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Safety Effects of Protected and Protected/Permissive Left-Turn Phases

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ABSTRACT

This study evaluated the approach-level safety performance of left-turn phases at signalized intersections, including permissive, protected-permissive (PPLT), protected indications, and flashing yellow arrow (FYA). Data collection included exact dates of traffic signal changes, high-resolution datasets of left-turn and opposing volumes, and manual verification of crashes to correct vehicle travel directions and approaches. Analysis showed similar performance of the FYA indication compared with a permissive phase, and higher crash rates with the FYA indication compared with a PPLT phase (an increase of 0.28 crashes per approach per year for an average approach, and a CMF of 1.33 ± 0.12). An important caveat to direct and strict comparisons between FYA and PPLT arise from differences in their operational capabilities, not included in this evaluation. As expected, crashes with protected phases did not show valid systematic trends since crashes were not a result of permissive movements, but due to traffic violations. A time-of-day analysis revealed higher-than-expected concentration of crashes before the afternoon peak (2 pm to 4 pm), pointing at opportunities to further reduce crashes. Lastly, a new metric to estimate risk of left-turn crashes using high-resolution data (5-minute counts) was introduced to monitor intra-day risk fluctuations in real time.

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AASHTO	American Association of State Highway and Transportation Officials
AMF	Accident Modification Factor
ATSPM	Automated Traffic Signal Performance Measures
CMF	Crash Modification Factor
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
ITE	Institute of Transportation Engineers
LT	Left Turn
MUTCD	Manual on Uniform Traffic Control Devices
NB	Negative Binomial
NCHRP	National Cooperative Highway Research Program
PPLT	Protected-Permissive Left Turn
PLT	Protected Left Turn
SPF	Safety Performance Function
TAC	Technical Advisory Committee
UDOT	Utah Department of Transportation
VBA	Visual Basic for Applications

EXECUTIVE SUMMARY

Previous research has demonstrated the overall safety effectiveness of protected left-turn phases, but the extent of the safety effects for protected-permissive left-turn phases, particularly with the recent introduction of the flashing yellow arrow (FYA) indication, has not been clearly established. This study is aimed at help reducing this gap in research by presenting an approach-level evaluation of the safety performance of left-turn phases, including permissive, protected-permissive (PPLT), and protected indications, and FYA.

Extensive data collection efforts were needed to obtain and post-process field data necessary to create reliable approach-level datasets. These efforts included manual identification of locations and extraction of exact dates of FYA installations, extraction and processing of long-term high-resolution left-turn and opposing volumes, and manual verification of crashes to correct travel directions and crash assignments to specific approaches.

Statistical models produced consistent trends among the three main groups being evaluated (permissive to FYA, PPLT to FYA, and protected to FYA) using an empirical Bayes (EB) before-after methodology. SPFs were developed for permissive, PPLT, and FYA indications, and used the natural log of the cross product [ln (cross product)] as the independent variable describing demands and conflicts.

Comparisons of safety performance between permissive and FYA indications showed a slight reduction in expected yearly crash frequencies for lower ln (cross product) values when using FYA, but a slight increase as the ln(cross product) increased. Thus, the CMF value was dependent on the range of ln (cross product). For the sample evaluated, the CMF showed a slight increase (1.16 ± 0.38), although not statistically significant. Estimates for the second group, including approaches that changed from PPLT to FYA, resulted in a CMF of 1.33 ± 0.12. While this increase was significant, the actual magnitude for the average ln (cross product) value was equivalent to an increase in 0.28 LT crashes per approach per year, and for the highest value in the range it represented an increase of 0.9 LT crashes per approach per year. Changes from protected to FYA phasing showed an increase in crashes, and the magnitude of this change was within expectation and as a direct result of allowing permissive movements (similar yearly crash frequencies compared with those in the PPLT to FYA group).

An important caveat to direct and strict comparisons between FYA and PPLT arise from differences in their operational capabilities, with FYA indications having greater flexibility to improve traffic operations over traditional PPLT. Operational advantages and possible indirect safety benefits reflected in other types of crashes should be considered altogether with the direct safety effects quantified in this study when evaluating left-turn phase alternatives.

An analysis based on time of day of individual crashes showed flatter crash distributions when using an FYA indication, with smaller crash increases during peak hours, but higher crash concentrations during off-peak periods. In particular, the two-hour period between 2 pm and 4 pm was observed to have similar number of crashes per hour as the afternoon peak hours (from 4 pm to 7 pm). This finding hints at opportunities to reduce unexpected peaks in crash frequencies during off-peak afternoon by considering operational strategies from peak periods whenever possible.

A new metric for estimating the risk of left-turn crashes was introduced in this study. The proposed approach uses high-resolution data from ATSPM and an event-based method to calculate a true measure of risk accounting for the complete history of conflicting volumes using five-minute counts. Results of applying the proposed risk metric are very encouraging and produced consistent trends and safety estimates ready for implementation. The method is also ideal for real-time applications and allows for more proactive strategies that can target intra-day periods with high risk potential by adjusting phase and timing plans for specific time of day, day of the week, or even preemptively upon unexpected risk changes.

1. INTRODUCTION

1.1 Problem Statement

Protected left-turn phases at signalized intersections are intended to reduce the frequency of angle collisions that result from conflicts between left-turning vehicles and opposing through and right-turning vehicles. AASHTO's "NCHRP 500 series" also notes that the frequency of rear-end and sideswipe crashes between left-turning vehicles and following through vehicles can also be reduced with properly timed, protected left turns [1]. A consensus on the extent of this safety effectiveness under different intersection conditions does not exist. This project will estimate the safety effects of protected and protected-permissive left-turn phases for different intersection conditions. Intersection conditions of interest will be selected with input from the project's technical advisory committee, but may include factors such as turning volumes, opposing through volumes, pedestrian crossing volumes, approach speeds, sight distance, number of lanes, and type of channelization.

Various studies have demonstrated the overall safety effectiveness of protected left-turn phases [2, 3]. A consensus on the extent of this safety effectiveness under different intersection conditions does not exist. While separate left-turn phasing may reduce delay for left-turning vehicles, it may increase the overall intersection delay and disrupt traffic progression. It is therefore important to understand the safety effects of protected left-turn phases under a variety of intersection conditions so that appropriate operational and safety trade-offs can be quantified and considered by agency decision makers. Protected-permissive left-turn phasing is sometimes used as a compromise between fully protected and permissive only phasing. Information on the safety effects of protected-permissive under a variety of intersection conditions is needed as well.

1.2 Objectives

The primary objective of this research project is to estimate the safety effects of left-turn phases for different conditions and provide operational recommendations. The operational recommendations will be in the form of a framework that demonstrates how the results of this research can be incorporated into an analysis of operational and safety trade-offs associated with different left-turn phasing alternatives.

1.3 Scope

The project objective was approached through the following major tasks:

1 Synthesis of Literature and Practice. Review literature and practice regarding left-turn phasing considerations, safety effects of left-turn phasing, and operational and safety tradeoffs associated with different left-turn phasing alternatives.

2 Pilot Data Collection. Preparation of a comprehensive data matrix of all applicable intersection types, phasing types, and corresponding data elements relevant to this study. A pilot data collection effort to gather preliminary information on left-turn signal phasing, turning volumes, opposing through volumes, pedestrian crossing volumes, approach speeds, sight distance, number of lanes, types of channelization, and other elements at a sample of Utah intersections drawn from different parts of the comprehensive data matrix. At this initial stage, all types of left-turn phasing are considered. Intersection types, phasing types, and corresponding data elements are prioritized using the experience gained during the pilot data collection effort. It is important to note that during the data collection UDOT began installing supplemental signage associated with protected-permissive left turns in late 2014/early 2015, and followed it up with several months of

an educational blitz on different types of left-turn phasing. While it is often difficult to explicitly quantify the safety effects of educational campaigns, consideration of the signage changes will be included in the data collection and analysis.

