RESEARCH & DEVELOPMENT

Guidelines for Left Turn Signal Phasing Options by Time-of-Day: A Safety and Operational Study

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16. Abstract

In recent years, North Carolina has been increasingly adopting a flashing yellow arrow (FYA) traffic control for protected-permitted (PPLT) and permitted left turns. The use of three and four section heads with FYA's is believed to minimize driver confusion between the conventional green ball and green arrow, increasing safety by reducing the potential for angle crashes. As expected, an early study of the FYA in North Carolina found that there appeared to be a significant safety benefit when converting traditional 5-section heads to 4-section FYA, per Simpson and Troy study in 2015. This has led to increased use of FYA's across the state.

With more PPLT operation being implemented across the state, NCDOT recognized that there is little research on when it is actually appropriate to implement protected-permitted, or even permitted only, left turn operation by time-of-day (TOD). Oftentimes, the decision to protect, protect/permit, or permit a left turn during various times-of-day is made based on some combination of traffic volume "cross products" or engineering judgement – with modifications to a TOD plan made at some point (often years) later in time as crashes show there may be a problem and left turn protection is needed.

The research team developed updated CMF's for NC-specific intersections where protected-only left turn signals were converted to PPLT operation. The project found that overall, safety decreased slightly at the intersections deploying FYA for PPLT. However, an obvious trade-off existed when analyzing the individual treatment approaches – left turn same roadway crashes increased significantly while rear-end collisions decreased significantly. Second, our team developed an Excel-based simulation tool to provide guidance for PPLT and permitted turn operation by accounting for both operations (delay-based) and safety by TOD. The tool is unique in that it estimates 24-hour volume distributions from limited volume inputs and provides timing recommendations across every hour of the day. The tool recommends protected only left turn phasing based on "conflict-point SPFs" and conflicting traffic volumes. Using both safety and operational findings from this project, NCDOT engineers will have access to improved planning tools during the decision-making process for left turn signalization by TOD.

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Executive Summary

North Carolina has recently adopted the use of flashing yellow arrows (FYA) at many intersections across the state as a means of providing protected-permissive left turns (PPLT) while minimizing driver confusion that can often accompany the left turn operation when using traditional traffic control devices such as the 5-section (a.k.a. "dog-house") signal. Prior research by Simpson and Troy in 2015 provided a first look at how PPLT with FYA's were operating in NC. This research effort aims at providing additional guidance to engineers on when PPLT FYA use was appropriate for use. With more implementations of PPLT anticipated in NC, NCDOT requested additional research on the effectiveness of this treatment. Two specific objectives were developed at the onset of the project, namely:

> *Objective 1: Provide an updated CMF, or CMF's, that would give an overall assessment of the use of PPLT FYA's in NC*
>
> *Objective 2: Provide guidance on when to consider permitted vs. permitted-protected vs. protected only left turn phasing by TOD.*

In meeting Objective 1, an overall safety analysis was conducted to update one or more NC-specific CMF's for PPLT FYA intersections. The analysis collected an additional three years of crash data from prior sites in Simpson and Troy's initial effort while also adding newly treated sites. Based on that evaluation, the results suggested that *total crashes* at intersections with PPLT FYA did not change significantly ($CMF_{\textbf{total Crashes, All}}$ = 1.044, or 4.4%); however, when looking at severity there appeared to be a statistically significant increase in those specific crashes ($CMF_{\textbf{total Crashes, Injury}}$ = 1.199, or 19.9%). Filtering by specific crash types, there appears to be a trade-off between increased *left turn crashes* (CMF's ranging from 3.73 to 10.51, or increasing 273% to 951%) and decreased *rear-end crashes* (CMF's ranging 0.66 to 0.23, or decreasing 34% to 76%). It also appears, on first glance, that there may be room for improving safety at the PPLT FYA approaches by implementing protected-only phasing more extensively on the fringes leading into the peak periods as traffic volumes begin to ramp up. Even so, the 24-hour results to not show large differences in CMF's when compared to PPLT only, so those improvements would likely be minor based on the results of this study.

Second, in meeting Objective 2, an Excel-based simulation tool was developed to assist NCDOT with implementing PPLT FYA by TOD. User inputs such as geometry, traffic volume, current timing plans (cycle lengths, phase lengths, etc.), isolated vs. coordinated operation, actuation, and signal default values were all incorporated into the guidance-based tool. Using the inputs, the tool incorporated a two regime Cowan distribution to simulate vehicle generation under isolated and coordinated control at a 0.1 seconds resolution. Delay was calculated from a queue accumulation polygon at the intersection approaches and the recommended left turn treatment was based on overall delay. Safety was incorporated into the tool as a key measure since traffic operations would always improve with a permitted or permitted-protected solution for efficiency reasons. Three methods were considered for safety guidance; however, the conflict point safety performance function (CP-SPF) methodology developed through another NCDOT research project is recommended. This method predicted the hourly crash frequency over a given year based on left turn and opposing through and right turn traffic volumes. If the hourly crash frequency over a given year exceeds the threshold provided in the tool, protection of the left turn is recommended in lieu of a permitted or PPLT left turn option.

Table of Contents

1. INTRODUCTION

North Carolina has adopted the use of flashing yellow arrows (FYA) at many intersections across the state as a means of providing protected-permissive left turns (PPLT) while minimizing driver confusion that can often accompany the operation when using traditional traffic control devices such as the 5-section (a.k.a. “dog-house”) signal. In 2015, NCDOT completed a study to develop crash modification factors (CMFs) associated with the conversion of left turn protection at intersections to FYA. Since that study, data from additional intersections has become available as this operational plan is implemented across North Carolina. This project considers that additional data to refine the CMFs developed by Simpson and Troy and answer new safety questions regarding FYA operation.

In addition to this safety work, this research project developed guidelines for the implementation of PP and permitted left turn phasing by time-of-day (TOD). Currently, for an intersection that has no safety restrictions (due to sight distance restrictions, opposing traffic speeds, excessive number of opposing lanes, etc.), the decision to implement protected or permissive left turn phasing is based on vehicle volumes or engineering judgment as no crash data are yet available and no crash studies incorporated TOD effects. Compounding the problem, when traffic volumes are only available for the peak period or partial days, it can be challenging to determine whether protected only phasing should be extended to non-peak hours. Using continuous count stations and spot intersection turning movement counts, the research team developed methods to assist engineers in extrapolating the volumes to off-peak hours. Using these volumes, guidelines were developed to quantify the delay savings that can be expected by all users of the intersection if some form of permissive phasing was implemented in off-peak hours. In addition, this project provides similar guidance regarding the safety-related impacts by TOD using a novel approach developed in research project 2018-20 which used “conflict-point SPFs” based on traffic volumes and type of conflict. Using both safety and operational findings from this project, NCDOT engineers will have access to improved planning tools during the decision-making process for left turn signalization by TOD.

1.1. Need Definition

This project addresses the effectiveness of protective-permissive left turns from both a safety and operational viewpoint. Shortly after North Carolina adopted flashing yellow arrows (FYAs), NCDOT staff developed crash modification factors (CMFs) for five different types of conversions to FYAs (Simpson and Troy, 2015). By the time this research began, three additional years of crash data became available for the sites studied by Simpson and Troy. In addition, more sites have come online since the conclusion of that project, allowing our research team to account for additional impacts common in safety studies. This additional data and sites assisted in further refining the CMF for the conversion of protected only left turn signals to PPLT by TOD with FYA signal.

Despite the growing acceptance of FYAs across North Carolina, many signals in the state still have appropriate sight distance, a reasonable number of oncoming lanes, moderate vehicles speeds, and no history of crash problems due to permissive lefts. Yet, with increasing peak hour left turns and opposing through volumes, protected left turn phasing is often adopted even in the off-peak periods. This results in excessive delays for left turning vehicles in the off-peak period where permitted or protected-permitted phasing may be more appropriate. Additionally, protected phasing during periods when it is not warranted also increases delays experienced by the through movements and cross street vehicles as well as for pedestrians. To determine which portions of the off-peak periods have volume levels conducive to permissive operation, as well as to identify the time saving benefits for those vehicles, it is critical to understand the distribution of vehicle volumes by TOD. Therefore, this project also develops a methodology for determining the distribution of vehicle flows by TOD and develop guidance to assist engineers in determining the appropriate use of permissive phasing in those cases.

1.2. Research Scope and Objectives

This research effort seeks to determine the operational and safety impacts of allowing permissive left turns at signalized intersections by Time of Day (TOD), where proper sight distance is adequate considering the opposing traffic speed. Across North Carolina, many signals have acceptable sight distances, reasonable approach speeds, few number of opposing lanes and little-to-no history of left turn crashes. However, some do experience sufficiently high peak hour volumes warranting a protected-only left turn phase. During lower volume hours, motorists wonder why permissive left turns are prohibited despite the presence of adequate gaps in the opposing traffic stream. These drivers then contact NCDOT requesting changes to the signal phasing plan.

However, absent guidance on how to quantify delay savings and safety impacts of permissive phasing to vehicles in off-peak periods, NCDOT engineers cannot make informed decisions for the best option for off-peak signal phasing. This research effort established two specific objectives geared at addressing these problems.

> *Objective 1: Provide an updated CMF, or CMF's, that would give an overall assessment of the safety impact of PPLT FYA's in NC*
>
> *Objective 2: Provide guidance on when to consider permitted vs. permitted-protected vs. protected only left turn phasing by TOD.*

By adding three more years of crash data and additional study sites, the team expects to further refine and strengthen the value of current PPLT FYA crash modification factors, thus allowing NCDOT to make decisions about signal phasing that are backed by rigorous research and reliable data. In addition, the guidance-based tool will provide empirically sound evidence on left turn operation based on both operations and safety.

1.3. Organization of the Report

This report contains five sections beginning with this introductory chapter. Chapter 2 provides a brief discussion of signalized intersection safety and operations background information. Chapter 3 explains the safety analysis which resulted in updated crash modification factors for conversion from protected to PPLT signal operation. Chapter 4 provides the development of operational and safety guidelines that are ultimately employed in an Excel-based tool. Conclusions and recommendations are presented in Chapter 5.

2. BACKGROUND

2.1. Safety

Using FYAs for left turns and converting protected-only left turn to PPLT have been at the center of several research efforts over the last several decades. However, less attention has been given to FYAs for left turns. The following two sections provide a summary of safety studies related to the FYA as well as signal phasing schemes related to the FYA.

2.1.1. Safety Impact of Flashing Yellow Arrows (FYAs)

Over the last two decades, research has determined the safety of implementing FYAs for left turn displays. The results from these studies were largely dependent upon the signal timing plan being used with the FYA. One of the first major studies on FYAs was completed by Brehmer *et al.* as NCHRP Report 493 *(2)*. The study was an extensive, national-level examination of different signal displays for protected-permissive left turn control and how they were understood by drivers. They completed field studies in Maryland, Arizona, Oregon, and Florida and concluded that FYAs are highly versatile and generally yielded positive feedback from users. In addition, an analysis of crash data identified that the FYA display had the lowest crash rate, concluding that it has the highest safety rating among other display options, including flashing red arrow and the “Dallas Display.” However, at the Arizona treated site, PPLT was removed because of safety concerns from city management. Additional findings of this study included that left turn conflict rates were low for all PPLT displays. The authors found that the conflicts were caused by aggressive driving rather than a misunderstanding of the signal. The findings from this effort resulted in support of additional experiments about the use of FYAs, including North Carolina-specific results.

One such additional experiment included the efforts of Noyce *et al. (3)*. This follow-on safety study examined more than 50 intersections nationwide, including the original sites considered by Brehmer *et al*. *(2)*, where the FYA was used for PPLT signalization. The additional treated sites considered were in California, Colorado, Michigan, Minnesota, North Carolina, Virginia, Washington, and Wyoming. The results demonstrated that crashes initially increased when the existing signal operated as protected-only in the before period. However, the overall crash frequency decreased over time.

In 2012, Lin *et al.* were among the first to complete a state-level study examining PPLT operations using FYA signal at a single location in the Tampa Bay area of Florida *(4)*. This study was conducted after this signal plan was included in the MUTCD. The authors used a before-and-after study and primarily focused on gap acceptance behavior. Gap acceptance was considered as a measure of short-term safety. The authors determined that the opposing traffic volumes were related to the benefits yielded by this operational plan. For instance, the authors found that drivers tended to accept longer critical gaps after the implementation of FYA signal, resulting in safer turning movements. On the other hand, there were no noticeable benefits under heavy opposing traffic as permissive left turns were limited.

An Indiana-specific safety study was completed by Rietgraf and Schattler and studied six intersections. A comparison of three signal head types were made—FYA, circular greens, and flashing red arrows—to signal the permissive interval of PPLT phases *(5)*. The authors observed the gaps accepted by drivers under the three operations. They concluded FYAs were most easily understood by drivers, as the drivers demonstrated quick decision-making to proceed through the intersections. This led to FYAs having the highest response rate for safe and efficient actions combined compared to circular green and flashing red arrows.

In another locally-focused study, Schattler *et al.* examined the safety impacts of left turns with FYA in Peoria, Illinois *(6)*. This study investigated whether additional signage reduced the number of crashes under this signal operation. The signage in question had the text of "Left Turn Yield on FYA" to provide additional guidance on how to perform under a FYA. The study considered impacts on all users as well as a subset of drivers age 65 or older, extracting the age of drivers from the crash reports. The results showed a reduction in crashes with the signage. However, drivers age 65 and older did not experience the same reductions.

In North Carolina specifically, Pulugurtha *et al*. examined six FYA-PPLT signalized intersections in Charlotte, NC *(7)*. The study found fewer crashes at five of the six intersections. Afterward, Pulugurtha *et al.* extended the research by evaluating additional sites that came online since the 2011 study *(8).* The authors completed a before-and-after crash analysis using Empirical Bayes at 18 intersections with FYAs to determine the direct and indirect effects of the FYA treatment. The study investigated both total and left-turning vehicle crashes as the target crashes from 18 intersections in Charlotte, NC. They calculated the ratio of the actual crashes to the expected crashes and found that the total and left turn crashes had the average ratios of 0.39 and 0.61, respectively, for the 18 study intersections. The results showed that both the total and left turn crashes had a statistically significant reduction of crashes at a 99% level.

2.1.2. Safety Impact of Changes to Phasing Schemes

Other research has sought to determine the safety implications of converting from protected-only signal phasing to FYA-PPLT. These studies primarily considered quantifying crashes at the state level. TOD operation was not considered by most of these safety studies.

In 2008, Wang and Tian examined the economic impact of changing a signal in Nevada from protected-only to protected-permissive operations *(9)*. Synchro/SimTraffic was used to quantify the operational impacts and Empirical Bayes analysis was used to quantify safety impacts. These were later projected in terms of monetary benefits using a benefit-cost analysis. The authors used different costs based on the severity of crashes. They found that improved efficiency exceeded the cost of increased crashes for a case study in Nevada. The analysis results showed that the total benefits from the decreased delay were $89,273.74 per year, while the total cost from the increased crashes was about $10,543 per year. Therefore, the protected/permissive operation saved $78,730 per year at the study intersection. However, the authors also conceded potential error in the calculation. Since the delay was calculated with the optimized signal timing, and the crash analysis was conducted by the method of sample moments, it might include errors due to a limited number of samples.

Yi *et al*. studied 51 intersections in Texas and Washington to develop guidelines for implementing FYA-PPLT operations *(10)*. The intersections in Texas all had PPLT operation in the before period (n=12), whereas the intersections in Washington had protected-only (n=8), permissive-only (n=23), and PPLT (n=8) operation in the before period. As a part of the study, they analyzed the safety impact of the conversion from the traditional four-section protected-only to FYA-PPLT, which was implemented on the seven intersections among the 51 studied sites. Of the seven sites, five experienced increased crash rates after the conversion to FYA-PPLT. The authors suggested that these crashes most likely resulted from heavy traffic volumes, high speeds, and multiple turning lanes. These results indicate that it is important to understand the opposing traffic volumes when evaluating the conversion of left turn signaling.

Srinivasan *et al.* evaluated intersections that changed from permissive, protected, or permissive-protected to FYA-PPLT in Oregon, Washington, and North Carolina *(11)*. The study developed separate CMFs for Oregon and Washington combined, North Carolina alone, and Oregon, Washington and North Carolina combined. It is also important to note that the authors considered the conversion by individual approaches in order to have a more robust calculation. The CMFs developed for the conversion of protected-only to FYA-PPLT are summarized in Table 1. The results show implementing FYA-PPLT does not improve safety.

