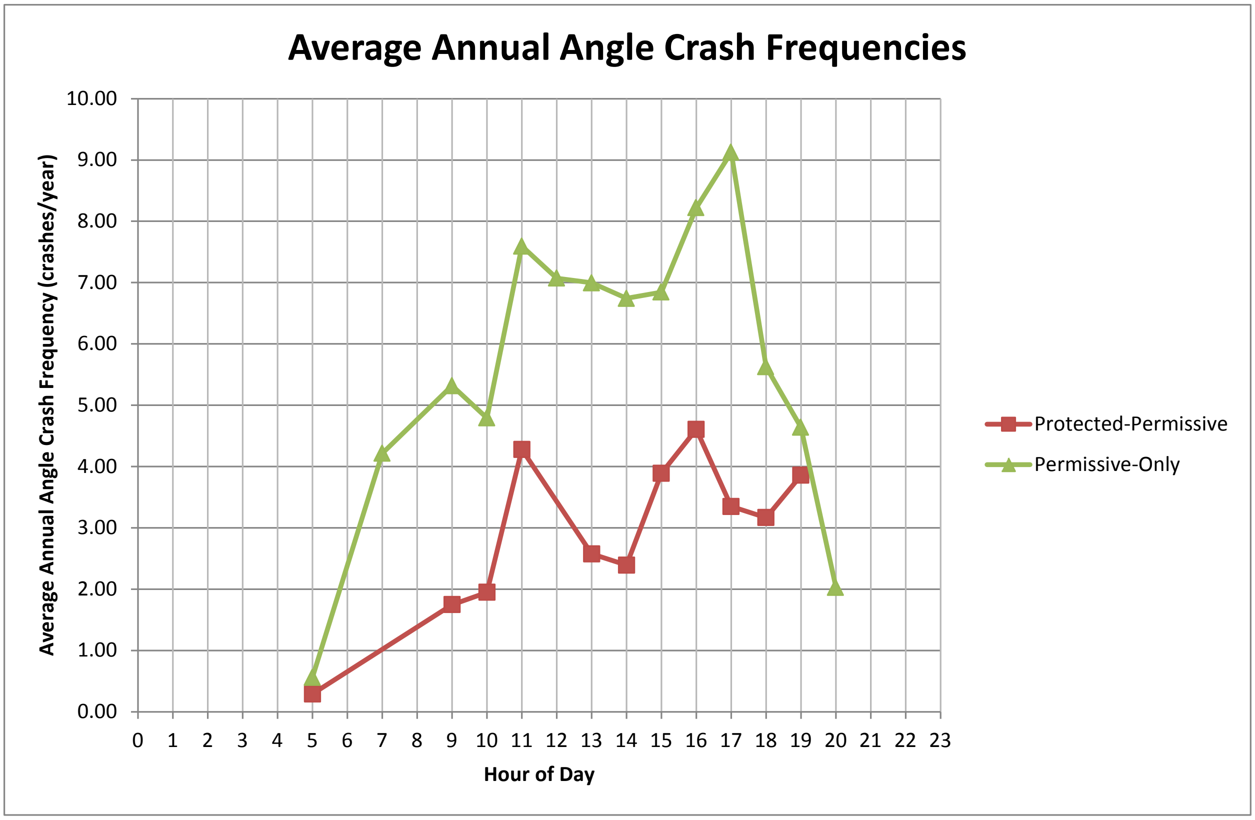


Figure 15. Sample Crash Frequency Plot for Spreadsheet Tool

CONCLUSIONS

Safety Effects of Signal Conversions From PPLT to PPLT-FYA

- *Converting left-turn signal displays from PPLT to PPLT-FYA can produce significant safety benefits for intersections. According to the results of this study, an approximately 30 percent reduction in the target crash type of angle crashes can be expected for all severity types. In addition, fatal and injury crash severities for all crash types can be reduced by approximately 14 percent. The expected reduction in total crashes (all types and severities) was estimated as 12 percent. These results support the findings of previous studies that the FYA display is better understood than the traditional green ball for the permissive portion of PPLT phasing.*

Simulation Models

- *Simulation results were used successfully to create models to predict capacity and conflicts for permissive-only and PPLT left-turn control modes. The models were found to have several predictor variables, such as different signal timing, traffic volume, and intersection characteristic parameters. Both the capacity and conflict models were successful in providing a method to evaluate time-of-day safety and operations. In addition to these models, a crash prediction model was found to provide acceptable crash risk by time of day. This model proved to match the data for Virginia intersections significantly better than a previously developed model.*

Decision Support Tool

- *A spreadsheet tool to assist engineers in the time-of-day evaluation of left-turn modes was successfully created using models developed in this study. The tool requests signal timing, volume, and intersection parameters and outputs the predicted capacities and safety risk for each hour of the day, both as a table and as a set of graphs. As there have been no prior tools to help with this decision in Virginia, the support tool will allow for optimal left-turn control mode choice based on changing conditions throughout the course of a day.*

RECOMMENDATIONS

1. *VDOT's TED should continue to support replacing traditional green ball displays with FYA left-turn indications for PPLT phasing.* As indicated by several previous studies and the results from the CMFs developed in this study, the FYA improves safety over the green ball indication. In addition, previous studies have shown that the reduction in crashes can outweigh the conversion costs in most cases. Therefore, VDOT should continue to replace green ball displays for PPLT left-turn modes with FYA to improve the safety of signalized left turns. This recommendation is consistent with the TED's Instructional & Informational Memorandum "Flashing Yellow Arrow Signal Indication for Permissive Left-Turn Movements" (IIM-TE-381)[32] issued in January 2016.

2. *VDOT's TED should encourage and support the use of the spreadsheet tool developed in this study to help guide engineers in the time-of-day analysis of left-turn control modes.* The spreadsheet tool consolidates capacity and crash prediction into one worksheet, allowing for the two to be evaluated concurrently. In addition, the tool enables time-of-day analysis of left-turn modes to be completed, so that signalized intersections can be designed to have the left-turn control mode vary throughout the course of the day, based on changing conditions.

IMPLEMENTATION AND BENEFITS

Implementation

With regard to Recommendation 1, VDOT's TED will continue to support (through emails, conferences, and memoranda) the replacement of traditional green ball displays by FYA for PPLT phasing.

With regard to Recommendation 2, the project team will work with the TED to incorporate the spreadsheet tool into VDOT's *Guidance for Determination and Documentation of Left-Turn Phasing Mode.*[1] Within 1 year of the publication of this report, the TED will reconvene its Left-Turn Phasing Committee to discuss how best to incorporate the tool into the process and make it more user-friendly. The meeting will also be used to elicit guidance regarding critical parameters including an "acceptable" tradeoff between safety and operations.

The entire implementation is expected to be complete within 2 years of the publication of this report.

Benefits

Implementing the study recommendations is expected to lead to safer and more efficient left-turn traffic signal operations at intersections in Virginia.

The benefits of implementing Recommendation 1 will be the support of a cost-effective signal display mode that is well-understood by drivers and has been shown to be safer.

The benefits of implementing Recommendation 2 will be the consistent application of time-of-day left-turn analysis techniques by VDOT engineers. Better and consistent application of time-of-day control modes will lead to more efficient left-turn traffic signal operations at intersections throughout Virginia.

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