3   Development of Draft Detailed Work Plan. Development of a detailed work plan for estimating the safety effects of protected and protected-permissive left-turn phases under a variety of intersection conditions. The plan included study designs, sample sizes, data collection protocols, and data analysis approaches. The plan also included an approach to supplement the statistical crash analysis with a more in-depth, clinical-style analysis of a selected number of individual left-turn crashes.

4   Execution of Approved Work Plan. Execution of the proposed work plan, including all data collection and analysis activities approved by the TAC.

5   Preparation of Report and Framework. Documentation of the entire research effort in the final research report. A stand-alone framework is developed that demonstrates how the results of this research can be incorporated into an analysis of operational and safety trade-offs associated with different left-turn phasing alternatives.

1.4   Outline of Report

This report is organized in the following sections:
- Introduction
- Synthesis of Literature and Practice
- Pilot Data Collection
- Data Collection and Methodology
- Data Analysis and Modeling
- Conclusions, Recommendations, and Future Work

2.   SYNTHESIS OF LITERATURE AND PRACTICE

2.1   Overview

Protected left-turn phases at signalized intersections are intended to increase capacity for left-turn movements while reducing the frequency of collisions with opposing through vehicles. However, they also come at a price by adding transition and lost time, and potential for increased overall intersection delay.

The 2010 Highway Capacity Manual (HCM) indicates that a left-turn lane should be provided when implementing left-turn phasing and sets warrants for installing one lane when left-turning vehicles exceed 100 vehicles in a peak hour or dual left-turn lanes when reaching 300 vehicles an hour [4]. However, agencies may also opt to install left-turn lanes for safety or before they are warranted, anticipating the future need.

At locations where it has been decided to implement left-turn phasing, agencies also decide between permissive left-turn only, protected left-turn (PLT) only, or protected-permissive left-turn (PPLT) phasing. PPLT can be implemented using a traditional five-signal head (doghouse) or using a flashing yellow arrow (FYA) indication. Most FYA installations have a four-signal head with separate yellow arrows for the steady and the flashing indications, but an interim approval by FHWA also allows the use of a three-signal head with the middle section used for both the steady and the flashing indications [5]. The decision process is unique to each agency and depends on operational, geometric, and safety-related considerations, as well as local knowledge from traffic engineers.

First, in order to investigate the safety effects of different left-turn phasing options, this chapter presents an overview of past studies where field evaluations were conducted, consolidates their results, and provides a general set of conclusions for each phasing type. This literature review emphasizes the effects of converting/updating from one signal indication to FYA, using the current MUTCD recommendation for protected-permissive operations, even though most intersections operate with the more traditional five-section or three-section signal head configurations [6].

Second, this chapter also includes the results of an outreach effort to contact all 50 states regarding their left-turn policies and determine the current state of practice throughout the U.S. This effort was important to identify common criteria, significant differences, and factors that states prioritize to make decisions regarding left-turn phasing.

Lastly, we discuss the safety implications of different left-turn phasing decisions in light of the information gathered from the literature and state agencies, and identify a series of elements that could be targeted for field data collection and analysis. We also provide a list of recommended external, national experts that could be contacted to serve as independent reviewers of the results obtained in this study.

2.2   Literature Review

This review is divided into two sections containing a summary of relevant studies on 1) protected and protected-permissive left-turn phases, and 2) flashing yellow arrow indications. As the Utah DOT continues updating existing signalized intersections with flashing yellow arrows and installing them at new intersections, the safety evaluation of flashing yellow arrow indications and its comparison with other left-turn phasing options quickly became the central focus of this study.

2.2.1 Protected Left-Turn (PLT), Protected-Permissive Left-Turn Phases (PPLT)

Studies on the safety effects of PLT versus PPLT or permissive only left-turn movements have been conducted for over 20 years, with one general trend being predominant in most cases: A PLT phase tends to result in fewer total crashes than a PPLT or a permissive only phase. Fewer crashes is an expected trend from PLT, particularly at locations with increasing traffic where the number of gaps available to accommodate the left-turning demands is reduced. As it is widely known, fewer gaps may result in safety concerns at an intersection [7].

A literature review on accident modification factors (AMF) included in the NCHRP Report 617 showed that out of 100 intersections, roadway segments, and miscellaneous treatments explored, adding an exclusive left-turn lane and adding a left-turn phase (PLT or PPLT) occupied high priority levels when it came to how important it was to have an AMF for these treatments [2]. It was also noted that adding a left-turn lane was classified as a treatment that had an AMF with high level of predictive certainty, but adding a left-turn phase had a medium-low predictive certainty. This finding highlights the need for more thorough understanding of the safety effects of the different types of left-turn phasing under specific traffic and geometric conditions.

In 2008, Wang and Abdel-Aty modeled left-turn crash occurrence at intersections and determined that PLT-only phasing reduced crash frequency of left-turn crashes from an opposing direction through moving vehicles, but increased the number of left-turn crashes with adjacent through moving vehicles [8]. They also determined that PPLT phasing usually has more left-turn crashes than permissive due to the complexity of driver attention and awareness at the intersection.

In 2009, Qi et al. analyzed the safety impacts of left-turn safety treatments using crash data from 111 pairs of intersection approaches in Texas (104 for a cross-sectional study, and seven for a before-and-after study) [9]. A simple comparison using the cross-sectional locations showed crash rates for PPLT and permissive only being about 2.2 and 1.9 times those for PLT only locations, respectively. However, NB models were also created to predict crashes by phasing type. For the before-after study, the empirical Bayes (EB) method was followed and showed that the overall change from PLT to PPLT resulted in an increase of LT-related crashes by a factor of 1.32. The study generated guidelines for choosing LT phasing.

Srinivasan et al. (2012) provide crash modification factors (CMFs) when changing the left-turn signal phasing [10]. The study showed a reduction in left-turn opposing through crashes, but with an increase in rear-end crashes changing from permissive to protected-permissive. The study also determined that implementation of flashing yellow arrow provides a benefit at locations where permissive phasing was previously used, but a dis-benefit at locations when protected only phasing was operating.

De Pauw et al. (2013) performed a before-and-after comparison of implementing PPLT or PLT-only phasing at 103 intersections in Flanders-Belgium. After controlling for regression-to-the-mean and general trend effects, left-turn phasing resulted in a 50% reduction in left-turn crashes with no change to rear-end crashes, resulting in a 37% reduction in overall intersection crashes [11].

A study using data from Utah evaluated the safety effects of signal improvements through the development of crash modification factors for modifying left-turn phasing from permissive only to PPLT [12]. A hierarchical Bayesian model was used to conduct the analysis, which found there was a slight increase in the overall and non-severe crashes (CMF=1.36 and 1.15 for new and modified signals, respectively), and a decrease in severe crashes (CMF=0.56 and 0.54 for new and modified signals, respectively). Additional CMFs were also developed by crash type.

Chen et al. (2015) conducted a quasi-experimental analysis at 68 intersections in New York City [13]. The study determined no benefit in reducing intersection crashes from changing permissive left-turn signal phasing to PPLT or PLT-only phasing. The reduction in crashes from changing to protected only phasing was offset by a possible increase in overtaking crashes, where vehicles making left-turns would overtake other through traffic in their rush to turn within the protected left-turn phase and avoid the wait when missing it.

A study conducted in Texas developed guidelines for pedestrian safety treatments at intersections considering the effects of permissive and PPLT and their incidence level on vehicle-pedestrian crashes [14]. A part of the guidelines includes recommendations for left-turn mode selection based on pedestrian safety; also shown are predictions for an increase in pedestrian-related crash costs as a function of the cross product of pedestrian and left-turning volumes when the phase changes from PLT, or to PPLT, with leading or lagging phasing.

In general, evidence from recent studies supports the idea that a PLT phasing results in lower frequency of left-turn crashes when replacing a permissive only indication; but a combination of mixed results have been found when PPLT replaces a permissive indication, as shown in Table 2.1.

In addition to studies evaluating the safety effects of traditional left-turn treatments, and as a result of federal guidance on the use of an FYA indication, new studies are emerging on the effects of using this phasing as an alternative for left-turn operations. The following section focuses on these evaluations and explores the safety effects observed so far throughout the United States.