TABLE 1. CMFS DEVELOPED FOR THE CONVERSION FROM PROT-ONLY TO FYA-PPLT BY SRINIVASAN ET AL. *(11)*

Location	Crash Type	CMF
Oregon and Washington	Total	1.187
Oregon and Washington	Left Turn	2.043
Oregon and Washington	FYA Left Turn	2.073
North Carolina	Total	1.509
North Carolina	Injury and Fatal	1.479
North Carolina	Rear End	1.752
North Carolina	Left Turn	2.683
North Carolina	Left Turn Opposing Through	3.696
Oregon, Washington, and North Carolina	Total	1.338
Oregon, Washington, and North Carolina	Left Turn	2.242

Note: FYA left turn crashes are left turn crashes from the treated approaches.

The safety benefits of changing a left turn signal from permissive to protected-permissive or protected-only were studied by Chen *et al.* in 2015 *(12)*. The authors considered police crash reports to develop a regression model to determine factors that influence the safety of this conversion. This study included vehicular, bicycle, and pedestrian crashes. A before-and-after study was also completed, and the results showed that a change in the left turn signal did not significantly reduce the number of intersection crashes when the protection of some form was added. In addition, the authors suggested that geometry, traffic flows, and operations should be considered before implementing a protected or protected/permissive signal plan.

Simpson and Troy developed initial CMFs for the conversion to FYA from five different initial configurations in North Carolina *(1)*. These configurations included permissive only to FYA-PPLT, protected only to FYA-PPLT, protected only to FYA-PPLT with TOD operation, five-section PPLT to FYA-PPLT, and permissive only to FYA-permissive only. The measures of effectiveness for the study were total, injury, and left turn-same roadway crashes within 150 feet of the intersection. A before-and-after analysis with safety performance functions (SPFs) was used to develop CMFs. For the category specific to our research effort (a conversion from protected-only to FYA-PPLT with TOD operation), there was a 10% reduction in total crashes and a 7% reduction in total injury crashes at the entire intersection. However, there was a 173% increase in target crashes on the treated approaches when evaluated alone. Since Simpson and Troy's study, more sites with similar conversions have occurred in North Carolina, suggesting that these values could be refined with updated crash data.

2.2. Operations

Most intersection analysis tools fall into one of two broad categories: analytical/deterministic, or some form of macro, meso or microsimulation. Existing tools are well-suited to predicting intersection delay, and may allow sufficient control over an individual intersection's signal timing to calculate, albeit with some effort, the operational differences between running an intersection in a protected versus protected-permitted left turn mode. However, there is a gap in the existing state of the practice in that no currently available tools are 1) optimized for a simultaneous safety and operational analysis over 2) a full-day period at an intersection under consideration for signal timing changes.

2.2.1. Macroscopic (Deterministic) Models

The intersection assessment methodology presented in the Highway Capacity Manual (HCM), Sixth Edition: A Guide for Multimodal Mobility Analysis (17) provides an extensive computational framework for assessing intersection operation using purely deterministic methods. In addition to providing a delay-based level of service score for automotive operation at a given intersection, the HCM methodology can assess the quality of service provided to pedestrians and cyclists under different operating conditions. Intersection geometry, vehicle type, and local driver behavior are accounted for through a combination of adjustment factors and changes to default parameters.

The HCM signalized intersection methodology can assess protected, protected-permissive, and permissive-only left turn signals, on either exclusive or shared left turn lanes. A geometric method is used to calculate part of the intersection delay, with additional equations capturing the effects of cycle-by-cycle random variation in arrivals, initial queue at the beginning of the analysis period, or oversaturation. HCM methods can also be applied to assess the performance of an existing facility, or series of road links and intersections. However, many signal progression measures, such as bandwidth and progression efficiency, are beyond the scope of its methodology.

Many commercial software packages, such as Synchro (18), SIDRA Intersection (19), and McTrans HCS (20) either implement Highway Capacity Manual-based models or expand upon them.

2.2.2. Microscopic (Stochastic) Models

Simulation provides an alternative method to the analytical methods developed in the Highway Capacity Manual. The FHWA Traffic Analysis Toolbox Volume II (21) addresses types of simulation models and general recommendations for their use. Simulation models can generally be described as macroscopic, mesoscopic, or microscopic. Macroscopic models consider sections of a facility as a whole, rather than individual vehicles; as a result, they require the least information to calibrate. Microscopic models simulate individual vehicles in the most detail, including varying individual driver and vehicle types and considering the effects of roadway geometry on the progression of a vehicle through the network. Mesoscopic models provide an intermediate level of detail. Simulation models excel at evaluating congestion on a network; they can used to model interference between nearby locations where downstream oversaturation leads to upstream impacts. Simulation models may also explicitly address the non-homogenous nature of drivers and vehicle streams. However, simulation models require more data than HCM methods, and must be calibrated and error-checked.

Pell, Meingast, and Schauer (22) reviewed seventeen traffic simulation software programs in the context of selecting an appropriate software for real-time traffic estimation and short-term forecasting over about 6,000 kilometers of roads in Austria. Their area of interest consisted of urban and rural roads, with mixed traffic streams, difficult geometry, and interference from pedestrians. Their work highlighted the intelligent transportation systems (ITS) functionality built into many modern models. Most models studied incorporated coordinated and adaptive traffic signals; some incorporated more advanced ITS features, such as ramp metering, vehicle-to-vehicle and vehicle-to-infrastructure communication, and probe vehicles.

Modern microsimulation options include SimTraffic (17), VISSIM (23), and Transmodeler (24), among many others. All three programs include options for analysis at multiple resolutions. SimTraffic is designed for easy integration with Synchro, a macroscopic analysis program (25). TransModeler offers microscopic, mesoscopic, and macroscopic simulation options (26), while VISSIM offers both microscopic and mesoscopic microsimulation. All three of the above also offer three-dimensional visualization capabilities.

Cowan (27) reviewed four stochastic headway models for appropriateness in traffic simulation, ranging in complexity from a Poisson process to a mixed distribution accounting for platoons of vehicles. Of these, two models are used in this report to describe isolated and coordinated signal operation, respectively. Cowan’s M2 model, a shifted exponential distribution, describes random arrivals with all arrivals separated by at least a minimum headway. Cowan’s M3 model incorporates both minimum headway considerations and the effects of platooning, or bunching, in its arrival generation.

3. CMF DEVELOPMENT

For the safety analysis, this study investigated the safety impact of the conversion from protected to flashing yellow arrow protective-permissive left turns (FYA-PPLT) with TOD operation. Shortly after North Carolina adopted FYAs, NCDOT staff developed CMFs for five different types of conversions to FYA *(1)*. When this research began, three additional years of crash data were available for the sites studied by Simpson and Troy. Additionally, more sites have come online since the conclusion of the original project, allowing this research team to extend and further refine the CMFs for the target treatment, which is the conversion from protected only to FYA-PPLT with TOD operation. The addition of three more years of crash data and additional study sites provides a more robust set of CMFs and safety guidelines for the implementation of this particular treatment.

3.1. Methodology

To estimate CMFs for the target treatment, this study employed a before-and-after design using the comparison group (C-G) method. This method is appropriate because it correctly assumes that treatment sites were not chosen for safety reasons, but instead opted for PPLT for its operational benefits. Thus, the impact of regression-to-the-mean can be assumed negligible.

For the site selection, the research team included the treated sites studied in the 2015 effort as well as identified additional sites that since came online *(1)*. After identifying the treated sites, the team considered some combination of two-to-four comparison sites for each treated site. For the comprehensive list of treated and comparison sites, crash reports were collected and reviewed to determine the target crashes related to the left-turning vehicles on treated approaches. Next, the treated sites were reviewed and classified to determine if any other significant changes in signalization, traffic control device, or geometry were present that might cause additional crash impacts. Once sites were classified (target treatment only vs. multiple treatments), with the comprehensive datasets CMFs were developed for total and target crashes.

3.1.1. Site Selection

3.1.1.1. Treatment Sites

To conduct the safety analysis, the research team extended the 2015 efforts by Simpson and Troy, concentrating on the sites listed as "Category 2A: Protected-Only to FYA-PPLT with TOD Operation" *(1)*. The research team also contacted NCDOT Division and City Engineers to collect additional sites that have implemented the target treatment to further increase the sample size for calculating CMFs. Throughout the process, sites were excluded if there had been a change to the physical geometry (e.g. the addition of an opposing exclusive right turn bay), signal head (e.g. an opposing right turn signal head modification), or signal timing plans. This was done to exclude the impacts of other additional modifications on the target crashes and ensure integrity of the results. In addition, dual left turn lanes and three-section signal heads were excluded from this project because both had limited application with TOD operation in North Carolina at the beginning of this study.

Table 2 shows the list of 44 treatment sites and their total number of approaches (n=171) at the intersection. The selected sites are located in Charlotte and Raleigh. The team also collected the number of opposing through and right turn lanes for the treatment approaches which were later used for the safety guidelines development in Section 4.2. The results showed the treatment approaches had the average of 2.45 opposing through and right turn lanes.

TABLE 2. THE 44 SELECTED SITES WITH TARGET TREATMENT IN NORTH CAROLINA

Site Code	Road Names	Num of Approaches	Site Code	Road Names	Num of Approaches
T-Meck-1	Claude Freeman/Mallard Creek Church	4	T-Meck-3	3rd/Queens	4
T-Meck-10	Albemarle/Lawyers	4	T-Meck-30	Tyvola/Westpark/McDonalds	4
T-Meck-11	Monroe/Sardis Rd N	4	T-Meck-31	South/Westinghouse/Cressida	4
T-Meck-12	Randolph/Wendover	4	T-Meck-32	Morehead/Wilkinson	3
T-Meck-13	Randolph & Sharon Amity	4	T-Meck-33	Wilkinson & Remount	4
T-Meck-14	Providence/Queens	4	T-Meck-34	Ashley/Wilkinson	4
T-Meck-15	Providence/Wendover	4	T-Meck-35	Old Steele Creek/Westerly Hills/Wilkinson	4
T-Meck-16	Providence/Sharon Amity	4	T-Meck-36	Morris Field/Wilkinson	4
T-Meck-17	Alexander/Providence/Rea	4	T-Meck-37	Harlee/Stafford/Wilkinson	4
T-Meck-18	Sharon Rd & Southpark Dr	4	T-Meck-38	Boyer/Wilkinson	4
T-Meck-19	Fairview/South Park	4	T-Meck-4	Eastway & Woodland	4
T-Meck-2	7th & Charlottetowne	4	T-Meck-40	Albemarle/Wilgrove-Mint Hill	3
T-Meck-20	Barclay Downs/Runnymede	4	T-Meck-41	Carmel/Pineville-Matthews	4
T-Meck-21	Albemarle/Winterhaven	4	T-Meck-42	Park/Birnen/Johnston	4
T-Meck-22	Albemarle/Harrisburg	4	T-Meck-44	Monroe/Gander Cove Ln	4
T-Meck-23	Albemarle/Executive Center/Jenkins	4	T-Meck-5	Albemarle/Sharon Amity	4
T-Meck-24	South/Tyvola	4	T-Meck-6	Central/Eastway	4
T-Meck-25	Remount/Tryon	4	T-Meck-7	Albemarle/Reddman	4
T-Meck-26	Clanton/Tryon	4	T-Meck-8	Albemarle/Farm Pond	4
T-Meck-27	Billy Graham/Tryon/Woodlawn	4	T-Meck-9	Albemarle/Harris	4
T-Meck-28	Remount / West Blvd	4	T-Wake-1	Gorman at I-40 EB Ramp	3
T-MECK-29	I-77 SB Ramp/Westinghouse	3	T-Wake-2	Gorman at Thistledown Drive	3

3.1.1.2. Comparison Sites

For the before-and-after study with the C-G method, the research team selected two to four comparison sites for each treated site. Some of the comparison sites were used more than once because they were in close proximity to more than one treated site. With the 54 unique comparison sites, a total of 174 candidate comparison sites were selected for the 44 treated sites. The comparison sites were selected through inspection of similar characteristics (e.g., similar geometry and traffic conditions for each site). However, proximity to the site of interest was the primary factor for selecting a comparison site because seasonal impacts (such as weather or special events) and similar driver characteristics would have similar impacts at comparison and treatment sites. It was assumed that the selected comparison sites would experience similar population growth as well. Last, for this effort, each comparison site considered fell within a threshold of three miles of its associated treated site, and most comparison sites were within 2 miles.

3.1.2. Crash Data

The research team, with assistance from NCDOT and city department staff, collected the crash data, crash reports, and signal timing plans. For treatment sites, crash reports and data were collected and later reviewed to ensure that the filtered crashes are the target crashes that involve the left-turning vehicles traveling the treated approach. For comparison sites, crashes were collected to determine the best combination of comparison groups and to calculate the corresponding comparison ratio. Since there was no treated approach on the comparison sites, target crashes for individual approaches that were not collected. Therefore, the team used the total crashes in the calculation of sample odds ratios and comparison ratios that will be discussed in section 3.2.

3.1.2.1. Collection of Crash Data

Crash data were collected for a period of five years before, and at least three years after the implementation of FYA-PPLT. For sites treated more recently, any available data for the after period was considered. For the CMF development, the team defined the before period as five years before the target treatment, a transition period as the two months after the target treatment, and the after period from right after the transition period to the most recent crash data on record. The before and after periods' crashes were used to estimate CMFs in this study.

This study collected data for the crashes occurred within 150' of the intersection as the research team was only interested in the impacts of the signal timing instead of extraneous factors such as turn pocket length or visibility issues. Nearly all of the sites had left turn bay lengths greater than 150'. This selection is also consistent with the efforts of Simpson and Troy.

The crash data were primarily requested through NCDOT's query process in the Traffic Engineering Accident Analysis System (TEAAS). The query process allows crash data to be pulled more quickly than traditional methods. This process, however, does not account for crashes with mislabeled information. Thus, a small percentage of crashes could not be filtered via a query alone, so every crash report needed to be checked manually for consideration in the analysis. This is especially true for sites that include on- and off-ramps.

3.1.2.2. Target Crash Data Filtering

For treated sites, the team filtered target crashes by inspecting individual crash reports. This crash filtering process was conducted for the target crash filtering only and did not affect the total crashes. Using the first harmful event codes recorded in crash reports, the target crashes can be filtered easily if there is no misclassification in the dataset. However, crash reports often include misclassified records for the first harmful events. So, the team determined actual target crashes by reviewing the crashes with possible first harmful event types, including 'left turn, same roadway', 'left turn, different roadway', 'rear-end, slow or stop', 'rear-end, turn', 'angle', 'head-on'. By manually inspecting crash reports, the team identified actual cause and location of the crash to ensure it was one of the following four target crash categories.

- *Category* 1: Left turn, same roadway (LTSR) crashes occurring on target-treatment approach
- *Category 1A:* LTSR crashes occurring on target-treatment-only approaches
- *Category* 2: Rear-end crashes occurring on target-treatment approaches
- *Category 2A:* Rear-end crashes occurring on target-treatment-only approaches

For the target crash data filtering, a target-treatment approach was defined as an approach with the target treatment; however, it could include other treatments such as an exclusive right turn lane or signal modification to the opposing right turn movement. The target-treatment-only approach was defined in this study as a treated approach that had no other change besides the target treatment that could affect the target crashes. The classification types for the treated approaches and sites are defined in detail in section 3.1.3.

Also, the team inspected the target crashes and filtered out if the cause was unrelated to the traffic signal. For instance, the crashes were removed if they were driver-related, such as the use of alcohol or poor parking maneuvering, as well as crashes that resulted from external forces such as crashes with animals or trains.

The team obtained a total of 594 actual target crashes observed in the before and after periods through manual inspection of crash reports. Table 3 provides crash counts by the first harmful events for target crash category 1 (left turn, same roadway) and category 2 (rear-end). The category 1 crashes consisted of variety first harmful events that were reclassified into left turn, same roadway crashes, while a majority of the category 2 crashes were properly coded as rear-end, slow or stop crashes. The addition of crash samples, especially for the category 1, shows the detailed inspection of crashes is necessary to filter the target crashes appropriately.

TABLE 3. CRASH COUNTS FOR TARGET CRASH CATEGORIES

First Harmful Event Recorded in Crash Report	**Target Crashes**		
	Category 1 (Left Turn, Same Roadway)	**Category 2 (Rear-End)**	**SUM**
Left Turn, Same Roadway	134	0	134
Left Turn, Different Roadway	71	0	71
Angle	142	3	145
Head-On	21	1	22
Rear-End, Slow or Stop	1	200	201
Rear-End, Turn	0	6	6
Others	10	5	15
Total	379	215	594

3.1.3. Approach and Site Classification

3.1.3.1. Filtering Target-Treatment Approaches

For the 171 approaches at the 44 treated sites, the team filtered the target-treatment approaches using a series of criteria, as shown in Figure 1. When filtering, the team inspected signal plans and Google Maps street view. First, signal plans were reviewed to confirm each approach had a FYA left turn signal, and 100 approaches passed that filter. Next, the 100 approaches were reviewed to determine if the approach was converted from a protected-only signal. In this step, the team looked at Google Maps street view in the before period and determined if the signal was converted from a protected-only signal or other types of phasing (e.g., permissive or permissive-protected left turn signal). If all views of the signal in Google Maps street view were blurry, past signal plans were consulted to establish the type of signal in the before period. Fifteen sites were cut in this step as they did not have protected-only phasing in the before period, leaving 85 approaches that were originally protected-only. The remaining 85 approach signal plans were reviewed to confirm if they were operated by TOD, resulting in one approach being filtered out. Last, for the remaining 84 approaches, those with four-section signal heads were kept, and those with three-section signal heads were excluded from the study due to different operational characteristics[1]. This final filter yielded 82 approaches for analysis.