2.2.2 Flashing Yellow Arrow

Approval and support for the FYA indication has allowed state and local agencies to implement more flexible left-turn phasing operations. The 2009 Manual on Uniform Traffic Control Devices (MUTCD) creates the standard for implementing FYA based on the National Cooperative Highway Research program (NCHRP) Report 493 [15]. The report identified that "…a flashing yellow arrow PPLT display was consistently found to be equal or superior to existing PPLT displays both in a laboratory environment and in cities where the display was experimentally implemented in the field." FYA operations allow for permissive only left-turn phasing when turning volumes are low, but switching to PPLT or PLT only phasing as intersection volumes increase by time of day or as delay to key movements would be adversely affected.

After the release of NCHRP Report 493, an increasing number of agencies began turning their attention to FYA. While the first efforts were mostly directed at preparing for the new standard and understanding driver comprehension of the signals, safety studies followed soon after field data became available. Perhaps the earliest extensive safety-related study on FYA was conducted under NCHRP Project 20-7, Task 222 by the University of Wisconsin-Madison [16, 17], and included limited data from 104 locations out of the nearly 200 intersections with FYA nationwide, with only 50 locations having at least one year of post-implementation data. Three main conclusions summarized the safety effects of the first FYA installations:
1. Safety improved when the left-turn phasing changed from a traditional PPLT to FYA with PPLT phasing;
2. Safety did not improve when the left-turn phasing changed from PLT to FYA with PPLT phasing;
3. No conclusive results from locations that had permissive only phasing and changed to FYA due to insufficient data.

Table 2.1 Summary Effects of Changing a Permissive Phase to PPLT or PLT Phases

Study	Treatment					
	Permissive to PPLT			Permissive to PLT		
	Sites	Crash Type	Effect	Sites	Crash Type	Effect
NCHRP 617 (2008) [2]	3	All crashes	Not significant	8	All crashes	Not significant
		Left turn Only	Not significant		Left turn Only	Significant decrease (CMF = 0.021)
Qi et al. (2009) [9]	5	Left turn Only	Significant increase (CMF = 1.32)			
Srinivasan et al. (2012) [10]	50 *	All crashes	Significant increase (CMF = 1.081)			
		Left turn Only	Not significant			
	21 **	All crashes	Not significant			
		Left turn Only	Significant decrease (CMF = 0.787)			
DePauw et al. (2013) [11]	25	All injury	Significant decrease (CMF = 0.68)	78	All injury	Significant decrease (CMF = 0.62)
		Injury LT	Significant decrease (CMF = 0.54)		Injury LT	Significant decrease (CMF = 0.48)
		All severe	Significant decrease (CMF = 0.35)		All severe	Significant decrease (CMF = 0.43)
Schultz et al. (2014) [12]	31	All crashes	Significant increase (CMF = 1.15)			
		Left turn Only	Significant increase (CMF = 1.55)			
Chen et al. (2015) [13]	59	All crashes	Not significant	9	All crashes	Not significant
		Left turn Only	Significant increase (Rate change = 0.3 crashes/2 yrs.)		Left turn Only	Significant decrease (Rate change = 0.9 crashes/2 yrs.)

In 2009, Oregon DOT reported preliminary safety data from five intersections with signals converted from a five-head cluster ("doghouse") to FYA, indicating a reduction of 67% in the frequency of left-turn related crashes [18, 19] . Later in 2010, a direct before-and-after evaluation from seven intersections converted to FYA in Federal Way, WA, showed an overall 9% reduction in crash rates and 8% reduction in severity rates, but also showed significant variation between intersections [20]. Changing from traditional PPLT to FYA resulted in a 39% reduction in crash rates and a 64% reduction in crash severity; whereas, changing from PLT only to FYA resulted in a 15% increase in collision rates and a 41% increase in severity rates. The study also pointed out a distinct increase in crash rates during the first year after the FYA installation and in the frequency of fixed-object crashes, even though no clear explanation was found for this trend.

In 2011, Caltrans conducted a preliminary investigation on the safety implications of using FYA for permissive left turns [21]. However, besides NCHRP report 493 and the web-only document 123, the authors did not find results from other field safety evaluations, and the investigation focused on FYA installations planned or in progress, national guidance, expert opinions, and driver understanding of FYA indications.

A study from Texas Southern University developed guidelines for FYA with PPLT operations, using operational and safety data from intersections in Texas and Washington [22]. The safety component of the study included before-and-after historical crash data from 51 locations, as well as detailed data specifically collected for a traffic conflict study at five additional intersections. Results showed that the overall crash rates were lower after the installation of FYA, except for locations converted from PLT only to PPLT with FYA, and also pointed to possible driver confusion during the steady yellow arrow transition at locations with high left-turn and opposing volumes, or with lead-lag pashing.

In 2014, a before-and-after study using an empirical Bayesian approach showed a reduction in left-turn crashes (at 14 of 18 intersections), and a reduction in the total number of crashes (at 16 of the 18 intersection) in Charlotte, NC, when intersections were modified from a PPLT to an FYA phasing [23].

Simpson and Troy presented a comprehensive before-and-after evaluation of the effects of converting left-turn phasing to different modes of FYA using data from 222 intersections in North Carolina [24]. This study developed CMF for different types of conversions, including before conditions with permissive-only left turns, PPLT, and PLT phasing. Results showed consistently significant improvements in total and left-turn crashes when converting from a five-section PPLT to an FYA, and for left-turn and injury crashes when converting from permissive-only to a permissive-only FYA. For conversions from PLT to FYA, left-turn crashes consistently increased, but non-significant results were found regarding the total crash frequency or their severity. A more complete summary of the CMF for the different treatment types is shown in Table 2.2.

A more recent study published by the Illinois Center for Transportation (ICT) analyzed safety, driver comprehension, and operations based on data from 164 approaches located at 86 intersections with FYA in Peoria, IL [25]. Safety performance functions were developed for four types of crashes (total, injury, left-turn related, and left-turn opposing through crashes) using crash history (three years before and three years after), traffic volumes, and operational characteristics of 100 comparison sites. Overall, at the 164 approaches with FYA there was a 23.3% reduction in left-turn related crashes, and a 24.8% reduction in left-turn opposing through crashes. Reductions were higher for sites using a supplemental sign with the text "Left Turn Yield on Flashing Yellow Arrow," where left-turn related crashes were reduced by 31.9%, and left-turn opposing through crashes were reduced by 30.9%. Additional results for older and younger drivers, based on a naïve before-and-after method, showed no statistically significant changes for the subset of older drivers compared with the complete sample; however, higher reductions in crash rates were found for younger drivers. Lastly, the following CMFs were estimated using an empirical Bayes approach for two crash types, with and without a supplemental sign (using a 95% confidence level):
- Left-turn related crashes, FYA approach without supplemental sign: 0.617 ± 0.012
- Left-turn related crashes, FYA approach with supplemental sign: 0.589 ± 0.016
- Left-turn opposing through crashes, FYA approach without supplemental sign: 0.714 ± 0.016
- Left-turn opposing through crashes, FYA approach with supplemental sign: 0.711 ± 0.024

It is noted that a paper stemming from the same ICT study, but preceding the final project report, showed slightly different results between 18 to 30 months, given the limited data available for the after condition (compared with three years in the final report) [25]. In the paper, the naïve before-and-after comparison showed significant crash reductions in left-turn related and left-turn opposing through crashes, but the empirical Bayes study did not show any significant changes with FYA. Differences between the two publications highlight the importance of "long-enough" evaluation periods whenever possible.