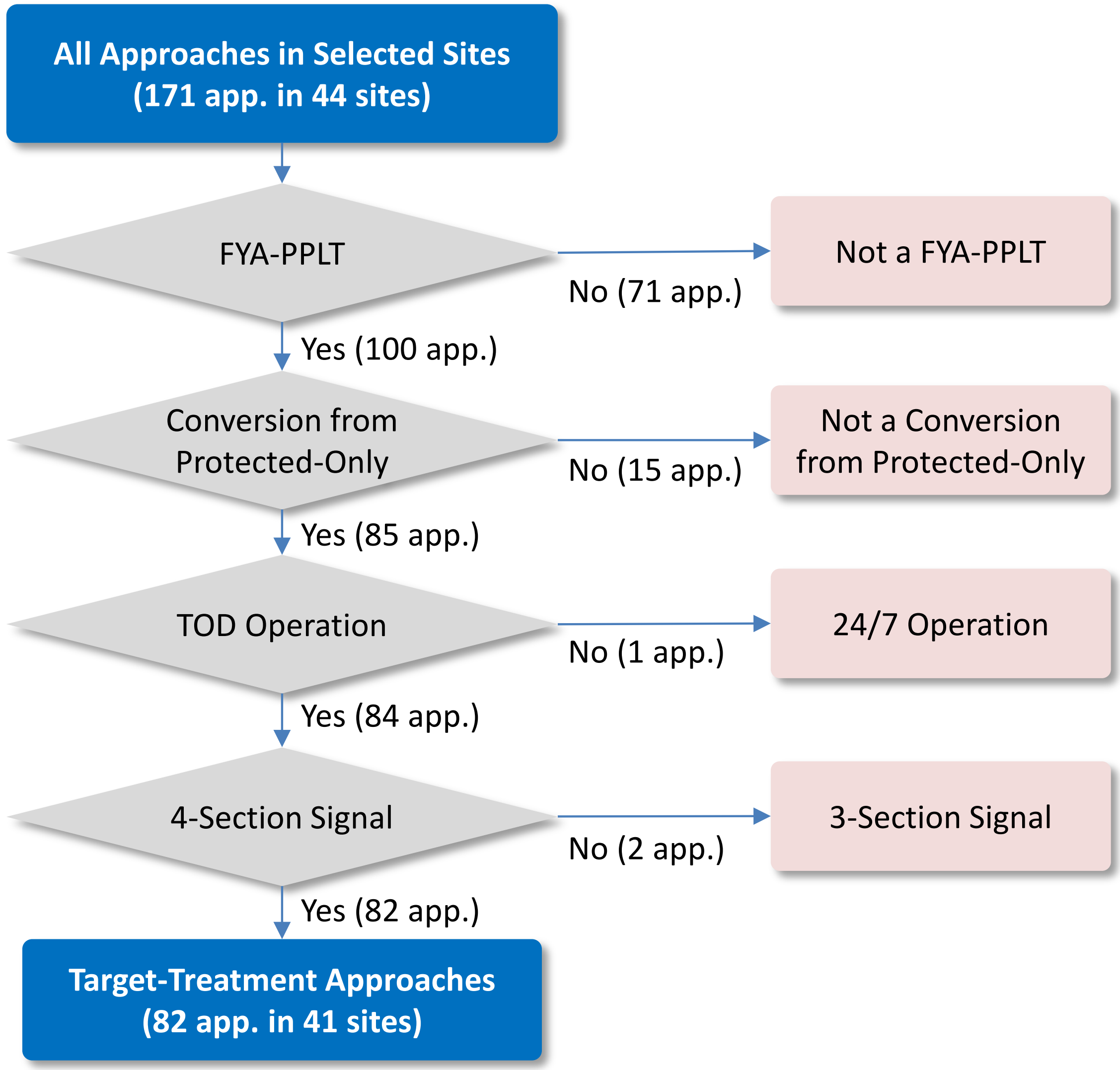


FIGURE 1. TARGET-TREATMENT APPROACH FILTERING

3.1.3.2. Classification of Treated Approaches and Sites

For classification purposes, the team defined these types of treated approaches and sites:

- *Target-treatment approach*: Any left turn *approach* that had the target treatment of conversion from protected-only left turn to FYA-PPLT with TOD operation.
- *Target-treatment-only approach*: A treated *approach* that had no other modifications besides the target treatment (FYA-PPLT by TOD) that could affect the *target* crashes.
- *Multiple-treatment approach*: A treated *approach* that had other changes besides the target treatment that could affect the *target* crashes.

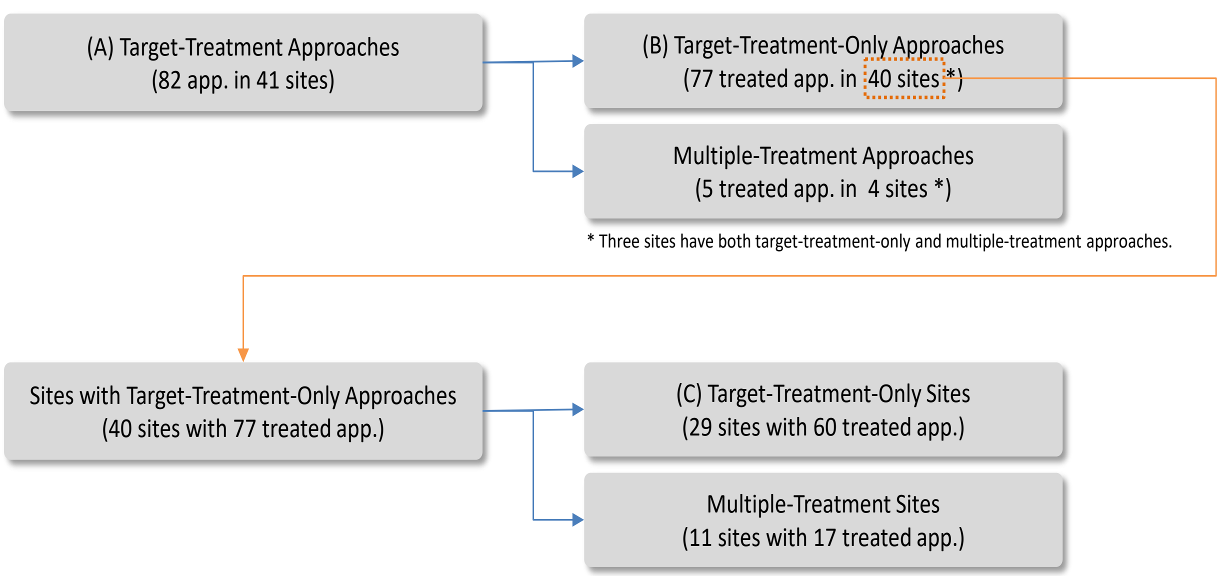
[1] Note: The *permissive-only conversions (three-section signal heads) were not evaluated because of the low sample size in our study.*

- *Target-treatment-only site*: A treated *site* that had no other changes besides the target treatment that could affect the *total* crashes.
- *Multiple-treatment site*: A treated *site* that had other changes besides the target treatment that could affect the *total* crashes.

The team recognizes there are very subtle differences in the classification process. It is important to note the distinction in approach versus site:

1) Approaches versus Sites: With regards to *approaches*, the second and third bullets are *subsets* of the first bullet. The *approaches* with a FYA-PPLT by TOD treatment either have a stand-alone treatment on the approach of interest (2^{nd} bullet) or have an additional treatment on the *approach* of interest (3^{rd} bullet).
2) Sites: With regards to *sites*, the fourth and fifth bullets are based on the sample target-treatment-only approaches in the second bullet. The treated *approach* in the second bullet is stand-alone; however, an alternate (and often opposing) *approach* may have an additional treatment (such as an exclusive right turn bay or right turn signal modification). For this reason, the fourth and fifth bullets distinguish between the two *site* types where an additional modification to the opposing *approach* could bias the results. Since all approaches are considered for the entire *site*, total crashes are utilized.

To summarize, the classification above was needed to ensure that the CMFs developed were based on sites and approaches that had no other effects on crashes due to a change in geometry or signal, either on the actual treated approach, or at a site where the opposing approach may bias the results. Figure 2 provides a visual of the classification process for treated *approaches* and *sites*.



- **Dataset (A) was used for the development of CMFs Category 1 & 2.**
- **Dataset (B) was used for the development of CMFs Category 1A & 2A.**
- **Dataset (C) was used for the development of CMFs for Total Crashes.**

Figure 2. Treated Approach and Site Classification

For the *approach* classification, the team classified the 82 target-treatment approaches previously filtered and shown in the prior section (labeled (A) in Figure 2) into the target-treatment-only and multiple-treatment approaches by looking at Google Maps street view. Approaches with no other changes that could affect target crashes on treated *approaches* were classified as target-treatment-only *approaches* (labeled (B) in Figure 2), and the others were classified as multiple-treatment *approaches*.

For the *site* classification, the team classified the 40 sites with 77 target-treatment-only *approaches* into the target-treatment-only and multiple-treatment *sites*. Intersections that had no other change that could affect total crashes, not limited to target crashes, were classified as target-treatment-only *sites*, and the others were classified as multiple-treatment *sites*. For example, a *site* with the target treatment on the westbound *approach* was classified as a multiple-treatment site if an exclusive right-turn only lane on the southbound approach was added that could affect the total crashes. *Note: the southbound approach here was not the opposing right turn lane, but it still impacted the overall crashes because it was an additional treatment at the site.*

Table 4 shows the number of target treatment sites and approaches. The 41 treated sites have 159 approaches in total, including the 82 treated and 77 non-treated approaches. Among the 41 treated sites, only 29 sites were classified as the target-treatment-only sites and they have 60 target-treatment-only approaches. Among the 82 treated approaches in the 41 treated sites, 77 approaches are target-treatment-only approaches, and only five are multiple-treatment approaches.

Table 4. The Number of Treatment Sites and Approaches

Site/Approach	Treatment Sites		
	Total	Target-Treatment-Only Sites	Multiple-Treatment Sites
Number of Sites	41	29	12
Number of Approaches	159	112	47
Approaches with Target Treatment	82	60	22
Target-Treatment-Only Approaches	77	60	17
Multiple-Treatment Approaches	5	0	5
Approaches without Target Treatment	77	52	25

3.1.3.3. Sample Approaches and Sites for CMF Development

This study developed separate CMFs for the total crashes and target crashes using different crash datasets (labeled as (A), (B), and (C) in Figure 2).

Table 5 summarizes the CMF categories and sample approaches and sites which were used to calculate the associated CMF's. The 29 sites labeled (C) in Figure 2 were used to develop the CMFs for total crashes. The target-treatment approaches labeled as (B) in Figure 2 were used to develop the CMFs for target crashes (Target – All, Category 1 and Category 2). The target-treatment-only approaches labeled as (B) in Figure 2 were used to develop the CMFs for the subgroup target crashes (Category 1A and Category 2A). Since dataset (B) is a subset of dataset (A), the CMF Category 1A and 2A are a subset of CMFs from Category 1 and 2.

TABLE 5. CMF CATEGORIES AND USED SAMPLES

Category	Crash Type	Sample Approaches/Sites	Number of Samples
Total Crashes	All	(C) Target-Treatment-Only Sites	29 sites with 60 target-treatment-only approaches
Target – All (Category 1 & 2)	Left Turn, Same Roadway & Rear-End	(A) Target-Treatment Approaches	82 target-treatment approaches in 41 sites
Category 1	Left Turn, Same Roadway	(A) Target-Treatment Approaches	82 target-treatment approaches in 41 sites
Category 1A	Left Turn, Same Roadway	(B) Target-Treatment-Only Approaches	77 target-treatment-only approaches in 40 sites
Category 2	Rear-End	(A) Target-Treatment Approaches	82 target-treatment approaches in 41 sites
Category 2A	Rear-End	(B) Target-Treatment-Only Approaches	77 target-treatment-only approaches in 40 sites

3.1.3.4. Additional Changes in After Period

The team also reviewed if there were other major changes in signal or geometry in the after period of the target treatment implementation. For the treated *sites*, any change in geometry, signal, or signal operation that could affect the total crashes was reviewed. Similarly, for the treated *approaches*, any other significant change in geometry, signal, or operation in either the FYA signal approach or the opposing through and right turn signals were considered. If there was any additional change to the site or approach in the after period, the end of after period was modified to the point in time just before the change was made.

3.2. Development of Crash Modification Factors (CMFs)

A CMF is a multiplicative factor that is multiplied by the expected crash frequency without treatment to estimate the expected crash frequency after implementing the target treatment at a specific site. The Highway Safety Manual provides the CMFs for the type of left turn signal phasing (permissive, protected-permissive or permissive-protected, and protected), which can be determined for each approach and multiplied together to predict the intersection total crash frequency (*14*). A CMF value less than 1.0 implies a reduction in expected crashes, and a CMF value greater than 1.0 implies an increase in expected crashes after implementing the target treatment. For example, a CMF value of 1.3 indicates a 30% expected increase in crashes after implementing the target treatment (*15*).

For this research effort, the team estimated a CMF for the target treatment using the observed crashes for treatment and comparison groups in the before and after periods. The notations for observed and expected crashes discussed in this section are summarized in Table 6.

TABLE 6. SUMMARY OF NOTATION FOR COMPARISON GROUP METHOD

	Observed Crashes		Expected Crashes
Time Period	Treatment Group	Comparison Group	Treatment Group
Before	$N_{obs,T,B}$	$N_{obs,C,B}$	$N_{exp,T,B}$
After	$N_{obs,T,A}$	$N_{obs,C,A}$	$N_{exp,T,A}$

As noted earlier, this study developed CMFs for the total crashes and target crashes (Category 1, 1A, 2, and 2A) according to the before-and-after comparison group method. The team selected an appropriate comparison group for each treated site by following the selection method suggested by Hauer (*13*). Next, using the comparison group associated with each treatment site, the comparison ratios were calculated using the total crashes. The comparison ratio was calculated for each comparison group by dividing the total observed crashes in the before period by the total crashes observed in the after period.

With the computed comparison group ratios and observed target crashes for the treated sites in the before period, the expected target crashes for treated sites ($N_{exp,T,A}$) that would have occurred in the after period without the target treatment, and its variance ($Var(N_{exp,T,A})$), were estimated by the following equations.

$$N_{exp,T,A} = N_{obs,T,B} \cdot r_c = N_{obs,T,B} \cdot \left(\frac{N_{obs,C,A}}{N_{obs,C,B}}\right)$$

$$Var(N_{exp,T,A}) = (N_{exp,T,A})^2 \cdot \left(\frac{1}{N_{obs,T,B}} + \frac{1}{N_{obs,C,B}} + \frac{1}{N_{obs,C,A}}\right)$$

Lastly, a CMF and its associated variance were estimated by the following equations. These estimations assumed ideal comparison groups.

$$CMF = \left(\frac{N_{obs,T,A}}{N_{exp,T,A}}\right) / \left(1 + \left(\frac{Var(N_{exp,T,A})}{(N_{exp,T,A})^2}\right)\right)$$

$$Var(CMF) = \frac{CMF^2\left[\left(\frac{1}{N_{obs,T,A}}\right) + \left(\frac{Var(N_{exp,T,A})}{(N_{exp,T,A})^2}\right)\right]}{\left[1 + \frac{Var(N_{exp,T,A})}{(N_{exp,T,A})^2}\right]^2}$$

3.2.1. Selection of Appropriate Comparison Group

The research team selected appropriate comparison groups for the treated sites according to the comparison group site selection method suggested by Hauer *(13)*. The comparison group method tests that trends for comparison and treatment sites are consistent in the before period. Assuming a good candidate group can be chosen, the comparison group trends can also be used to predict what would have happened at the treatment site had no treatment been installed. As a first step, the team defined the before period as five years before the target treatment, a transition period as the two months after the target treatment, and the after period from right after the transition period to the most recent crash data on record. Then, the total number of crashes was assigned to each year in the before and after periods.

Given that there are up to four comparison sites in the comparison group for each treated site, a treated site could have up to 15 combinations of comparison sites. For example, a treated site with candidate comparison site 1, 2, 3, and 4, there could be 15 combinations of (1), (2), (3), (4), (1,2), (1,3), (1,4), (2,3), (2,4), (3,4), (1,2,3), (1,2,4), (1,3,4), (2,3,4), and (1,2,3,4). The most appropriate comparison group was selected based on the sample odds ratios, which were calculated for each of the 15 possible combinations.

To quantitatively evaluate the suitability of a candidate comparison group, Hauer suggested using a sequence of sample odds ratios. For each before-after pair in the time series before the treatment is implemented, the sample odds ratios can be calculated as follows (*13*).

$$Sample\ odds\ ratio = \frac{(Treated_{before} * \ Comparison_{after})/(Treated_{after} * Comparison_{before})}{1 + \frac{1}{Treated_{after}} + \frac{1}{Comparison_{before}}}$$

where,

- $Treated_{before}$ = total crashes for the treatment group in year i.
- $Treated_{after}$ = total crashes for the treatment group in year j.
- $Comparison_{before}$ = total crashes for the comparison group in year i.
- $Comparison_{after}$ = total crashes for the comparison group in year j.

It should be noted that the parameters on the right side of the equation represent the crashes in the before period. For example, Table 7 gives an example calculation of a sequence of sample odds ratios for a treated site (T-WAKE-1) and its comparison site #1. As shown in the table, the sample odds ratio can be computed for each year in the before period.

TABLE 7. AN EXAMPLE OF SAMPLE ODDS RATIO CALCULATION (TREATED SITE: T-WAKE-1)

Time	**Year**	**Number of Crashes**		**Sample Odds Ratio (o)**
		Treated Site (T-WAKE-1)	**Comparison Site #1**	
Before Periods	-5	2	6	-
	-4	7	5	(2*5)/(7*6)/(1+1/7+1/6) = 0.1818
	-3	9	7	(7*7)/(9*5)/(1+1/9+1/5) = 0.8305
	-2	6	9	(9*9)/(6*7)/(1+1/6+1/7) = 1.4727
	-1	8	15	(6*15)/(8*9)/(1+1/8+1/9) = 1.0112
	SUM	32	42	
	Implementation			
After Periods	+0 (2 months)	11	13	
	1	17	18	
	+2 or more	16	14	
	SUM	44	45	

With the computed sequence of sample odds ratios, the sample mean, m(o), and standard error, s(o), can be computed for a candidate comparison group. A candidate comparison group is suitable if the sample mean, m(o), is sufficiently close to 1.0 (*15*). According to Hauer's method (*13*), if several comparison groups all having an $m(o)$ sufficiently close to 1 are available, one should choose the comparison group for which $\left(\frac{1}{N}+\frac{1}{M}+Var(\omega)\right)$ is smallest (*13*). The $Var(\omega)$ can be calculated by following equation.

$$Var(\omega) = s^2(o) - \left(\frac{1}{K}+\frac{1}{L}+\frac{1}{M}+\frac{1}{N}\right)\ if > 0\ and\ 0\ otherwise.$$

where,

K = average collisions at the treatment site in the before period, $Treated_{before}$,
L = average collisions at the treatment site in the after period, $Treated_{after}$,
M = average collisions in the comparison group in the before period, $Comparison_{before}$, and
N = average collisions in the comparison group in the after period, $Comparison_{after}$.

It should be noted that the K, L, M, and N represent the average crashes in the before period only.

To filter the candidate comparison groups, this study examined comparison groups if they had $m(o)$ between 0.95 and 1.05, which was assumed to be close to 1.0 for this study. Next, the $\left(\frac{1}{N}+\frac{1}{M}+Var(\omega)\right)$ was compared between the candidate comparison groups to determine the most appropriate one for calculating the expected crash rate in the after period. Table 8 shows an example of parameters for the comparison groups for a treated site (T-WAKE-1).

TABLE 8. AN EXAMPLE OF COMPARISON GROUP PARAMETERS (TREATED SITE: T-WAKE-1)

Parameters	Comparison Group Combinations														
	1	2	3	4	1,2	1,3	1,4	2,3	2,4	3,4	1,2,3	1,2,4	1,3,4	2,3,4	1,2,3,4
m(*o*) =	0.874	0.667	0.608	0.685	0.743	0.797	0.776	0.671	0.687	0.679	0.733	0.734	0.755	0.685	0.727
s(*o*) =	0.267	0.154	0.075	0.221	0.186	0.183	0.235	0.132	0.184	0.172	0.164	0.198	0.196	0.164	0.179
1/M + 1/N + Var(w)	0.238	0.094	0.400	0.139	0.068	0.149	0.088	0.076	0.056	0.103	0.058	0.045	0.072	0.049	0.041

If a treated site has no comparison group with $m(o)$ between 0.95 and 1.05, the team examined the comparison site with $m(o)$ closest to 1.0 if 1.0 was located within the confidence interval of $m(o)$. If 1.0 fell within the confidence interval, the comparison group was selected for consideration. Table 9 shows the suitability test results for the comparison groups for the treated site, T-WAKE-1.

TABLE 9. SUITABILITY TEST RESULTS FOR COMPARISON GROUPS (TREATED SITE: T-WAKE-1)

Test	Question		Answer
Test 1: Examine if there is m(o) between 0.95 and 1.05	How many comparison groups had m(o)s between 0.95 and 1.05?		0
	What was the value of the m(o) closest to 1.0?		0.87
Test 2: If there is no m(o) between 0.95 and 1.05, examine if confidence interval of m(o) includes 1.0 at 95% level	Which comparison group had the m(o) closest to 1.0?		Comparison Group #1
	What was the confidence interval of the closest m(o) to 1.0?	m(o) -1.96*s(o)	0.74
		m(o) +1.96*s(o)	1.40
	Does the confidence interval include 1.0?		Yes
Best Comparison Group			Comparison Group #1

The table shows that no comparison group had $m(o)$ between 0.95 and 1.05. However, comparison group 1 has a $m(o)$ of 0.87, which was closest to 1.0, and its confidence interval is [0.74, 1.40] at 95% level includes 1.0, which made it suitable for use. The suitability test was applied to all candidate comparison groups for each treated site. The results found that a suitable comparison group could be found for every treatment site.

3.2.2. Comparison Ratio

Once all the candidate comparison groups were determined for each treatment site, comparison ratios were used to determine the expected crashes in the after period for treatment sites. The comparison ratio indicates the expected change rate in crash counts when the target treatment was not implemented at the treated sites. The comparison ratios (r_C) were then computed by dividing the total crashes for comparison groups in the before period by the total crashes in the after period (= $N_{obs,C,A}$ / $N_{obs,C,B}$).

Table 10 shows the comparison ratios calculated for each comparison group for each treated site. It should be noted that for all categories of CMFs (total crashes, Category 1, 1A, 2, and 2A), this study used the comparison ratios calculated using total crashes for each treated site.

TABLE 10. COMPARISON RATIOS FOR COMPARISON GROUPS

Treated Site ID	Best Comparison Group (C-G)	C-G Crashes in Before	C-G Crashes in After	Comparison Ratio, r_C
T_Wake_1	1	42	45	1.07
T_Wake_2	1,3,4	139	220	1.58
T_Mecklenburg_1	3	37	57	1.54
T_Mecklenburg_2	1,2,3,4	129	55	0.43
T_Mecklenburg_3	1,2,4	160	192	1.20
T_Mecklenburg_4	1,2,4	244	296	1.21
T_Mecklenburg_5	2,3	163	281	1.72
T_Mecklenburg_6	4	190	297	1.56
T_Mecklenburg_7	1	72	96	1.33
T_Mecklenburg_8	1,2,3	146	240	1.64
T_Mecklenburg_9	1,2	67	121	1.81
T_Mecklenburg_10	1,3,4	326	545	1.67
T_Mecklenburg_11	4	38	58	1.53
T_Mecklenburg_12	2,3	80	170	2.13
T_Mecklenburg_13	2,3	92	128	1.39
T_Mecklenburg_14	1,2,3	78	8	0.10
T_Mecklenburg_15	1	113	186	1.65
T_Mecklenburg_16	2	31	60	1.94
T_Mecklenburg_17	1,3	36	56	1.56
T_Mecklenburg_18	2,3	83	98	1.18
T_Mecklenburg_19	1,2,3,4	453	771	1.70
T_Mecklenburg_20	1,3,4	313	526	1.68
T_Mecklenburg_21	1	62	115	1.85
T_Mecklenburg_22	2	88	155	1.76
T_Mecklenburg_23	1,3	145	244	1.68
T_Mecklenburg_24	1,3,4	231	298	1.29
T_Mecklenburg_25	1	19	27	1.42
T_Mecklenburg_27	1,2	65	109	1.68
T_Mecklenburg_29	1,4	156	94	0.60
T_Mecklenburg_30	1,2,3,4	233	380	1.63

Treated Site ID	Best Comparison Group (C-G)	C-G Crashes in Before	C-G Crashes in After	Comparison Ratio, r_C
T_Mecklenburg_31	2,3,4	105	168	1.60
T_Mecklenburg_32	2,4	82	176	2.15
T_Mecklenburg_33	1,2,3,4	66	135	2.05
T_Mecklenburg_34	2,3,4	95	206	2.17
T_Mecklenburg_35	2,3	113	184	1.63
T_Mecklenburg_36	1,3	53	110	2.08
T_Mecklenburg_37	2,3,4	119	183	1.54
T_Mecklenburg_38	1,4	66	119	1.80
T_Mecklenburg_40	1,2	144	254	1.76
T_Mecklenburg_41	1,2,3	170	276	1.62
T_Mecklenburg_42	1,4	99	60	0.61
T_Mecklenburg_44	2,4	73	106	1.45
T_Mecklenburg_26	2,3,4	82	176	2.15
T_Mecklenburg_28	3,4	68	15	0.22
Average	-	121.95	184.00	1.51

3.2.3. CMF Estimation Results

With the computed comparison group ratios and observed target crashes for the treated sites in the before period, the expected target crashes for treated sites ($N_{expected,T,A}$) that would have occurred in the after period without the target treatment, and its variance ($Var(N_{expected,T,A})$), were estimated by the following equations.

$$N_{expected,T,A} = N_{observed,T,B} \cdot r_c = N_{observed,T,B} \cdot \left(\frac{N_{observed,C,A}}{N_{observed,C,B}}\right)$$

$$Var(N_{expected,T,A}) = (N_{expected,T,A})^2 \cdot \left(\frac{1}{N_{observed,T,B}} + \frac{1}{N_{observed,C,B}} + \frac{1}{N_{observed,C,A}}\right)$$

Next, a CMF and its associated variance were estimated by the following equations. These estimations assumed ideal comparison groups.

$$CMF = \left(\frac{N_{observed,T,A}}{N_{expected,T,A}}\right) / \left(1 + \left(\frac{Var(N_{expected,T,A})}{(N_{expected,T,A})^2}\right)\right)$$

$$Var(CMF) = \frac{CMF^2\left[\left(\frac{1}{N_{observed,T,A}}\right) + \left(\frac{Var(N_{expected,T,A})}{(N_{expected,T,A})^2}\right)\right]}{\left[1 + \frac{Var(N_{expected,T,A})}{(N_{expected,T,A})^2}\right]^2}$$

Table 11. CMF Development Results for Total Crashes shows the CMFs for the total crashes for 24 hours that were developed to assess the overall impacts of the target treatment on intersection safety. Table 12 shows the CMFs developed for target crashes (Target – All (Category 1 & 2), Category 1, 1A, 2, and 2A) to assess the impacts of target treatment on the target crashes (left turn, same roadway, and rear-

end crashes). As discussed in Section 3.1.3, the CMFs for Category 1 and 2 were estimated using the target crashes on all treated approaches, while Category 1A and 2A were estimated using the target crashes on the target-treatment-only approaches. The ‘Target – All’ in Table 12 represents the total target crashes including left turn, same roadway (Category 1) and rear-end (Category 2) crashes. To investigate the target crash CMFs more deeply, this study developed separate CMFs for the entire day (coded 24 hrs in the table) and by specific TOD operated by FYA-PPLT (coded PPLT in the table) using two different crash severity categories (all and injury only).

TABLE 11. CMF DEVELOPMENT RESULTS FOR TOTAL CRASHES

Category	Crash Type	Site/Approach	Time	Severity	$N_{exp,T,A}$	$N_{obs,T,A}$	CMF	Std. Err.
Total	All	Target-Treatment-Only Sites All Approaches	24hrs	All	2925	3059	1.044	0.043
				Injury Only	870	1046	1.199**	0.074

Note: The CMFs in this table were calculated using the total crashes in the unfiltered raw dataset.
Note: The statistical significance for the estimated CMFs are on the right of each CMF.
Statistical Significance: '**' < 0.01 < '*' < 0.05 < '.' < 0.1

TABLE 12. CMF DEVELOPMENT RESULTS FOR TARGET CRASHES

Category	Crash Type	Site/Approach	Time	Severity	$N_{exp,T,A}$	$N_{obs,T,A}$	CMF	Std. Err.
Target – All (Category 1 & 2)	Left Turn, Same Roadway & Rear-End	Target-Treatment Approaches[1]	24hrs	All	238	432	1.804**	0.175
				Injury Only	90	203	2.206**	0.332
			PPLT Only	All	28	257	4.665**	0.817
				Injury Only	11	135	5.072**	1.296
Category 1	Left Turn, Same Roadway	Target-Treatment Approaches[1]	24hrs	All	78	325	4.105**	0.625
				Injury Only	37	171	4.468**	0.958
			PPLT Only	All	28	257	8.562**	2.023
				Injury Only	11	135	10.505**	3.623
Category 1A	Left Turn, Same Roadway	Target-Treatment-Only Approachsdfes[2]	24hrs	All	76	289	3.732**	0.577
				Injury Only	37	150	3.919**	0.848
			PPLT Only	All	28	223	7.429**	1.763
				Injury Only	11	114	8.871*	3.073
Category 2	Rear-End	Target-Treatment Approaches[1]	24hrs	All	160	107	0.660**	0.093
				Injury Only	54	32	0.577**	0.141
			PPLT Only	All	30	22	0.699	0.212
				Injury Only	15	4	0.246**	0.134
Category 2A	Rear-End	Target-Treatment-Only Approaches[2]	24hrs	All	151	99	0.650**	0.095
				Injury Only	49	30	0.594**	0.150
			PPLT Only	All	26	19	0.676	0.217
				Injury Only	11	3	0.233**	0.141

Note: “Target – All” category indicates the total target crashes including both left turn, same roadway and rear-end crashes (Category 1 + 2).
Note: “PPLT Only” in the time column indicates the time-of-day operated by FYA-PPLT.
Note: The statistical significance for the estimated CMFs are on the right of each CMF.
Statistical Significance: '**' < 0.01 < '*' < 0.05 < '.' < 0.1

[1] A target-treatment approach was defined as an approach with the target treatment; however, it could include other treatments such as an exclusive right turn lane or signal modification to the opposing right turn movement.
[2] The target-treatment-only approach was defined in this study as a treated approach that had no other change besides the target treatment that could affect target crashes. The classification types for the treated approaches and sites are defined in detail in section 3.1.3.

The results in Table 11. CMF Development Results for Total Crashes showed a CMF of 1.044 for the *total crashes* with all severities for 24 hours; however, the results were not statistically significant implying the conversion from protected-only to FYA-PPLT had not change in overall intersection safety. When looking at severe crashes only for this category, there was a statistically significant increase of 19.9% in this crash type.

As for the target crashes, the CMFs for 'Target – All' had the value greater than 1.0, which implies that the target treatment caused an increase of 80.4% (= $(1.804 - 1) \times 100\%$) in target crashes. When looking at the subgroups, Category 1 and 1A had the value greater than 1.0, while Category 2 and 2A had the value lower than 1.0. These results imply that the target treatment caused subsequent increase in Category 1 and 1A crashes, but reduced Category 2 and 2A crashes. For example, the CMF for Category 1 for 24 hours was 4.105, so we can expect an increase of 310.5% (= $(4.105 - 1) \times 100\%$) after the target treatment. The CMFs for Category 1 and 1A for PPLT had higher values than those for 24 hours. With the CMFs for PPLT, we can estimate the increase/decrease rate in target crashes for the hours operated by FYA-PPLT. For example, the CMF for Category 1 crashes for PPLT was 8.562, which implies that we can expect an increase of 756.2% (= $(8.562 - 1) \times 100\%$) for the left turn, same roadway crashes for the hours operated by FYA-PPLT after the implementation of target treatment. Contrary to Category 1 and 1A, all CMFs for Category 2 and 2A showed the value less than 1.0, indicating that rear-end crashes are expected to decrease after the target treatment. With the estimated CMFs for Category 2, we can expect a reduction of 34.0% (= $(0.660 - 1) \times 100\%$) in rear-end crashes for 24 hours and a reduction of 30.0% (= $(0.699 - 1) \times 100\%$) in rear-end crashes for the hours operated by FYA-PPLT.