Beyond studying the overall safety effects of FYA, research efforts have also focused on time-of-day strategies to take advantage of the combination of PLT and PPLT phases possible with FYA. A study by Radwan et al. (2013) analyzed data from 23 approaches located at 13 intersections in central Florida to develop dynamic guidelines for FYA operation [26]. Intersection parameters were selected to predict left-turn volumes by time of day and to assess the operational and safety impacts of the left-turn phasing, resulting in a decision support tool to assist engineers in determining turning policies sensitive to left-turn demands. Similarly, Davis et al. (2015) quantified the change in risk for left-turn crashes with changes in traffic-flow conditions within the day using data from Minnesota [27]. Risk was a function of left-turn demand, opposing through volume, and approach classification based on speed limit, sight-distance, and type of left-turn protection; and the analysis also generated guidelines for permissive left-turn phasing using FYA [27].

In summary, studies have shown that the use of an FYA indication generally results in a reduction in crash rates when the left-turn phase is converted from a standard permissive phase or a PPLT indication, as shown in the selected results from Table 2.2 and Table 2.3. On the contrary, Table 2.4 shows that conversion from a protected-only left-turn phase to an FYA increases the rate of left-turn crashes (as well as the overall crash severity), with relatively smaller effects on the overall crash rate.

Table 2.2 Summary Effects of Changing a Permissive LT Phase to FYA

Study	Permissive to FYA		
	Sites	Crash Type	Effect
Yi et al. (2012) [22]	23	All crashes	Decrease (-9% to -45% crash rate)
Simpson and Troy (2015) [24]	13 (20 approaches)*	All crashes	Decrease (-6.5% crash rate)
		LT only	Decrease (-26.2% crash rate)
Simpson and Troy (2015) [24]	9 (14 approaches)* FYA permissive only	All crashes	Decrease (-10.8% crash rate)
		LT only	Decrease (-59% crash rate)

= Intersections where no major changes other than the FYA

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Table 2.3 Summary Effects of Changing a Protected-Permissive LT Phase to FYA

Study	Protected-Permissive to FYA		
	Sites	Crash Type	Effect
NCHRP Web-Only Doc 123 (2007) [28]	13*	All crashes	Decrease (-2.2 crashes/year)
		LT only	Decrease (-0.9 crashes/year)
McCarroll (2009) [19]	5	LT only	Decrease (-67% crash rate)
Perez (2010) [20]	2	All crashes	Decrease (-39% crash rate)
Yi et al. (2012) [22]	20	All crashes	Decrease (-5% to -39% crash rate)
Pulugurtha (2014) [23]	18	All crashes	Decrease (-39% crash rate)
		LT only	Decrease (-61% crash rate)
Simpson and Troy (2015) [24]	105 (193 approaches)*	All crashes	Decrease (-6.6% crash rate)
		LT only	Decrease (-22.2% crash rate)
Schattler et al. (2016) [29]	90 approaches (with supplemental FYA sign)	All crashes	Decrease (-8.1% crash rate)
		LT only	Decrease (-31.9% crash rate)
Schlattler et al. (2016) [29]	74 approaches (without supplemental FYA sign)	All crashes	Decrease (-7.3% crash rate)
		LT only	Decrease (-11.5% crash rate)

* = Intersections where no major changes other than the FYA

Table 2.4 Summary Effects of Changing a Protected-Only LT Phase to FYA

Study	Protected-only to FYA		
	Sites	Crash Type	Effect
NCHRP Web-Only Doc 123 (2007) [17]	18*	All crashes	Increase (0.7 crashes/year)
		LT only	Increase (1.6 crashes/year)
Perez (2010) [20]	3	All crashes	Decrease (-15% crash rate)
Yi et al. (2012) [22]	8	All crashes	Increase (15% to 222% crash rate)
Simpson and Troy (2015) [24]	20 (43 approaches)*	All crashes	Increase (12% crash rate)
		LT only	Increase (344% crash rate)
Simpson and Troy (2015) [24]	13 (28 approaches)** FYA with TOD operation	All crashes	Decrease (-10% crash rate)
		LT only	Increase (273% crash rate)

* = Intersections where no major changes other than the FYA

2.3   State of Practice

Signal operation, management, and control is different for each state. In some states, traffic engineers oversee the signal operations throughout the state and perform maintenance and signal optimization at the state level. Other states provide signal phasing guidelines and warrants for city traffic engineers to follow when operating state maintained and owned signals. Still, other state agencies also turn over complete maintenance and signal operation to the city or county after construction, and only offer assistance or suggestions when requested by the city or when construction facilitates a change in signal operations. Regardless of the management tactic employed, each signal requires a decision for phasing operation.

In 1986, a survey sent to transportation engineers, not only in the United States but also internationally, showed the diversity of approaches followed by agencies and recommended ITE to use the findings of the study to establish nationally recommended techniques to warrant the use of left-turn phases [30]. Today, some states use the ITE guidelines, variations from it, or a variety of warrants that consider a combination of the following factors:

- Left-turn volume
- Opposing volume or cross product of opposing volume to left-turn volume
- Safety consideration
- Delay consideration
- Geometric conditions and sight distance

Left-turn volume warrants typically consider an average number of vehicles per cycle or a minimum peak hour left-turn volume. Average left-turn volume considerations are generally two or more left-turning vehicles per cycle, where at least two vehicles make a left turn during the green time from a single approach, or a more stringent requirement is two vehicles make a left turn at the end of the green time during the yellow clearance time. Typical minimum left-turn volume is 100 vehicles in the peak hour with some states (Louisiana, Michigan, and South Carolina, for example) requiring only 50 vehicles per hour when in conjunction with other left-turn or speed requirements.

The volume cross product requirement is a standard for many states in determining left-turn phasing options. The typical cross product value requirement is greater than 50,000 for a two-lane roadway (one opposing lane) and greater than 100,000 for a four-lane roadway (two opposing lanes).

Safety considerations include left-turn crash limits typically set at five or more crashes within a 12-month rotating period for one approach. Other considerations are made for a two- or three-year period to determine if left-turn crashes are occurring regularly. Sight line distance is of concern for most guidelines, including special consideration for the posted speed limit and resulting sight line needs.

Few states offer a left-turn phase guideline based upon vehicle delay. Typically, the left-turn delay warrant is 2.0 vehicle hours during the peak period or an average delay of more than 35 seconds/vehicle.

An engineering study is typically required for left-turn phasing warrants. Some additional items suggested for consideration in the engineering study include operation and vehicle progression, intersection geometry, confusing approaches, or left-turn receiving lanes.

Each state also considers a decision sequence for which order of implementing left-turn phasing. Typical order progression is to consider the least invasive or controlling phasing possible and progressing to more controlling as is required. The least invasive is permissive only without left-turn phasing, progressing to PPLT phasing and then PLT only. Oregon and Rhode Island, however, utilize the opposite approach by beginning with the most restrictive (PLT only) to the least restrictive (permissive) with the expectation that increased restrictions provide greater safety.

Additional consideration is given for PLT only phasing beyond the left-turn phasing warrants. Volume cross product requirements for PLT only phasing are near 150,000 to 300,000 for two-lane and four-lane roadways. When left-turning vehicles face three or more opposing lanes, PLT only phasing is typically used, or when speeds limits are equal to or exceed 45 mph. PLT only phasing is also typically considered for dual or triple left-turn lanes; however, Arkansas, Kansas, Minnesota, Mississippi, Nebraska, North Carolina, Texas, and Wyoming are known to allow permissive dual left turns under certain conditions.

2.3.1 Information from State Agencies

Information was obtained to better understand the different approaches used by state agencies to manage their left-turn operations. To do this, guidelines and policies were first gathered from DOT websites, followed by email or phone requests to state traffic or signal engineers who provided either an internal document with phasing guidelines, a written response to a set of questions, or an oral response to the same questions (Appendix A lists the complete set of questions). This process resulted in 42 responses of the 50 states contacted.

After analyzing the data, policies for left-turn phasing from all states were divided into five groups:
1. States following the FHWA and ITE Signal Timing Manual flowchart
2. States following the FHWA Signalized Intersections Informational Guide
3. States using original warrant criteria or modified guidelines to the flowchart of guide book
4. States using a formulaic approach to determine when demand exceeds capacity or meeting a minimum left-turn volume criteria, with additional considerations for safety/crash history
5. States with no statewide warrant criteria (engineering judgment alone, case-by-case analysis)

The classifications for each state using the five categories described above are in Table 2.5.

Table 2.5 Left-Turn Phasing Policies by State

ITE Flowchart (8 states)	FHWA Guidelines (4 states)	State Adapted Criteria (14 states)	Formulaic Demand (6 states)	No Statewide Guidelines (12 states)
Alaska	Hawaii	Arizona	Alabama	Arkansas
Delaware	Kentucky	Georgia	Idaho	Connecticut
Louisiana	Nevada	Michigan	Illinois	Florida
North Dakota	Vermont	Minnesota	Indiana	Iowa
Rhode Island		Mississippi	Missouri	Kansas
South Dakota		Nebraska	Montana	Maine
Texas		New York		Massachusetts
Wyoming		North Carolina		New Hampshire
		Oregon		Ohio
		Pennsylvania		Oklahoma
		South Carolina		Virginia
		Tennessee		Washington
		Utah		
		Wisconsin		

* Non-responding states: California, Colorado, Maryland, New Jersey, New Mexico, West Virginia

Eight states were grouped in the first category as following the ITE flowchart or FHWA Signal Timing Manual. Several similar publications provide adaptions of a flowchart/decision tree for considering left-turn phasing (see Figure 2.1 [31-34]). The decision tree considers a variety of warranting criteria for left-turn phasing, including crash history, sight distance, intersection geometry, left-turn volume, 85th percentile speed, through lane and left-turn cross product, and vehicle delay. The flowchart/decision tree assists the user in determining permissive, PPLT, or PLT only phasing by considering successive warranting criteria. The decision tree first considers warrants requiring the use of PLT only phasing, then decreasing the amount of control to PPLT phasing, and finally reaching permissive only phasing as the least amount of signal control.

Safety warrants are first considered in the flowchart for left-turn phasing. The first safety decision is based on crash history. The crash history considers either one or both approaches for the subject road with corresponding one-, two-, and three-year left-turn related crash histories for warrant criteria. Intersections with multiple left-turn related crashes will warrant either PLT only or, if left-turning volumes are greater than two vehicles per cycle, then PPLT. The second safety decision is based on sight line distance of the left-turn lane and the possibility to fix any sight line problems. Sight line problems that cannot be addressed will warrant PLT only. The third safety decision is based on the number of left-turning or opposing through lanes, where two or more left-turn lanes or four opposing lanes will warrant PLT only. The fourth safety consideration is if the 85th percentile speed of the opposing vehicles to the left-turning movement is greater than 45 mph, the intersection will warrant PLT only. If safety considerations do not warrant PLT only, the next set of warrant considerations is for vehicle volumes.

Vehicle warrant criteria consider both left-turn volumes and opposing through volumes. The first vehicle warrant criteria was part of the crash history safety consideration where two or more left-turning vehicles in the peak hour will lead to considering if the crash history will warrant PPLT. The second vehicle warranting criteria uses the cross product of the left-turning vehicles with the opposing through vehicles in conjunction with the number of opposing through lanes. More opposing through lanes require a higher warranting cross product value. The cross product value for one, two, or three opposing through lanes are 50,000, 100,000, and 100,000, respectively. Each warranting criteria for volumes will warrant PPLT (desired) or PLT, leaving discretion to the traffic engineer doing the study. If vehicle warrant criteria do not warrant PPLT or PLT, the final warrant consideration is for vehicle delay.

Vehicle delay considers both individual left-turn vehicle delay and the total left-turn vehicle hours during the peak hour. A 35 sec/veh delay or a 2.0 veh-hr delay will warrant PPLT (desired) or PLT only phasing. In the event none of the earlier warranting criteria have been met, the default phasing is permissive only.

Another publication being used is the Signalized Intersections Information Guide 2nd Edition, published by the FHWA Safety Program. Four states are using the information guide which outlines left-turn phasing in table form rather than a flowchart. The warranting criteria are similar to the ITE decision tree warrants, but with differing values and are considered in a different order. Figure 2.2 and Figure 2.3 are adapted versions of the FHWA guidelines. The major difference in the flowchart to the tables is the guideline to provide separate PLT only guidelines beyond the PPLT warrants. The flowchart recommends either PPLT or PLT only, but does not provide supporting warrant criteria for volume cross product. The information guide provides supporting criteria for the volume cross product, as well as modifications for rural or urban settings and for crash history criteria.

Start

Has the critical number of crashes C_{pt} been equalled or exceeded? — Yes → Protected

No ↓

Is left-turn driver sight distance to oncoming vehicles less than SD_c (equals 5.5 s travel time)? — Yes → Can sight restriction be removed by offsetting the opposing left-turn lanes? — No → Protected

No ↓ ← Yes

How many left-turn lanes are on the subject approach? — 2 or more → Protected

Less than 2 ↓

How many through lanes are on the opposing approach? — 4 or more → Protected

Less than 4 ↓

Is left-turn volume 2 veh/cycle or less during the peak hour? — Yes →

No ↓

Is 85th percentile, or speed limit, of opposing traffic greater than 45 mph? — Yes → Protected

No ↓ ⊕

How many through lanes on the opposing approach?

1 ↓ | 2 or 3 ↓

Is V_{lt} x V_o > 50,000 during the peak hour? | Is V_{lt} x V_o > 100,000 during the peak hour? | Is left-turn delay equal to: a. 2.0 veh-hrs or more, and b. greater than 35 s/veh during the peak hour? — No → Has the critical number of crashes C_{p+p} been equalled or exceeded? — No → Permissive

Yes / No | Yes / No | Yes | Yes

Protected + Permissive (desirable) or Protected only

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

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

Variables
V_{lt} = left-turn volume on the subject approach, veh/h
V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

Figure 2.1 Flowchart for left-turn phasing guidelines (Signal Timing Manual Figure 4-11)

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Left-turn phasing (protected-permissive, permissive-protected, or protected only) should be considered if any one of the following criteria is satisfied:

1. A minimum of 2 left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceeds the appropriate following value:

    a. Random arrivals (no other traffic signals within 0.5 mi):

        One opposing lane: 45,000; Two opposing lanes: 90,000

     b. Platoon arrivals (other traffic signals within 0.5 mi):

        One opposing lane: 50,000; Two opposing lanes: 100,000

2. The left-turning movement crosses 3 or more lanes of opposing through traffic.

3. The posted speed of opposing traffic exceeds 45 mph.

4. Recent crash history for a 12-month period indicates 5 or more left-turn collisions that could be prevented by the installation of left-turn signals.

5. Sight distances to oncoming traffic are less than minimum distances

6. The intersection has unusual geometric configurations, such as five legs, when an analysis indicates that left-turn or other special traffic signal phases would be appropriate to provide positive direction to the motorist.

7. An opposing left-turn approach has a left-turn signal or meets one or more of the criteria in this table.

8. An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, and operational requirements unique to preemption systems.

Figure 2.2 Guidelines for use of left-turn phasing (Adapted from Signalized Intersections Informational Guide 2nd Edition, Exhibit 11-6)

The type of phasing to use can be based on the following criteria:

1. Insignificant number of adequate gaps in opposing traffic to complete a left turn.

2. Permissive left-turn phasing may be considered at sites that do not satisfy any of the left-turn phasing criteria listed in Figure 2.2.

3. Protected-permissive left-turn phasing may be considered at sites that satisfy one or more of the left-turn phasing criteria listed in Figure 2.2 but do not satisfy the phasing criteria for protected-only phasing (see criterion 4 below).

Protected-permissive phasing is not appropriate when left-turn phasing is installed as a result of an accident problem.

4. Permissive-protected left-turn phasing may be considered at sites that satisfy the criteria for protected-permissive phasing and one of the following criteria:

    a. The movement has no opposing left turn (such as at a T-intersection) or the movement is prohibited (such as at a freeway ramp terminal).

    b. A protected-permissive signal display is used that provides the left-turning vehicle with an indication of when the driver must yield to opposing traffic, a flashing yellow arrow, or other such devices.