In the table, the CMF, standard error of CMF, and statistical significance for the 90%, 95%, and 99% confidence intervals are provided for each category. With the estimation results, the results were determined to be significant by examining if the true value of CMFs was within the confidence interval. For example, the 95% confidence interval of the CMF for "total crash CMF – 24 hours, all severity" is the [0.959, 1.129], which is the CMF ± 1.96 * SE(CMF) (= 1.044 ± 1.96 X 0.043). Since 1.0 falls in the confidence interval, it cannot be stated with 95% confidence that the true value of the CMF is not 1.0 *(13).* In short, the CMF was determined to be statistically significant because it is different than 1.0. In the results, all estimated CMFs were statistically significant at a 95% or 99% level except for the "Total - 24 hours, all severities", rear-end "Category 2 – PPLT, all severities" and "Category 2A – PPLT, all severities." In fact, these thee CMFs were not significant at any of the three tested levels (90%, 95%, and 99%). Therefore, it is not certain that the treatment was different from 1.0.

Based on the CMF development results, the following can be said about crashes at sites converted from protected only to PPLT:

- Overall, total crashes had slight increase and target crashes had relatively higher increase than the total at the treatment sites following implementation of the FYA-PPLT treatment at one or more approaches.
- When looking at crashes over the entire 24-hour day, regardless of treated only approach or all approaches, left turn crashes increased approximately 300% (CMF's range from 3.732 – 4.468) compared to rear-end crashes which decreased about 40% (CMF's range from 0.577 – 0.660). All findings were statistically significant.
- When looking at crashes only during use of the PPLT FYA, regardless of treated approach or all approaches, left turn crashes increased approximately 800% (CMF's range from 7.429 – 10.505) compared to rear-end crashes which decreased by 30-75% (CMF's range from 0.233 – 0.699). All CMF's were statistically significant, except for the rear-end PPLT crashes.

Summarizing, overall crashes over the entire 24-hour period showed no change in following the FYA-PPLT treatment; however, they did significantly increase the severity of crashes. Filtering crashes by left turn and rear end related crashes, there appears to be a significant trade-off that should be carefully considered prior to implementation of the treatment. It is possible that there may be room for improving safety by implementing protected-only use more on the fringes of the peak periods as traffic increases.

4. GUIDELINES FOR PPLT FYA USE BY TOD

4.1. Operational Considerations

From an operational analysis perspective, a key objective of this research is to provide a quantitative measure of the delay savings that result from the conversion of a left turn signal from protected-only to protective-permissive or permissive-only phasing by TOD to account for the volume variability across the day that may or may not warrant a protected phase 24 hours a day.

4.1.1. Methodology

To estimate the delay savings realized by different left turn protection plans under a wide variety of geometry and volume combinations, a microsimulation-based methodology was developed. The resulting tool tests two phasing scenarios, a “base” and “comparison” case, against each other over a 24-hour period to determine relative differences in delay. This approach differs substantially from existing macro and microsimulation programs, such as SYNCHRO or VISSIM, in several respects:

- Ease of Use: The methodology outlined below is fully contained in an Excel spreadsheet. It is designed as a guide to decision-making when it is not feasible, or desirable, to spend significant resources modeling multiple intersection configurations using commercial microsimulation software for each hour of the day.
- Full-Day Modeling: The model tests an entire day’s worth of signal timing plans at once. Users can quickly test the effects of varying left turn protection plans, cycle length, and coordination across a full 24-hour period.
- Single-Intersection Focus: Most modern microsimulation packages explicitly account for traffic progression between multiple intersections. This tool provides analysis options for both coordinated and isolated intersections, but only models one intersection at a time using HCM arrival types to model the effect of coordination.

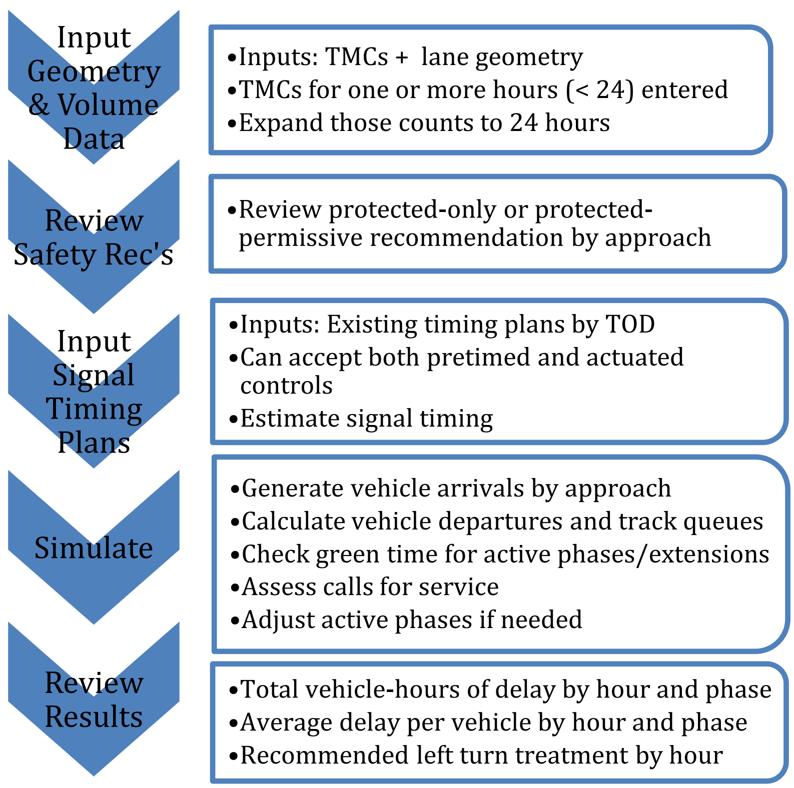


FIGURE 3. RROTECTED-ONLY OR PPLT RECOMMENDATION BY APPROACH

4.1.1.1. Overview

Figure 3 below summarizes the major steps of the simulation program. The following sections describe the required user inputs and discuss the computational algorithms used in each part of the operational evaluation process.

4.1.1.2. User Inputs

4.1.1.2.1. Intersection Geometry

This tool is designed to accommodate four-legged and T-intersections. It can model any number of exclusive left turn and exclusive through lanes. Each approach can either have one or more *exclusive* right-turn lanes or a single *shared* right and through lane, but not both. During development, it was assumed that shared left-through lanes would not operate under protected-permissive left turn timing; therefore, the tool was not designed to model them. For similar reasons, modeling of single-lane approaches is not supported.

4.1.1.2.2. Traffic Counts

The user can enter peak-hour, 13-hour, or 24-hour counts in either fifteen-minute or hour-long "bins." Next, these input volumes are expanded to represent the full day counts at 15-minute resolution. The expansion is based on hourly distributions developed in NCDOT 2014-11, *Evaluation of Life Cycle Impacts of Intersection Control* (28).

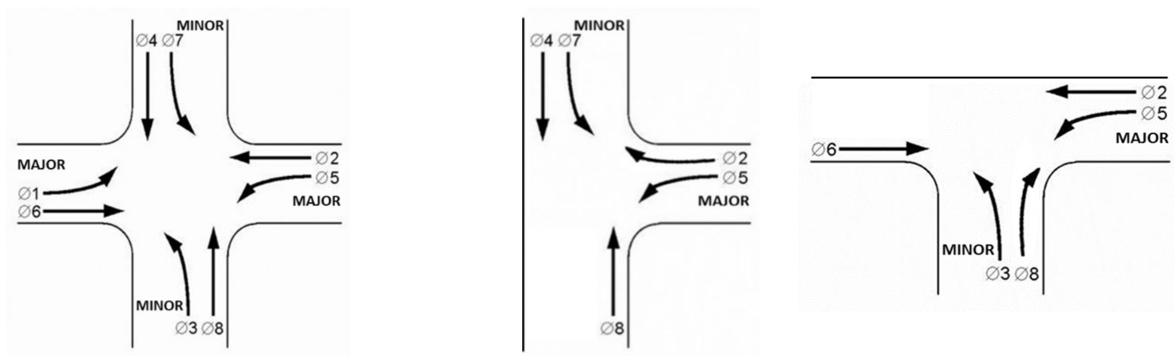
To predict turning movements over the entire 24-hour period, the tool features six predictive distributions:

- Two minor equivalent peaks (minor AM, minor PM)
- Two major equivalent peaks (major AM, major PM)
- Two peaks (minor AM, major PM)
- Three peaks (minor AM, Noon, major PM)
- Tourist area (no prominent peaks)
- Average (average of the previous distributions)

Once the appropriate distribution is selected, the operational tool will calculate the AADT for each movement. This is completed by determining what portion of traffic typically falls within the time period selected by the user, then back-calculating an AADT. For example, if the distribution suggests that 10% of the traffic volume occurs during the peak hour and the peak hour entry was 100 vehicles, then the AADT would be 1,000 vehicles per day. Once the AADT is determined, the counts outside of the user-input time window are estimated by multiplying the suggested percent of traffic volume that falls at that hour by the AADT using the appropriate hourly distribution. These estimates are further disaggregated into 15-minute counts using the following algorithm:

- 0-15 minutes: $0.25 * Hourly\ Volume$
- 15-30 minutes: $0.25 * Hourly\ Volume/PHF$
- 30-45 minutes: $0.25 * Hourly\ Volume$
- 45-60 minutes: $(Hourly\ Volume) - (Previous\ three\ counts)$

The simulation spreadsheet allows the user to input left-turn, through, and right-turn volumes for each intersection approach. However, these volumes are converted to NEMA phasing to calculate cycle lengths and operation delay. The NEMA phases are shown in Figure 4.



Four-Legged Intersection T-Intersection (Major) T-Intersection (Minor)

Le·FIGURE 4. NEMA PHASES FOR THREE INTERSECTION TYPES MODELED IN GUIDANCE-BASED TOOL

conversion of through and right-turn movements to phases 2, 4, 6, and 8 differs for four-legged intersections and T-intersections. At four-legged intersections, if an approach has a shared right-turn lane (and thus no exclusive right-turn lanes), right-turning volumes are added to through movements using the following equation:

$$Volume = \frac{Through\ Lane\ Sat\ Flow\ Rate}{Exclusive\ Right - Turning\ Lane\ Sat\ Flow\ Rate} * V_{right} + V_{through}$$

where V_{right} and $V_{through}$ are the right-turning and through volumes, respectively. On approaches with exclusive right-turning lanes, right turns are assumed to be served concurrently to throughs on the same approach and/or shadowing the neighboring left turn on the cross street, and therefore are not included in further analysis; the NEMA through phase corresponding to that approach is set equal to the through volume. At T-intersections, the assumptions above hold for all approaches except at the stem of the T approach. On that approach, since there are no through movements, the right-turning volume is converted into Phase 2 volumes (if the major road is terminating) or Phase 8 volumes (if the minor road is terminating) using the following equation:

$$Volume = \frac{Through\ Lane\ Sat\ Flow\ Rate}{Exclusive\ Right - Turning\ Lane\ Sat\ Flow\ Rate} * V_{right}$$

Note that these "adjusted" volumes are used only for internal calculations; all final report metrics, such as delay, are based on the actual number of vehicles counted at the intersection (or predicted to be at the intersection based on hourly distributions.)

4.1.1.2.3. Left Turn Protection Plan by Time of Day

Section 3 of this report details the algorithm used to provide hour-by-hour recommendations of whether to constrain each approach at the subject intersection to protected-only left turns based strictly on safety concerns. These recommendations are provided on an individual-approach basis; however, it is assumed that if one left turn approach along a road indicates a need for protected-only operation, both left turns along that roadway will be operated using protected-only phasing.

Based on existing or projected field conditions, up to twenty signal timing plans can be specified for both the base and comparison scenarios. For four-legged intersections, each road can be set to protected-only, protected-permissive, or permissive-only left turn operation. As noted above, protection type is constrained to be the same for both approaches along a road, although it can differ between the major and minor roads. Lead-lead, lead-lag, and lag-lag left turn timing patterns are all supported. For T-intersections, a reduced set of options is available, reflecting that at the stem of the T the approach will discharge left-turning and right-turning vehicles simultaneously.

4.1.1.2.4. Intersection Coordination

This tool allows the intersection to switch between isolated and coordinated operation during different time-of-day plans. Isolated plans operate under the following assumptions:

- Variable cycle length.
- Arrivals on all approaches follow a shifted negative exponential distribution.
- Platoon ratio, defined as the ratio of the fraction of vehicle arrivals in green to the green to cycle ratio, is 1.00 for all approaches.
- Soft recall to major-road through is in effect.

Coordinated plans operate under the following assumptions:

- Fixed, background cycle length.
- Arrivals on the major-road through movement follow a Cowan M3 distribution; some of the vehicles arrive in platoons, separated by the minimum headway, and the remainder follow a shifted negative exponential distribution.
- All other approaches' arrivals follow a shifted negative exponential distribution.
- Provided in TABLE *13*, the platoon ratio varies depending on the level of coordination.

TABLE 13. PLATOON RATIO ASSUMPTIONS

Option	Phase 2	Phase 6	All Others
Phase 2 Coordinated	1.33	1.06	1.00
Phase 6 Coordinated	1.06	1.33	1.00
Balanced	1.17	1.17	1.00

- Floating force-off: All unused time defaults to the major-road through phases.

4.1.1.2.5. Signal Actuation

The intersection can be modeled as either pre-timed or actuated. If signal actuation is selected, all approaches are assumed to have the appropriate detection scheme.

4.1.1.2.6. Coordinated Cycle Length

If coordinated operation is selected, the cycle length and minimum green for the major road are both required inputs. Minimum green for the major road is assumed to be a predetermined constraint based on desired signal progression.

4.1.1.2.7. Signal Timing by Phase

Signal timing is, by default, a user-input parameter. However, the simulation tool includes an optional signal timing estimation algorithm based on equalizing the volume-to-capacity ratio on all approaches. Depending on whether the intersection is operating in isolated or coordinated mode, the goal of the program varies slightly:

- *Isolated*: The algorithm will attempt to equalize v/c ratios to meet a user-input goal without exceeding a user-defined minimum and maximum cycle length (see Default Values section below.) By default, the target v/c is 0.85 but can be altered by the user.
- *Coordinated*: The algorithm will equalize v/c ratios, given that the cycle length must equal the given coordinated cycle time.

Timing plans are estimated based on the 15 min highest-volume encompassed by the plan. An iterative process is used. Initially, the cycle length is set to the sum of minimum greens and lost times for all conflicting phases. The cycle length is increased in 0.1-second increments using the following process until the relevant condition above is met:

- The volume-to-capacity ratio is calculated for Phases 1 to 8.
- The phase with the highest v/c ratio has one tenth of one second added to its green time.
- The non-conflicting phase on the same road with a higher v/c ratio has one tenth of one second added to its green time. For example, if a through movement was selected for time extension in the previous step, either the opposing through movement or same-approach left turn would be eligible for time extension in this step.

V/C ratios for protected left turns and through movements are calculated according to the equation:

$$v/c\ (phase) = \frac{15 min\ volume}{0.25 * \ saturation\ flow\ rate * \frac{LT\ green\ time}{Cycle\ length}}$$

The additional capacity granted by the opposing through green for protected-permissive left turns is calculated using a variant of the Highway Capacity Manual's queue accumulation polygon method. Uniform arrivals are assumed to estimate the queue at the beginning of the opposing green and time required to discharge the queue. Any additional opposing green time is converted to an equivalent capacity using the relationship:

$$Permissive\ Capacity\ every\ 15\ Minutes = \frac{g_u}{C} * [\frac{v_{opp} * e^{-v^{opp} * \frac{t_{cg}}{900}}}{1 - e^{-v_{opp} * \frac{t_{fh}}{900}}}]$$

where the bracketed term represents the opposed left turn saturation flow rate, and:

- $g_u \ = Opposing\ Through\ Green\ Not\ Blocked\ by\ Discharging\ Queue$
- $C \ = Cycle\ Length$
- $v_{opp} = Opposing\ Through\ 15 - Minute\ Volume$
- $t_{cg} \ = Critical\ Headway$
- $t_{fh} \ = Follow - Up\ Headway$

It is assumed that in cases where there is an exclusive right-turn lane on the opposing approach, right-turn movements do not impact left-turning drivers' gap acceptance.

4.1.1.2.8. Model Default Values

The tool calculates movement delay across a full day of signal operation for two scenarios, a base and a comparison case. The default values listed in TABLE *14* are assumed constant throughout the entire day, but can be varied between the two scenarios. These values may be changed by the analyst if desired to better reflect local intersection conditions during the base scenario, comparison scenario, or both.