5. Protected-only left-turn phasing should be considered if any one of the following criteria is satisfied:

    a. A minimum of 2 left-turning vehicles per cycle and the product of opposing and left-turn hourly volumes exceed 130,000-150,000 for one opposing lane or 300,000 for two opposing lanes.

    b. The posted speed of opposing traffic exceeds 45 mph.

    c. Left-turning crashes per approach (including crashes involving pedestrians) equal 4 or more per year, or 6 or more in 2 years, or 8 or more in 3 years.

    d. The left-turning movement crosses three or more lanes of opposing through traffic.

    e. Multiple left-turn lanes are provided.

    f. Sight distances to oncoming traffic are less than required minimum distances.

    g. The signal is located in a traffic signal system that may require the use of lead-lag left-turn phasing. This criterion does not apply if:

      i. An analysis indicates lead-lag phasing is not needed.

      ii. An analysis indicates that protected-permissive phasing reduces total delay more than lead-lag phasing.

      iii. A protected-permissive signal display is used that allows a permissive left turn to operate safely opposite a lagging protected left-turn phase (see Chapter 2 for discussion of left-turn trap).

    h. An engineering study indicates a need for left-turn signals. Items that may be considered include, but are not necessarily limited to, pedestrian volumes, traffic signal progression, freeway interchange design, maneuverability of particular classes of vehicles, number of older drivers, and operational requirements unique to preemption systems.

Figure 2.3 Guidelines for selection of type of left-turn phasing (Adapted from Signalized Intersections Informational Guide 2nd Edition Exhibit 11-7)

The first two state groupings follow the flowchart and guidelines without modifications. Minor modifications have been made by some states to the warranting crash history table, as well as to the left-turn volumes, and the cross product values that were grouped into a third category. A total of 14 states that chose to modify, remove, or add warranting criteria were grouped into one category. Table 2.6 outlines many of the modifications made to the flowchart and guidebook for the left-turn and through volume cross product and the crash history criteria. Most modifications to the flowchart and guidelines are in regard to the volume cross product value and the resulting warranting criteria. The modifications the states make are usually an increase to the warranting criteria for PLT only and a decrease for the warranting criteria for PPLT.

Table 2.6 Cross Product and Crash History for State Adapted Criteria

State	Cross Product	Crash History
Arizona	Rural: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) >150,000 (3 opposing lanes) Urban: >75,000 (1 opposing lane) >150,000 (2 opposing lanes) >225,000 (3 opposing lanes) PLT with 3 opposing lanes	One approach: 4/yr.; 6/2yrs. Two approaches: 6/yr.; 10/2yrs.
Georgia	>50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT with 3 opposing lanes	4/yr. or 6/2yrs.
Kansas	>50,000 (1 opposing lane); >100,000 (2 opposing lanes) Any volume (3 opposing lanes)	One approach: 4/yr.; Two approaches: 6/2yrs.
Michigan	> 50,000 (1 opposing lane); >100,000 (2 opposing lanes); Any volume (3 opposing lanes)	If crash pattern would be corrected
Minnesota	PPLT: >50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT: >80,000 (1 opposing lane) >100,000 (2 opposing lanes) Any volume (3 opposing lanes)	5/3yrs.
Mississippi	PPLT: Urban >40,000 (1 opposing lane) >60,000 (2 opposing lanes) Rural >30,000 (1 opposing lane) >40,000 (2 opposing lanes) PLT >150,000 (1 opposing lane) >60,000 (2 opposing lanes)	Urban: 4/yr./approach; Rural: 3/yr./approach.
Ohio	>100,000 (1 or 2 opposing lanes) PLT with 3 opposing lanes (not mandatory)	5 LT/yr.
Oregon	PPLT >50,000 (1 opposing lane) >100,000 (2 opposing lanes) PLT >150,000 (1 opposing lane) >300,000 (2 opposing lanes) Any volume (3 opposing lanes)	5 LT/yr.

Pennsylvania	PPLT with No LT lane: >35,000 for 2 peak hours (1 opposing lane) >45,000 for 2 peak hours (2 opposing lanes) PPLT with LT lane: >50,000 for 2 peak hours (1 opposing lane) >65,000 for 2 peak hours (2 opposing lanes) PLT >67,500 for 2 peak hours (1 opposing lane) >90,000 for 2 peak hours (2 opposing lanes)	
Rhode Island	>50,000 (1 opposing lane) >100,000 (2 or 3 opposing lanes). PLT only (4 opposing lanes)	One approach: 4/yr.; 6/2 yrs.; 7/3 yrs. Two approaches: 6/yr.; 9/2 yrs.; 13/3 yrs.
South Carolina	>100,000 PLT only (3 opposing lanes)	5 LT /yr.
Tennessee	>50,000 (1 opposing lane); >90,000 (2 opposing lanes); >110,000 (3 opposing lanes).	One approach: 4/yr.; 6/2 yrs.; Two approaches: 6/yr.; 10/2 yrs.
Utah	PPLT: Random arrival: >50,000 (1 opposing lane); >100,000 (2 or 3 opposing lanes). Platooned arrival: >60,000 (1 opposing lane) >120,000 (2 or 3 opposing lanes) PLT: High speeds & 3 opposing lanes	History of severe crashes in past 3 years.
Vermont	PPLT: Random arrival: >45,000 (1 opposing lane); >90,000 (2 opposing lanes). Platooned arrival: >50,000 (1 opposing lane); >100,000 (2 opposing lanes). PLT: >130,000 (1 opposing lane) >300,000 (2 opposing lanes) Any volume (3 opposing lanes)	5/yr.

Five states do not use set warranting values and opt to use a formulaic approach. The methods and equations used by the five states are shown in Table 2.7. Consideration for left-turn capacity is common to all five states. Safety is also a consideration for each state using the formula approach, but only Alabama and Idaho have adopted a crash history warrant.

Table 2.7 Formulaic Criteria for Left-Turn Phase Consideration

State	Criteria
Alabama	Critical left-turn volume based on opposing through lane number and volume adjusted for G/C. 5 LT crashes/yr.
Idaho	Critical left-turn volume based on opposing through lane number and volume adjusted for G/C. 5 LT crashes /3yrs.
Illinois	Consider left-turn phase where the demand for left turn exceeds the left-turn capacity of the approach lane. Consider crash history but no set guidelines.
Indiana	Capacity where demand exceeds capacity of approach lane. $C_L = 1200G - V_{OPP}$. G = %green time. Consider crash history but no set guidelines.
Missouri	When LT + opposing volume exceeds 600 * G/C. 5 LT crashes/yr. on same approach. Vehicle conflicts exceed 29 in an 11-hour day.
Montana	When LT volume exceeds LT capacity of approach lane, calculated as (1,200*G/C-Opposing Volume), not less than 2 veh/cycle. Consider crash history but no set guidelines.

Eleven states have not adopted guidelines or other techniques to determine left-turn phasing, and instead rely on engineering judgment and analysis on a case-by-case basis. Typically, the states which rely on engineering analysis will use some form of data collection and analysis, but the end decision is up to the engineer and controlling organization. Connecticut and Washington, for example, use traffic modeling software to perform a capacity analysis for each intersection decision.

An engineering decision is a final stipulation for all states, no matter the category each state is grouped in. Most states will perform an engineering study for each intersection and will defer to an engineering decision even when warrants are not met. Additionally, left-turn phasing will also be implemented in anticipation of future need, without current demand meeting warrants. FYA also adds capability for left-turn phasing to implement permissive, PPLT, and PLT only phasing, depending on time of day. Many states are in a trial period in implementing FYA, and will continue to adjust signal phasing as crash history, operational data, and public feedback become available.

The decision made by each state for left-turn phasing criteria is partly based on the ability to implement the criteria state-wide. A state agency that does not maintain and operate signals on state roads is less likely to establish left-turn phasing warrants, while those states that do operate all signals on state roads are more likely to establish left-turn phasing criteria. Larger states are also able to devote more resources toward establishing left-turn phasing criteria, while smaller states tend to follow published guidelines.