TABLE 14. SIGNAL TIMING PARAMETERS

Parameter	Default Value	Units
Protected Left Turn Saturation Flow Rate per Lane	1750	veh/hr/ln
Through Saturation Flow Rate per Lane	1850	veh/hr/ln
Right Turn Saturation Flow Rate per Lane	1750	veh/hr/ln
Minimum Cycle Length	60	sec
Maximum Cycle Length	300	sec
Minimum Headway, Left Turns	2.0	sec
Minimum Headway, Through Movements	0.5	sec
Critical Gap for Left Turns	4.5	sec
Follow-up headway for Left Turns	2.5	sec
Max Left Turn Delay Setting	15	sec
Major Road: Minimum Protected Left Turn Green Time	7	sec
Major Road: Minimum Isolated Through Movement Green Time	10	sec
Minor Road: Minimum Protected Left Turn Green Time	7	Units
Minor Road: Minimum Through Movement Green Time	10	veh/hr/ln
Green Extension Time - Left Turns	3	veh/hr/ln
Green Extension Time - Through Movements	3	veh/hr/ln
Lost Time per Phase	6	sec

- *Saturation Flow Rate* is the number of vehicles that would be discharged, assuming a continuous queue and uninterrupted green from a lane in an hour. *Through and left turn saturation flow rate* are the analogous parameters for through and left turn lanes. *Right turn saturation flow rate* is relevant on approaches with shared through and right turn lanes, or on the terminating approach of a T-intersection. In both cases, the ratio between through saturation flow rate and right turn saturation flow rate is used to convert right-turning vehicles into an equivalent number of through vehicles.
- *Minimum and Maximum Cycle Length* apply if the tool's signal timing algorithm is used. If the user requests to determine timing for an isolated intersection, the tool will attempt to meet a target volume-to-capacity ratio while remaining between the minimum and maximum cycle lengths. If the user manually inputs maximum greens, these parameters do not apply.
- *Minimum Headways* apply on a per-lane basis. For example, if an approach has three through lanes and a minimum through headway of 0.9 seconds, through vehicle arrivals on that approach as a whole will never be separated by a value less than:

$$\frac{0.9\ seconds\ per\ lane}{3\ lanes} = 0.3\ seconds$$

- *Critical Gap for Left Turns* represents the smallest gap in opposing through traffic that, under protected-permissive or permissive left turn operation, a left-turning vehicle will utilize if no other vehicles have used that specific gap yet.
- *Follow-up Headway for Left Turns* indicates the additional gap width required for subsequent left-turning vehicles after one vehicle has already turned.

- *Max Left Turn Delay Setting* indicates how long a vehicle must be present at a left-turn detector before a call for service is placed. This is useful for low-volume protected-permissive operation to prevent calling a left-turn phase when it could be easily served by gaps in the opposing through stream.
- *Minimum greens* indicate the minimum amount of time a phase will be served once the corresponding signal has turned green. Different minimum greens can be assigned to the major and minor road left and through movements, for a total of four separate settings. A fifth minimum green setting, representing the minimum coordinated bandwidth on the coordinated road, only applies to major-road through movements during coordinated operation; unlike the others, this setting can be varied throughout the day.
- *Green Extension Time* indicates how long an active green phase will be extended, up to the maximum green, each time another vehicle arrives.
- *Lost Time per Phase* represents the yellow and all-red interval between phases. Lost time is allocated at the beginning of each phase. Start-up lost time and the extension of effective green are assumed to be equivalent and are not explicitly modeled. As a result, effective and actual green times are equal.

4.1.1.3. Simulation Algorithm

Delays are calculated across the full day of signal timing plans specified by the analyst using a limited microsimulation approach. Arrivals are stochastically generated, but departure behavior is deterministic, and individual car-following is not implemented. A five-step process is implemented at 0.1-second resolution:

- Generate Arrivals
- Calculate Departures and Queues
- Check Green Time for Active Phases
- Assess Calls for Service
- Adjust Active Phases if Needed

Volumes, signal timing, left turn protection, and signal coordination are varied at fifteen-minute intervals, as specified by the analyst. Delay per phase (per period and per vehicle) is reported on an hourly basis at the end of the simulation run.

Each step is further explained in the subsections below. Depending on the capabilities of the computer being used, simulation run times can vary substantially. A newer laptop with 16GB of RAM can run the base and comparison scenarios across 24 hours in about five minutes; an older laptop with 8GB of RAM takes fifteen to twenty minutes.

4.1.1.3.1. Generate Arrivals

Arrivals are generated randomly on a phase-by-phase basis (i.e. at a four-leg intersection, there are eight arrival generation equations.) Coordinated through movements are modeled accounting for platooning and minimum headways. Arrivals in all other cases are modeled assuming no bunches or platoons. Coordinated movements must account for different mean headways during red and green based on the movement's platoon ratio. Given

$$R_p = P_g \frac{C}{g}$$

and

$$\bar{h} = \frac{900}{V_{15}} \quad \rightarrow \quad \bar{h}_{green} = \frac{900 * g/C}{V_{15} * P_g} \quad \rightarrow \quad \bar{h}_{red} = \frac{900 * \frac{C-g}{C}}{V_{15} * (1 - P_g)}$$

where,

- R_p = platoon ratio
- P_g = proportion of arrivals during green
- C = cycle length
- g = green time per cycle (effective and actual green are identical for this model)
- $\bar{h}_{green}$ = mean arrival headway during green
- $\bar{h}_{red}$ = mean arrival headway during red
- V_{15} = fifteen-minute volume

The above equations are valid for all approaches, but if a movement is not coordinated, Rp = 1 and the mean headways during red and green are equal. Conceptually, coordinated traffic can be described by two groups: a proportion of traffic traveling in platoons, separated by some minimum headway, and the remainder of traffic traveling at longer headways. Coordinated through arrivals are generated using Cowan's M3 model (19). The distribution of headways is defined by:

$$p(t) = \begin{matrix} 0 & h < \alpha \\ 1 - \vartheta & h = \alpha \\ \lambda\vartheta e^{-\lambda(t-\alpha)} & h > \alpha \end{matrix}$$

where,

- $p(t)$ is the probability density function of headway t,
- ϑ is the proportion of vehicles **not** in a platoon, or free vehicles
- λ is a Cowan model parameter
- α is the minimum headway (typically 2 seconds)

ϑ and λ are estimated as

$$\lambda = \frac{\vartheta}{h - \alpha}$$

$$\vartheta = e^{-\frac{\alpha}{h}}$$

where,

- h = mean arrival headway or inverse of the flow rate

and all other variables are as previously defined.

On non-coordinated approaches, arrivals are assumed to arrive without any influence from upstream traffic lights or platooning, i.e. $\vartheta = 1$. As a result, while a minimum headway is still observed, bunching into platoons is not expected. Cowan's M2 model (19) is used to generate headways:

$$p(t) = \lambda e^{-\lambda(t-\alpha)}$$

$$\lambda = \frac{1}{h - \alpha}$$

with all variables as previously defined.

4.1.1.3.2. Calculate Departures and Queues

Lost time, representing the yellow and all-red transition between phases, is allocated at the beginning of each phase. For simulation purposes, start-up lost time and the extension of the effective green are assumed to be equal, and not explicitly modeled. Thus, effective green and actual green times are equal.

During the entire green time, vehicles are served at saturation headway. At the termination of the left turn green, if a queue remains, up to two vehicles will be served. The first vehicle counteracts the tendency of this model to underestimate capacity. Without this correction, any fraction of time less than the saturation headway remaining at the end of the phase would not be used. The second vehicle accounts for "sneakers," drivers who traverse the intersection during the yellow or all-red period.

If protected-permissive left turns are enabled, left-turning vehicles will be served during the permissive period depending on the frequency and length of gaps in the opposing through movement. The first left turn will be served after no opposing through vehicles have passed for at least the critical gap time (by default, 4.5 seconds). Further left-turning vehicles will be served at the follow-up headway (by default, every 2.5 seconds) until another opposing through vehicle arrives; at that point, no more left turns will be served until the critical gap is once again available.

4.1.1.3.3. Check Green Time for Active Phases

Lost time and green time are tracked on a phase-by-phase basis across timesteps. During this part of the timestep loop, active phase timers are advanced by a 0.1-second increment.

4.1.1.3.4. Determine Calls for Service

Determination of calls for service is dependent on whether the intersection is pre-timed or actuated. Pre-timed intersections call all phases in turn, providing the same green time in each cycle. Actuated intersections place calls for service in the following situations:

- If the movement has a green light:
    - The minimum green has not been reached yet.
    - The maximum green has not been reached yet, and the last vehicle arrived within the green extension time.
- A through movement has a red light and there is a queue.
- A left-turn movement has a red light and a queue has been present long enough for the left turn delay timer to expire.

4.1.1.3.5. Adjust Active Phases if Needed

The intersection is modeled as a finite-state machine. The operations tool enumerates every non-conflicting combination of green phases as shown in TABLE *15*. In this scheme, lost times are allocated to the beginning of each "green" phase.

TABLE 15. POSSIBLE PHASE COMBIMINATIONS

Intersection States								
State	Phase 1	Phase 2	Phase 3	Phase 4	Phase 5	Phase 6	Phase 7	Phase 8
1	Red	Red	Red	Red	Red	Red	Red	Red
2	Green	Red	Red	Red	Green	Red	Red	Red
3	Green	Red	Red	Red	Red	Green	Red	Red
4	Red	Green	Red	Red	Green	Red	Red	Red
5	Red	Green	Red	Red	Red	Green	Red	Red
6	Red	Red	Green	Red	Red	Red	Green	Red
7	Red	Red	Green	Red	Red	Red	Red	Green
8	Red	Red	Red	Green	Red	Red	Green	Red
9	Red	Red	Red	Green	Red	Red	Red	Green

At each timestep, the intersection will either remain in its current state (i.e. continue serving the same phases), or switch to a new state (i.e. serve a new pair of phases.) The progression between states is defined by several factors:

- Lead-lead, lead-lag, or lag-lag phasing. In the presence of constant demand, the signal will follow a predictable series of states; for example, for lead-lead phasing on the major road, Phases 1 and 5 (State 2) would be served before Phases 2 and 6 (State 5).
- The current state. Regardless of demand, the signal will not revert to an earlier "step" until it completes an entire cycle. For example, if a minor road operating under lead-lead timing has progressed to serving both through movements, the only state changes it can make are to continue serving both through greens or gap out.
- The presence or absence of demand on each approach. Returning to the previous example, if there was never any left-turn demand on Phase 3 or 7, the "lead-lead" portion would be skipped automatically, and Phases 4 and 8 would be called early.

The state table, shown in *TABLE 16,* is used to enumerate every combination of timing plan, current state, and calls for service by approach. Each combination occurs only once, and maps to the resulting state the intersection will have for the next timestep. An excerpt of the table used in the operations tool is included below.

TABLE 16. SIGNAL STATES

Timing Plan	Current State	Calls for Service								Next State
		Ph. 1	Ph. 2	Ph. 3	Ph. 4	Ph. 5	Ph. 6	Ph. 7	Ph. 8	
1 Lead, 5 Lead	1	Active	Active			Active	Active			2
1 Lead, 5 Lead	1	Active	Active			Active	Inactive			2
1 Lead, 5 Lead	1	Active	Active			Inactive	Active			3
1 Lead, 5 Lead	1	Active	Active			Inactive	Inactive			3
1 Lead, 5 Lead	1	Active	Inactive			Active	Active			2
1 Lead, 5 Lead	1	Active	Inactive			Active	Inactive			2

4.1.2. Performance Measures

The guidelines outlined in this section provide a framework for interpreting the potential changes in delay caused by switching between protected, protected-permissive, and permissive left turn operation. In many cases, safety considerations or policy decisions may outweigh the operational benefits realized by protected-permissive or permissive-only operation. This section provides a summary of the delay-based performance measures that are provide from the simulation run and presented on an hour-by-hour basis.

Total delay per phase is calculated as the product of the queue length and time, as illustrated in the diagram below. This shares many aspects with Queue Accumulation Polygon shown in the 2016 Highway Capacity Manual (17).

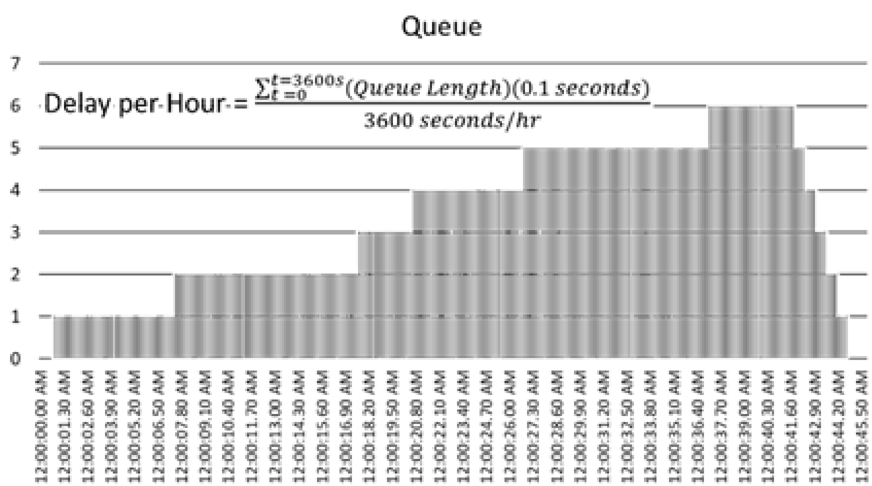


FIGURE 5. QUEUE ACCUMULATION POLYGON (17).

Vehicles arriving during a green light and immediately traversing the intersection are not included in the queue calculations; delay serves as a measure of additional transit time imposed as a result of the intersection signal control. Average delay per vehicle is calculated by allocating the total hourly delay per phase to vehicles that arrived during the hour:

$$Average\ Delay\ per\ Vehicle = \frac{Total\ Delay}{Hourly\ Volume}$$

In cases where right-turning vehicles were converted to equivalent through movements, the unadjusted number of vehicles was used to determine volume. On approaches where right-turn volumes were discarded from analysis due to the presence of exclusive right-turn lanes, the average delay is calculated for through movements only. Both total delay and average delay may assign some proportion of an oversaturated intersection's delay to the next (undersaturated) hour, since the accumulated queues will not dissipate until then. Finally, Level of Service (LOS) is calculated based on average delay per vehicle, and is consistent with the categories used in the 2016 Highway Capacity Manual, show below in Table *17*.

Table 17. LOS (17)

LOS	Avg Delay (sec/veh)
A	≤10
B	>10 - 20
C	>20 - 35
D	>35 - 55
E	>55 - 80
F	>80

4.2. Safety Considerations

The purpose of the safety guidance provided in this report is to support engineers in making informed decisions about whether to implement the target treatment – the PPLT FYA. Without considering safety guidelines, operational models will always find that a permissive or PPLT treatment is more efficient than a protected-only movement; however, that may or may not be the best decision based on safety. Even though the estimated CMFs indicate the expected changes in yearly crash frequencies, engineers may still want to know when the FYA-PPLT operation is acceptable as traffic volumes vary throughout the day. This study considered three methods of hourly crash analysis: cross-product volumes by hour-of-day, regression tree analysis, and a conflict point safety performance function (CP-SPF). Although all three methods are described herein, the CP-SPF method was used to develop safety guidelines in the integrated simulation tool.

The CP-SPF is one of the two model types (conflict point and non-conflict point SPFs) for the movement-based safety performance functions (MB-SPFs) that were proposed in a previous NCDOT project investigating the operational and safety performance of grade-separated intersections (*15*). The CP-SPF predicts the number of crashes that would occur at a conflict point where two different turning movements (e.g., Southbound left turn and Northbound through) conflict. For the crash prediction, the CP-SPF can use the two conflicting movement volumes and the type of conflict point (crossing, merging, and diverging). Given that the target crashes are the left turn-related crashes, the CP-SPF in this study was developed using the two conflicting movement volumes only. The detailed model development process is discussed in Section 4.2.4.

4.2.1. Analysis Data

For the three methods of hourly crash analysis, this study used the after-period crash data of Category 1 (left turn, same roadway), Category 2 (rear-end), and turning movement counts (TMCs) for 13 hours from 6:00 AM to 7:00 PM. In this process, one hour (e.g., 6:00 to 6:59 AM) was excluded from the analysis if its operation type was different between weekdays and weekends (e.g., operated by protected left turn on weekdays and PPLT on weekends) because the TMC data do not distinguish between weekdays and weekends. Also, some TOD hours operated by FYA-PPLT were not included in the analysis since the FYA-PPLT was implemented during off-peak hours in most of the treated sites.