2.4   Summary and Conclusions

This chapter summarizes findings from previous studies on the safety effects of different left-turn phase options at signalized intersections, and presents an overview of the methodologies followed by most states to warrant the use of a left-turn phase. The literature review includes the safety effects of modifications between permissive, protected only (PLT), and protected/permissive left turn (PPLT) phases, and emphasizes the effects of moving from the traditional options to a flashing yellow arrow (FYA) indication, as recently approved by FHWA and included in the MUTCD.

Past studies seem to reach a general consensus on the direction (positive or negative) of the net effects of some types of left-turn phase changes; but in all cases, the results seem to vary significantly in terms of the overall crash rate change and the effect on target crashes involving left-turning maneuvers.

In general, changes from a permissive to a protected only phase consistently reduced left-turn crashes, without a necessary reduction in the overall crash rate. On the other hand, changes from a permissive to a protected-permissive phase did not always result in a reduction of left-turn or the overall crash rate, with net effects ranging widely for different types of crash breakdowns (from a factor of 0.35 reducing all severe crashes, to a factor of 1.55 increasing overall left-turn crashes). Modifications that incorporated an FYA indication decreased total and left-turn crashes when the FYA replaced a permissive or a protected-permissive phase. However, a wide range of reduction rates were also reported. When changing from permissive to FYA, total crash rates changed between -6.5% and -45%, and total left-turn crashes changed between -26.2% and -59%. When the left-turn phase was converted from PPLT to an FYA indication, changes for all crashes combined were in the order of -5% to -39% (a study also showed an overall reduction of -2.2 crashes per year), and left-turn crashes changed between -11.5% and -67% (a study also showed reduction in terms of 0.9 crashes per year).

Different trends were found when changing from a protected left-turn phase to an FYA, with effects pointing at an increase in left-turn crashes (by a factor of 2.73 to 3.44, or a crash rate of 1.6 crashes per year) and an increase or decrease in the overall crash rate. Relatively unchanged total crash rates, while increasing left-turn crashes will necessarily indicate a reduction of other types of crashes, such as rear-end crashes.

An outreach effort to collect information from all 50 states resulted in 44 states responses. States were grouped by the type of criteria used to make decisions on left-turn phases into the following: state-adapted criteria from ITE and FHWA guidelines (14 states), no statewide guidelines (12 states), ITE flowchart (8 states), a formulaic set of criteria (6 states), and the FHWA guidelines (4 states).

Larger states are also able to devote more resources toward establishing left-turn phasing criteria, while smaller states tend to follow published guidelines. In all cases, regardless of the type of criteria, the engineering decision is a final stipulation even when warrants are not met. Many states are in a trial period in implementing FYA and will continue to adjust signal phasing as crash history, operational data, and public feedback become available.

Left-turn phasing guideline values followed by state DOTs are influenced by many sources. Some states reference the Texas Transportation Institute threshold values for number of lanes, opposing volume, and minimum critical left-turn value. Other states show a likely combination of following the recommendations by ITE or FHWA. Most left-turn guidelines offer engineering judgment and require adequate documentation that threshold values are being met prior to left-turn phasing implementation. Other states, however, have no left-turn phasing requirements or guidelines and rely completely on engineering judgment on a case-by-case basis.

The wide variety of left-turn phasing guidelines has given rise to suggest nationwide left-turn warrant criteria, an opinion that is still divided. On one side, many other national standards exist for geometric design, speed, and a "design vehicle" without unique consideration for the diverse geographic locations, driver behaviors, and signal operations throughout the United States. Adoption of national left-turn phasing criteria would be establishing and implementing safety and operation expectations nationwide. However, creating a nationwide warrant criterion would create signal operations, which could result in drastic changes to some established intersections. The driving culture is either established or reflected in the signal operations of each state. Those states that emphasize safety will sacrifice operations for greater protection, while other states that need higher operations will optimize to reduce delay.

While the debate continues, additional support to justify the use of a specific set of criteria may be needed. This study will analyze the effects of recent left-turn phasing changes in Utah, including conversions to FYA, leading to new conclusions that may or may not be in support of using specific criteria from a safety perspective. In any case, it will provide new evidence for the safety effects of specific left-turning phases through a comprehensive analysis of a wide range of locations.

3. PILOT DATA COLLECTION

Initial data exploration efforts were directed at identifying locations that have undergone changes in left-turn phasing, making them suitable target locations for analysis. The University of Utah team inspected a comprehensive compilation of reports from UDOT-sponsored studies between 2009 and 2015 and selected all 142 left-turn related studies for further inspection.

From the left-turn related studies, we extracted information on existing left-turn phasing, recommended phasing changes (if any), the number of legs at the intersection, the legs subject to study, AADT for major and minor roads, and additional notes describing the motivation for the recommendations and general information related to the left-turn operation.

Table 3.1 shows the number of the intersections, approaches, and recommended left-turn phase changes for regions 2, 3, and 4 based on the studies identified from the compilation. Table 3.1 suggests that an important number of intersections could be used for our analysis, based on the study reports. However, data had to be further explored to address the following considerations:
1. Assuming the recommended changes took place shortly after the studies were conducted, it is necessary to estimate the total combined length of the "after" periods available for the study.
2. It is uncertain if and when recommended changes from UDOT studies actually took place; therefore, it is necessary estimate the effort level needed to find these facts.
3. Intersection modifications in addition to left-turn changes (e.g., geometry) need to be identified to determine if before and after periods are valid for inclusion in the analysis.
4. Crash data for pre-selected locations should be gathered and classified to determine if the expected sample size meet the needs of the study in terms of statistical significance.

Table 3.1 Summary of Recommendations from Left-Turn Studies in UDOT Records

Region	Locations subject to left-turn studies		Recommended left-turn phase change from studies (number of approaches)							
	Intersections	Approaches	No change	Permissive to protected	Permissive to PPLT	PPLT to protected	Permissive to FYA	PPLT to FYA	Protected to FYA	Other changes
Region 2	91	257	177	7	20	13	6	11	18	5 *
Region 3	41	125	85	7	6	2	21	4	0	0
Region 4	10	38	36	0	2	0	0	0	0	0

* = Other recommended changes included: 1 FYA to protected, 1 FYA to permissive, 2 protected to permissive, and 1 protected to protected-permissive

3.1 Intersection Data Availability

To address the first consideration, related to the combined length of "after" periods, locations with recommended changes from the UDOT studies were further classified based on the year the studies were conducted. Results of this classification are shown in Table 3.2, with separate columns for studies that took place after May 2014 (at most, two years of data available), studies from 2013 and 2014 (between two and three years of data available), and studies from 2012 and earlier indicating longer after periods (three or more years of data available).

Note that Table 3.2 summarizes the data in two different ways, indicating the overall number of intersection-years and the overall number of approach-years available. These estimates are conservative, where the available years for each category have been rounded down to the nearest year. For example, for

locations with two to three years of potential "after" data, only two years of data were counted as available. It is noted there are no concerns about the length of "before" data since the crash database allows us to cover more than three years of data for all locations.

Table 3.2 Potential Locations for Analysis from UDOT Studies - Estimated "After" Period

Left-turn phase change	Available "After" Crash Data							
	Less than 2 years	Between 2 and 3 years	3 or more years	Intersection-years from UDOT studies	Less than 2 years	Between 2 and 3 years	3 or more years	Approach-years from UDOT studies
Permissive to protected	3	1	3	14	6	1	7	29
Permissive to PPLT	7	5	6	35	9	11	8	55
PPLT to protected	1	5	3	20	1	10	4	33
Permissive to FYA	5	2	8	33	10	3	14	58
PPLT to FYA	3	2	2	13	7	4	4	27
Protected to FYA	2	8	0	18	3	15	0	33

3.2   Exact Dates of Left-turn Phase Modifications

As mentioned above, the assumption that changes recommended in the studies were actually executed may not hold, and further details on the actual field implementations are needed. To estimate the effort needed to address this issue, the University of Utah team visited the Utah Traffic Operations Center (TOC) and explored the feasibility of establishing a process to finalize the selection of subject locations. Given that the TOC updated the traffic management system in 2015, signal timing and phasing information for most locations before this date are not readily available, but can be extracted from archived files. The TOC demonstrated the process to extract this information, which involved loading databases from older clients and searching through logs in the legacy system.