After filtering the crash and TMC data, the team obtained the 143 target crashes in the after period. The 53 crashes occurred during the hours operated by PPLT, and 90 crashes occurred during the hours operated by protected LT, for a total 806 sample hours (165 hours for PPLT and 641 hours for the protected LT). This dataset was commonly used for the three methods of scatter plot, regression tree, and CP-SPF.

4.2.2. Cross-Product Volumes by Hour-of-Day

A common approach to determine if protected left turn signalization should be used is to compute the cross-product of the left turn (LT) and opposing through plus right turns (RT). The team took this first step approach by attempting to visually compare the hourly crash rates to cross-product volumes using scatter plots. Before the analysis, the research team hypothesized that the hourly crash rate should increase as the cross-product volume increases and, at some point, a “knee” in the curve would take place where safety became noticeably worse. The crash rate was calculated by following equation:

$$Crash\ Rate_{Target} = \left(\frac{Target\ Crashes_{After} \times 1{,}000{,}000\ veh}{Cross - Product\ Volume \times 365\ days \times After\ Period\ (yrs)}\right)$$

where,

$Crash\ Rate_{Target}$	= the target crash rate for the after period (hourly crashes/MEV·year)
$Target\ Crashes_{After}$	= the target crash counts for an hour in the after period
$Cross - Product\ Volume$	= the hourly cross-product volume for LT and TR movements (vph)
$After\ Period$	= the number of years for the after period (years)

Figure 6 shows the scatter plots for operation types and target crash categories. The first, second, and third rows represent the scatter plots for Category 1 (left turn – same roadway), Category 2 (rear-end), and Categories 1 & 2 (combined), respectively. The first and second rows are the subset of the third row. Similarly, the first, second, and third columns represent the prot/perm LT (PPLT), protected LT, and PPLT & Protected LT (combined), respectively.

Overall, the scatter plots showed that the actual trend between hourly crash rate and cross-product volume contradicts our expectation: the hourly crash rate decreased as the cross-product volume increased. Furthermore, there was no obvious threshold of cross-product volume where the hourly crash rate rapidly increased or decreased. A possible explanation for this counterintuitive result is that most hours in the dataset contained few or even zero crashes, even under the relatively high cross-product volume condition. This might lead to a rapid decrease in the hourly crash rate when the cross-product increases. For this reason, this technique was deemed unhelpful and alternative approaches were sought.

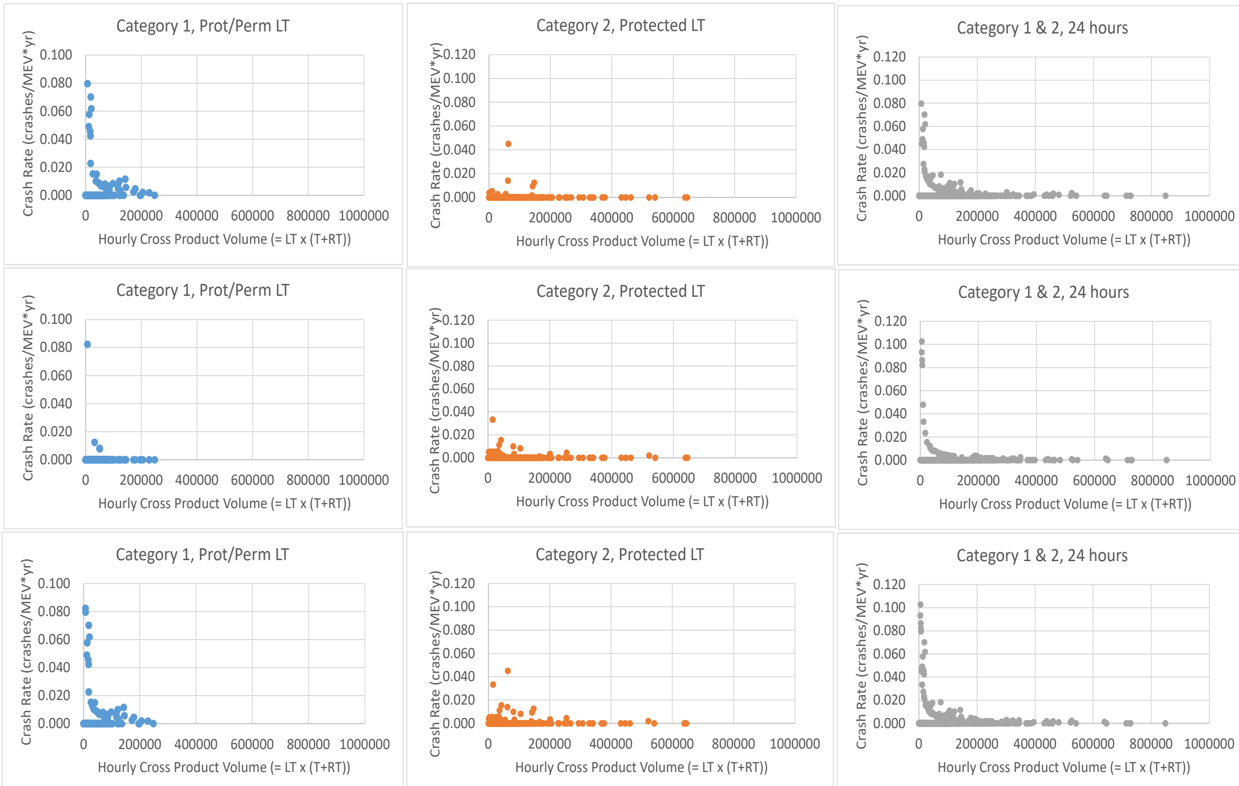
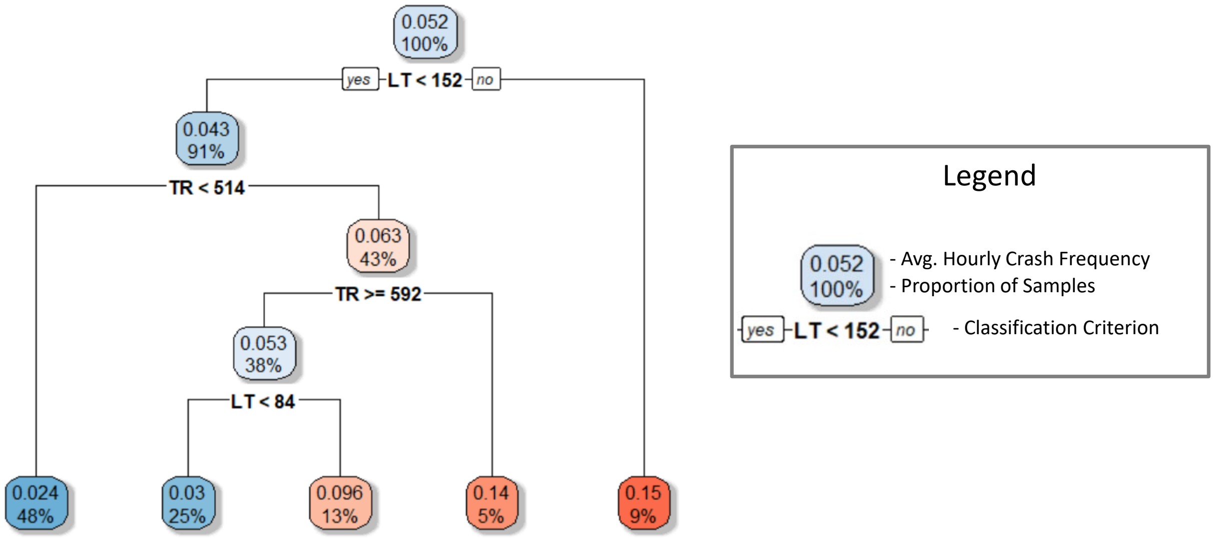


FIGURE 6. SCATTER PLOTS FOR HOURLY CRASH RATES TO CROSS-PRODUCT VOLUMES

4.2.3. Regression Tree

As an alternative, the team developed a regression tree that predicts the hourly target crash frequency (hourly crashes in given hour/year) for a given set of TMCs (vph). A regression tree is a simple supervised machine learning algorithm that has a structure like a tree with a root, branches, and nodes. In a regression tree, the data are split at multiple nodes according to a criterion of each independent variable. Independent variables are used as classifiers in the order of their importance. For example, the most important variable is used as the first classifier at the top node. The team developed a regression tree that will enable the prediction of hourly target crash frequency for a given range of hourly volumes for LT and TR movements. In doing so, the regression tree could simply estimate the appropriate thresholds of LT and TR volumes by using those two volumes as independent variables in the tree. Figure 7 shows the regression tree developed for the hourly target crash frequency. The tree was estimated with the complexity parameter (CP) of 0.02. That parameter controls the number of the terminal nodes in the regression tree. A higher value of CP makes a tree smaller by assigning a higher penalty in the complexity of the tree, which is associated with the number of terminal nodes.

For the regression tree estimate, the team used the sample data filtered by the filtering process discussed earlier in Section 4.2.1. As the tree was estimated only for the hours operated by PPLT, the samples for the hours operated by the protected LT were not included in the model estimation. So, the regression tree was estimated using the 53 hourly target crashes (Category 1 and 2) that occurred during the 165 sample hours operated by PPLT.



* The regression tree was estimated with the complexity parameter (CP) of 0.02

FIGURE 7. THE REGRESSION TREE DEVELOPED FOR HOURLY TARGET CRASH FREQUENCY

Figure 8 visualizes the boundaries of the developed regression tree. Using the LT and TR traffic volumes, the boundaries provide an intuitive method to examine whether PPLT is acceptable for a given threshold of hourly target crash frequency. For example, assume the safety threshold is set at 0.12 crashes per hour across the entire year for a treated approach. If this threshold were to be applied uniformly across the entire day, then the number of annual crashes should not exceed 0.12 × 24 = 2.88 crashes/year. If an approach has hourly volumes of 130 vph for LT and 1,200 vph for TR, the protected-permissive signal would be acceptable since the tree-predicted hourly target crash frequency of 0.11 does not exceed the threshold of 0.12. An interesting finding from the tree model is that the left turn volume governs the original node split, as it is the most important variable discriminating between the high and low hourly crash rates, regardless of the opposing flow. Surprisingly, Figure 8 also shows that the TR volume between 408 and 732 had higher expected crashes (0.14 for LT < 68 and 0.057 for LT >= 68) than the TR volume greater than 732 (0.03 for TR < 1088). This result is difficult to explain, given that crashes are positively associated with the traffic volume, which is the exposures to crashes. A possible reason is that the regression tree does not assume any relationship between dependent and independent variables, but it classifies the samples and provides the expected crashes for each group, highly depending on given samples. As long as the model assumption issue is not addressed, a large sample size of crash data might not resolve the problem and improve the model. Therefore, the team determined to use the conflict point safety performance function (CP-SPF) method and applied them for the development of safety guidelines in the following section.

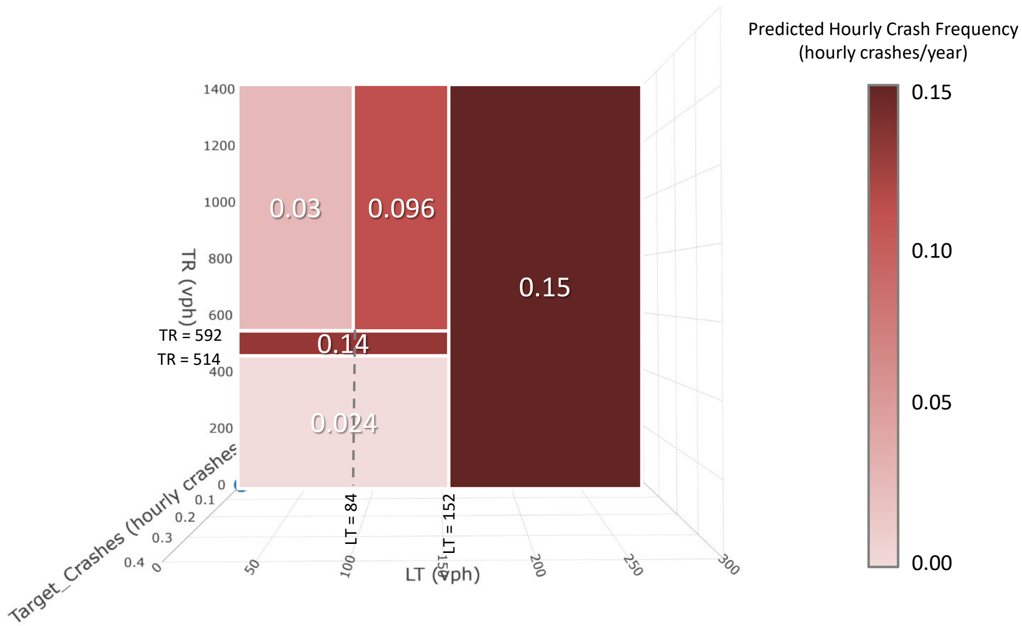


FIGURE 8. THE VISUALIZED BOUNDARIES OF DEVELOPED REGRESSION TREE

4.2.4. Conflict Point Safety Performance Function (CP-SPF)

In this study, a CP-SPF was developed for hourly target crash frequency using a negative binomial regression model. It should be noted that this study simply adopted the pre-developed model form and variables of CP-SPF proposed in the previous NCDOT project. Therefore, the model assumptions and statistical distribution were not fully examined in this study but should provide similar estimates for each treatment type for comparison (i.e. though the estimated CP-SPF may be low or high, it will be consistently low/high for treatments being compared).

The CP-SPF was developed to predict the hourly target crash frequency per year for a treated approach. In the model, the target crashes include both the left turn, same roadway and rear-end crashes. The log-transformed hourly TMCs for a treated left turn and opposing (through + right turn) movements were used as independent variables in the model. This study developed separate models of the PPLT and protected models for the crashes during TOD hours operated by FYA-PPLT and the hours operated by protected LT. The following equation shows the model form of the CP-SPF.

$$\boldsymbol{N_{Target}} = \mathbf{exp}(\boldsymbol{\alpha} + \boldsymbol{\beta_{LT}} \cdot \mathbf{ln}(\boldsymbol{LT}) + \boldsymbol{\beta_{TR}} \cdot \mathbf{ln}(\boldsymbol{TR}))$$

where,

N_{Target} = hourly target crash frequency per year for an approach (unit: hourly crashes/year)

LT = hourly turning movement count for left turn movement being considered

TR = hourly turning movement count for opposing through and right turn movements

The model estimation results for CP-SPF are shown in Table 18. The results showed that the $\ln(LT)$ and $\ln(TR)$ are positively associated with the hourly target crash frequency. The t-test results for the estimated parameters showed that $\ln(LT)$ and $\ln(TR)$ in the PPLT model, and $\ln(TR)$ in the protected model were not statistically significant at a 90% level. Possible reasons are that the limited number of crashes used for model estimation and the fact that many sites in the dataset had zero crashes. It is also expected that the predicted hourly crash frequencies would likely provide a low estimate; however, as noted earlier, they would be consistently low predictions for both treatment types being considered.

TABLE 18. ESTIMATION RESULTS FOR CP-SPF

PPLT Model	**Coefficient**	**Std. Error**	**p-value**
α (Intercept)	-8.8008*	4.0463	0.0296
$\ln(LT)$	0.4169	0.5153	0.4185
$\ln(TR)$	0.6592	0.5689	0.2466
Protected Model	**Coefficient**	**Std. Error**	**p-value**
α (Intercept)	-9.2447**	3.4388	0.00718
$\ln(LT)$	0.6352 ·	0.3257	0.0511
$\ln(TR)$	0.3795	0.4764	0.42564
Statistical Significance: '**' < 99% < '*' < 95% < '·' < 90% LT = hourly volume for the left turn movement RT = hourly volume for the opposing through and right turn movements			

Figure 9 shows the 3D graph drawn for the estimated PPLT and protected models. In Figure 9, (a) and (b) show different angles of the same graph where (a) represents the surface of PPLT model and (b) represents the difference in the predicted hourly target crash frequency between PPLT and protected models. In the 3D graph for the CP-SPFs, the hourly volumes (LT and TR) were used, instead of the log-transformed volumes ($\ln(LT)$ and $\ln(TR)$), making the model more intuitive to users for the purpose of developing safety guidelines. The 3D graph shows the predicted hourly target crash frequency is positively associated with the hourly volumes for the LT and TR movements in both PPLT and protected models. It also shows the difference in hourly target crash frequency increases when the LT and TR volumes increase.

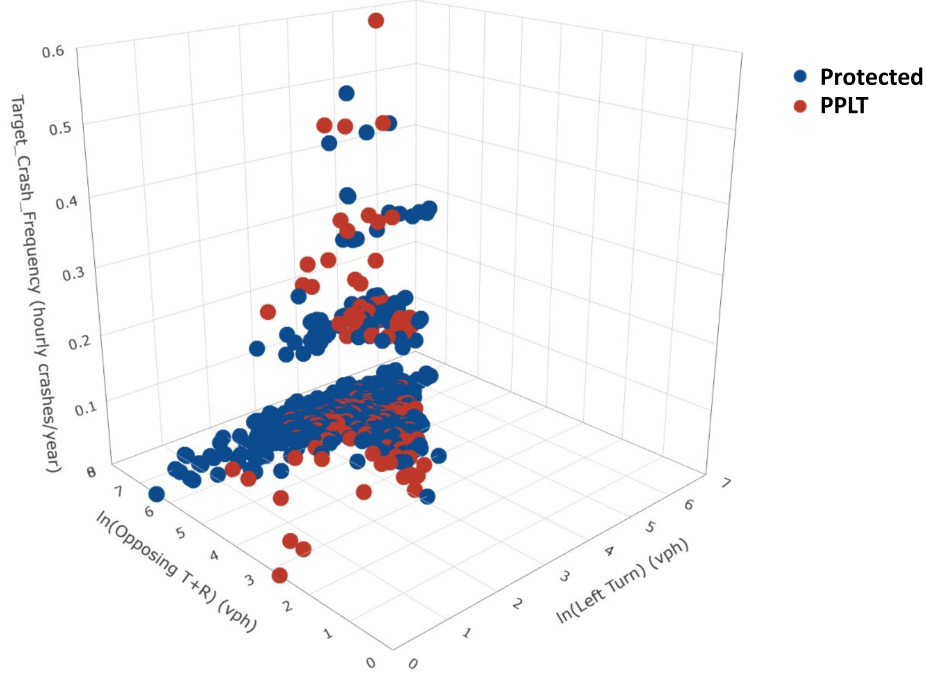


FIGURE 9. A 3D GRAPH FOR ESTIMATED CP-SPFS

Following discussions with members of the steering and implementation committee for this project, the CP-SPF model was determined to be most appropriate for developing safety guidelines. The primary reason is that the modeling aspect in the CP-SPF is based on the intuitively logical assumptions for the relationship between the target crashes and hourly volumes. As stated earlier, the regression tree provided the illogical results of a greater expected crash frequency for the middle level of TR volumes (between 514 and 592 vph) than the high level of TR volumes (greater than 592 vph). On the contrary, CP-SPF provides consistent and reasonable results for the target crash prediction, regardless of the level of traffic volumes, based on the assumption that target crashes and hourly volumes are positively associated. Using the estimated CP-SPF models, the team developed safety guidelines to examine if the target treatment (conversion from a protected-only to FYA-PPLT) is acceptable based on given set of hourly volumes. This section explains how to examine the acceptability of the protected-permissive signal for each hour by providing an example application of safety guidelines that can be used to determine when protected-only phasing should be deployed.

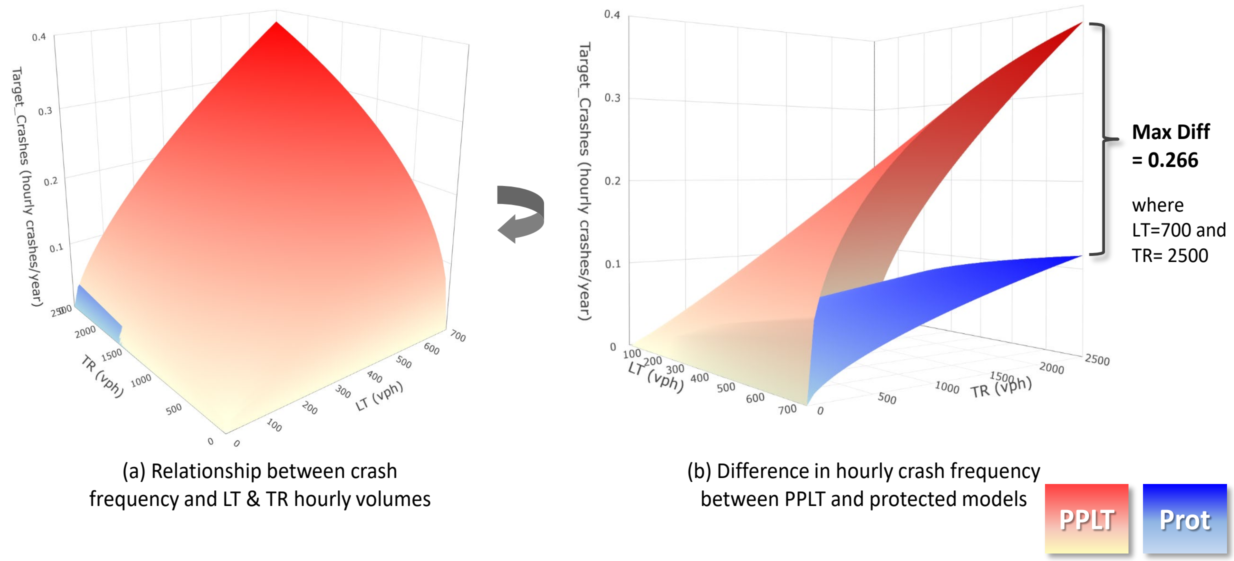
Table 19 shows the input and output matrix for the example application of safety guidelines for a left turn approach being considered for PPLT by TOD. In the simulation, when users enter the turning movement volumes as initial inputs, the light-yellow cells for hourly volumes are filled in automatically. Next, the adjacent columns for the predicted hourly target crash frequencies for the protected-permissive and protected-only, and the difference between them, are calculated. Finally, the last column shows the determination if the protected-permissive is acceptable based on a prespecified threshold of hourly target crash frequency set by the end users. In the example application, a threshold of 0.12 (hourly crashes/year) was assumed, but the value can be adjusted by users in the simulation tool. In the results shown in Table 19, the 12 hours starting from 7 AM to 7 PM were not recommended for implementing a protected-permissive phase on the approach.

TABLE 19. AN EXAMPLE APPLICATION OF SAFETY GUIDELINES

Time		Approach	Hourly Volume		Predicted Hourly Target Crashes (hourly crashes/year)		A difference in Target Crashes	Prot/Perm Acceptable?
From	To		LT	TR	Prot/Perm	Prot-Only		
12:00 AM	1:00 AM	NB	32	175	0.018	0.006	0.011	Acceptable
1:00 AM	2:00 AM	NB	28	95	0.011	0.005	0.006	Acceptable
2:00 AM	3:00 AM	NB	17	70	0.007	0.003	0.004	Acceptable
3:00 AM	4:00 AM	NB	21	65	0.008	0.003	0.004	Acceptable
4:00 AM	5:00 AM	NB	19	110	0.010	0.004	0.006	Acceptable
5:00 AM	6:00 AM	NB	18	430	0.026	0.006	0.019	Acceptable
6:00 AM	7:00 AM	NB	82	1176	0.094	0.023	0.072	Acceptable
7:00 AM	8:00 AM	NB	152	1554	0.147	0.037	0.110	Not Recommended
8:00 AM	9:00 AM	NB	129	1438	0.130	0.032	0.098	Not Recommended
9:00 AM	10:00 AM	NB	156	1210	0.126	0.034	0.091	Not Recommended
10:00 AM	11:00 AM	NB	169	1170	0.127	0.036	0.091	Not Recommended
11:00 AM	12:00 PM	NB	173	1373	0.143	0.038	0.104	Not Recommended
12:00 PM	1:00 PM	NB	167	1504	0.150	0.039	0.111	Not Recommended
1:00 PM	2:00 PM	NB	199	1685	0.174	0.045	0.129	Not Recommended
2:00 PM	3:00 PM	NB	224	1536	0.171	0.047	0.124	Not Recommended
3:00 PM	4:00 PM	NB	269	1789	0.205	0.056	0.149	Not Recommended
4:00 PM	5:00 PM	NB	348	2051	0.250	0.069	0.181	Not Recommended
5:00 PM	6:00 PM	NB	379	1922	0.248	0.071	0.177	Not Recommended
6:00 PM	7:00 PM	NB	267	1212	0.157	0.049	0.108	Not Recommended
7:00 PM	8:00 PM	NB	185	849	0.106	0.034	0.072	Acceptable
8:00 PM	9:00 PM	NB	170	750	0.094	0.031	0.063	Acceptable
9:00 PM	10:00 PM	NB	135	660	0.078	0.025	0.053	Acceptable
10:00 PM	11:00 PM	NB	71	590	0.056	0.016	0.040	Acceptable
11:00 PM	12:00 AM	NB	37	350	0.030	0.009	0.021	Acceptable
6 AM to 7 PM		NB	3447	23764	2.566	2.566	0.718	

* Note: The last column examines the acceptability of the prot/perm based on an initial threshold of hourly target crash frequency set by users. The threshold of 0.12 (hourly crashes/year) was used in this example.

The prediction results from Table 19 are visualized in Figure 10. The graph shows that the difference in predicted target crashes is relatively greater in the 12 hours from 7 AM to 7 PM where the PPLT was not recommended. For those 12 hours exceeding the threshold of 0.12, users can visualize how much the hourly target crashes are expected to change if PPLT or protected LT phasing is operational. The simulation provides users the opportunity to examine the results for all approaches at an intersection of interest, based on given or projected traffic volumes and threshold of hourly target crash frequency. The blue circles and yellow squares represent the hourly target crash frequencies for the PPLT and protected-only phases, respectively. The red horizontal line delineates the threshold of 0.12 (hourly crashes/year).



(a) Relationship between crash frequency and LT & TR hourly volumes

(b) Difference in hourly crash frequency between PPLT and protected models

FIGURE 10. PREDICTED HOURLY TARGET CRASH FREQUENCIES FOR PPLT AND PROTECTED LT SIGNALS

The graph shows that the difference in predicted target crashes is relatively greater in the 12 hours from 7 AM to 7 PM where the PPLT was not recommended. For those 12 hours exceeding the threshold of 0.12, users can visualize how much the hourly target crashes are expected to change if PPLT or protected LT phasing is operational. The simulation provides users the opportunity to examine the results for all approaches at an intersection of interest, based on given or projected traffic volumes and threshold of hourly target crash frequency.

4.3. Interpretation of Results

Based on the total intersection delay, either the base or comparison scenario will be recommended for each hour of the day. This generates a composite plan based on operational efficiency. By default, this recommended timing plan switches between the base and comparison timing scenarios based on any amount of operational improvement; however, a smoothing function can be implemented to only switch between recommended plans if the intersection level of service changes and the total intersection delay changes by at least five hours. This setting prevents over-sensitive switching due to random variation in arrivals, or an unnecessarily complicated timing plan attempting to save trivial amounts of time during early-morning hours. Safety issues do not automatically override the recommended timing plan. Instead, a safety flag system highlights any hours where the operational recommendation is predicted to lead to a crash rate over the limit specified by the analyst. If this occurs, it is recommended that the analyst re-design the comparison scenario, switching any flagged approaches to protected-only operation, and re-run the simulation analysis.

5. SUMMARY AND RECOMMENDATIONS

North Carolina has adopted the use of flashing yellow arrows (FYA) at many intersections across the state as a means of providing protected-permissive left turns (PPLT) while minimizing driver confusion that can often accompany the operation when using traditional traffic control devices such as the 5-section (a.k.a. "dog-house") signal. This research effort sought to provide additional guidance to engineers regarding when PPLT FYA phasing was appropriate for use. In doing so, two specific objectives were developed at the onset of the project: 1) an updated CMF, or CMF's, that would provide an overall assessment of the use of PPLT FYA's in NC and 2) guidance on when to consider permitted vs. permitted-protected vs. protected only left turn phasing by TOD.

An overall safety analysis was conducted to update one or more NC-specific CMF's for PPLT FYA intersections from prior work by Simpson and Troy in 2015. This analysis collected an additional three years of crash data from prior sites in that initial effort while also adding newly treated sites. Based on that evaluation, the results suggested the *total crashes* at intersections with PPLT FYA did not change significantly ($CMF_{\text{total Crashes, All}}$ = 1.044, or 4.4%); however, when looking at severity there appeared to be a statistically significant increase in those specific crashes ($CMF_{\text{total Crashes, Injury}}$ = 1.199, or 19.9%). Filtering by specific crash types, there appears to be a trade-off between increased *left turn crashes* (CMF's ranging from 3.73 to 10.51, or increasing 273% to 951%) and decreased *rear-end crashes* (CMF's ranging 0.66 to 0.23, or decreasing 34% to 76%), with the largest increases and decreases during PPLT FYA use. It appears, at first glance, that there may be room for improving safety at the PPLT FYA approaches by using protected-only phasing more extensively on the shoulder periods leading into and out of the peak periods as traffic volumes begin to increase or drop.

In meeting Objective 1, an overall safety analysis was conducted to update one or more NC-specific CMF's for PPLT FYA intersections. The analysis collected an additional three years of crash data from prior sites in Simpson and Troy's initial effort while also adding newly treated sites. Based on that evaluation, the results suggested that *total crashes* at intersections with PPLT FYA did not change significantly ($CMF_{\text{total Crashes, All}}$ = 1.044, or 4.4%); however, when looking at severity there appeared to be a statistically significant increase in those specific crashes ($CMF_{\text{total Crashes, Injury}}$ = 1.199, or 19.9%). Filtering by specific crash types, there appears to be a trade-off between increased *left turn crashes* (CMF's ranging from 3.73 to 10.51, or increasing 273% to 951%) and decreased *rear-end crashes* (CMF's ranging 0.66 to 0.23, or decreasing 34% to 76%). It also appears, on first glance, that there may be room for improving safety at the PPLT FYA approaches by implementing protected-only phasing more extensively on the fringes leading into the peak periods as traffic volumes begin to ramp up. Even so, the 24-hour results to not show large differences in CMF's when compared to PPLT only, so those improvements would likely be minor based on the results of this study.

Second, an Excel-based simulation tool was developed to assist NCDOT with implementing PPLT FYA by TOD. User inputs such as geometry, traffic volume, current and proposed timing plans (cycle lengths, phase lengths and sequence, etc.), isolated vs. coordinated operation, actuation, and signal default values were all incorporated into the guidance-based tool. Using these inputs, the tool incorporated a two-regime Cowan headway distribution to simulate vehicle arrivals every 0.1 seconds. Delay was calculated based on a queue accumulation polygon at each intersection approach. Delay was the operational measure by which a recommended left turn treatment was evaluated. Safety was incorporated into the tool as the discriminant measure since operations would always show that a permitted or permitted-protected solution is recommended for efficiency (lower delay) reasons. Three methods were considered for safety guidance; the study found that the conflict point safety performance function (CP-SPF) methodology developed through another NCDOT research project was the most appropriate for use. This method predicted the hourly crash frequency across the year based on left turn and opposing through and right turn traffic volumes. When the hourly crash frequency over a given year exceeds the threshold provided in the tool, or selected by the end user, protection of the left turn is recommended in lieu of a permitted left turn option.

6. FUTURE RESEARCH RECOMMENDATIONS

In the process of conducting this research effort, three primary recommendations for future work have become apparent to the research team.

1. First and foremost, the research team is increasingly encountering new applications for the CP-SPF methods developed as part of NCDOT research project 2018-20 "Reasonable Alternatives for Grade-Separated Intersections." The team recommends funding additional research in this area which would incorporate many more intersection conflict types into the predictive model. These models would provide a more realistic crash prediction that could be used for many crash prediction efforts such as the one completed for this project. As an example, one limitation of the crash prediction model in this current effort is the fact that the sample of sites the model was developed from included several zero crash locations. This means that the crash prediction will tend to be low. For the purposes of this project, we noted that although the crash prediction is low, it is consistently low for all applications. The associated threshold that was therefore assumed was also low as well. As such, the recommendations from the guidance in the tool would be correctly applied; however, the corresponding crash predictions are likely to be lower than they ought to be if more data /sites were included.
2. The safety guidelines developed for this project utilize an hourly crash "threshold" that needs to be prespecified by users in the integrated simulation tool. It would be advisable to establish a threshold based on more research, especially if the threshold needs to vary by time of day.
3. The current Excel tool has computational limitations in that a) depending on the speed of one's computer, it could take as long as 8 to 20 minutes to run a full day of scenarios and b) the tool is difficult to update because it is not distributed in a way that can easily accommodate updates (as opposed to a web-based tool). NCDOT could consider its conversion to a web-based tool to be housed in the ITRE DataLab repository where all other tools are currently located.

It is the team's conviction that the first research recommendation is one that has both state and federal implications. The methods currently being deployed here in NC are quite novel and have multiple uses for crash prediction. The second and third recommendations could be completed as part of a smaller effort or series of efforts. The second effort could likely be completed using a Technical Assistance Request; however, the third effort would likely require slightly more funding such as the use of Implementation Funds.

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