After searching for a few locations in the system, the TOC and the University of Utah team suggested consulting the signal cabinet logbooks as a feasible option to obtain precise information on the type of modifications and the date they took place. The University of Utah team received a brief introduction to UDOT cabinets at the TOC, and then planned a visit to 12 locations with FYA indications to explore the possibility of expanding this approach if it proved successful.

Cabinet logbooks were inspected April 18, 2016. It is noted that five additional locations with FYA were identified by the team throughout the day and included in the inspection. Logbook notes with exact dates when signals using FYA entered in operation were found for 15 of the 17 intersections, as shown in Table 3.3. Rows highlighted in grey show the remaining two locations without specific notes on the FYA installation date.

Based on these results, the University of Utah team believes this is an effective approach to eliminate uncertainty from installation dates initially approximated from UDOT studies.

Table 3.3 FYA Installation Dates from Cabinet Logbooks

Location No.	Major Street	Minor Street	FYA Approach	Date change	Notes
1	State	300 South	WBL	10/29/2013	FYA turned on by 3:20pm
2	State	1300 South	All	4/30/2015	May have had one direction later than others. FYA N-S on by 16:15
3	700 East	1300 South	NBL, SBL	5/2/2015	On at 01:30pm
4	700 East	1700 South	NBL, SBL	4/20/2015	On at 3:15pm
5	700 East	2700 South	EBL, WBL	2/8/2015	NBL, SBL Protected only. FYA on by 9:20am
6	700 East	3300 South	EBL, WBL	1/8/2015	On at 2:00pm
7	State	4500 South	NBL, SBL	6/24/2013?	Updated firmware (ASC/3 App 2.54, O/S - 1.14.03). New book on 6/13/13, no mention of FYA. New signal 7/12/12
8	State	4800 South	NBL, SBL	3/5/2014	2/26/2014 installed FYA, operational on 3-5-14 by 12:20pm (after installing new controller and MMU); EBL, WBL permissive only
9	State	Vine	NBL, SBL	3/5/2014	FYA on by 3:50pm; EBL, WBL protected only
10	State	Intermountain Drive	NBL, SBL	12/17/2012	On by 16:30. Pattern 16 1/22/13 at 12:10. EBL, WBL permissive only
11	5400 South	700 West	EBL, WBL	9/11/2015	Rebuilt intersection on 9/11/15. NBL, SBL dual LT on both
12	5300 South	320 West	EBL, WBL	2/22/2012	NBL, SBL Perm/Prot doghouse
13	State	8000 South	All	9/16/2012	On by 10:40; all approaches except NB? (Mention of NBL added 9/16/13). 7/31/12 "check FYA programming". 1st mention 5/9/12
14	State	7720 South	SBL	9/16/2012	On by 13:45
15	State	7500 South	NBL, SBL	8/2/2012	Confirmed with Street View from Oct 2012. Pattern 15-17 3/21/13 5:00pm, 4/9/13 pattern into TOD, 8/2/12 new signal
16	4700 South	2200 West	NBL, SBL	4/23/2015	EBL, WBL protected only, under construction during log reading
17	5400 South	5600 West	NBL, SBL	?	Current book starts on 2/2/15; no mention of FYA installation. EBL, WBL protected only - dual LT on both.

After visiting the selected intersections, the University of Utah team noticed that a significant number of intersections in the field have FYA indications, but did not have a specific left-turn study. This scenario is possible since new traffic counts, increases in crash frequency, geometry improvements, and many other events different from a left-turn study may be sufficient to warrant a left-turn phase update. To show some examples, intersections listed in Table 3.4 were identified based on personal experience but do not have a corresponding left-turn study. It is noted that some intersections have UDOT studies, but these were not specific for left-turn updates, and thus were not found in the initial exploration described above.

Having addressed the second consideration, the University of Utah team will also need to verify that no other major modifications have taken place at pre-selected locations. Further review of the completed UDOT studies, consultation with UDOT engineers, and aerial images from online services, such as Google's StreetView and Bing's Streetside services, will provide evidence to assess changes at each pre-selected location.

Table 3.4 Sample Locations with FYA without a Left-Turn Study

Region	Major Street	Minor Street	City	Study Y/N	Count in study	Notes
3	US-189 (University Ave)	300 South	Provo	N	N/A	Perm + Prot to FYA b/n Sept 2011 - Sept 2012
3	US-189 (University Ave)	1230 North (Bulldog)	Provo	N	N/A	Doghouse to FYA b/n Oct 2012 - Sept 2015
3	US-189 (University Ave)	University Pkwy	Provo	N	N/A	Perm + Prot to FYA b/n Sept 2011 - Sept 2012
3	Center St	Orem Blvd	Orem	N	N/A	Aug 2012 - July 2015
3	US-89 (State St)	700 South / 300 East	Pleasant Grove	N	N/A	Oct 2012 - July 2015
4	SR-34 (St George Blvd)	1000 East	St. George	4-290-06	Yes	Study was just for counts at several intersections along BLVD
4	SR-130 (Main St)	200 North	Cedar City	4-912-10	Yes	DLT study, no FYA, doghouse April 2009 - FYA March 2014
2	SR-172 (5600 W)	SR-173 (5400 S)	Kearns	N	N/A	Aug 2014 - July 2015
2	SR-68 (Redwood Rd)	4100 S (Meadowbrook Pkwy)	Taylorsville	2-140-07	N/A	Aug 2011 - July 2014, dual NBL but not implemented or
1	SR-39 (12th St)	1200 W	Ogden	N	N/A	Aug 2012 - Aug 2015
1	SR-108 (Antelope Dr.)	1200 W (University Park Blvd)	Ogden	1-153-07	Yes	Aug 2012 - Aug 2015, No LT phasing in 2007

3.3   Crash Data Availability

The last element needed to select a group of suitable locations for inclusion in the analysis is the extraction of crash data. The University of Utah team has access to UDOT's crash database, and thus will be able to identify and classify crashes for specific time frames. Analysis of crash records will be essential to understand the situations leading to the crash and will also provide support to confirm geometry and environmental changes. As an example, and to test the use of the crash database, the University of Utah team extracted records for some of the locations in Table 3.4 for up to three years before and after the intersection was converted to FYA, as shown in Table 3.5. Periods shorter than three years are highlighted in grey. Continuation of the crash analysis for these locations will include the classification of crashes by type, approach, time of day, etc.

Table 3.5 Sample Crash Data Extracted from Crash Database

Location No.	Major Street	Minor Street	Date change	Crashes up to 3 years before FYA conversion	Crashes up to 3 years after FYA conversion
1	State	300 South	10/29/2013	8	6
2	State	1300 South	4/30/2015	25	18
3	700 East	1300 South	5/2/2015	22	6
4	700 East	1700 South	4/20/2015	27	8
10	State	Intermountain Drive	12/17/2012	31	36
12	5300 South	320 West	2/22/2012	38	111
13	State	8000 South	9/16/2012	25	30
14	State	7720 South	9/16/2012	18	32
15	State	7500 South	8/2/2012	22	34

3.4 Estimation of Efforts Needed for Full Data Collection

Based on the experience from the pilot data collection, the University of Utah team quantified the level of effort needed to extract and analyze data for this study. As expected, there is a tradeoff between the type and size of data collected at each intersection and the overall number of intersections that can be studied.

Most of the intersection characteristics related to current geometry, AADT, and signal operation are available and can be gathered in a short time. However, some of the data for the "before" periods, such as the signal timing data from archived databases at the TOC, are not readily available and will require additional effort. Also, a collection of variables, such as current bicycle and pedestrian demands, may require even more extensive efforts, but may prove not to be consequential due to low volumes and/or crash data.

Therefore, data collection items should be prioritized with respect to the objectives of the study. Table 3.6 shows candidate items for data collection, the level of effort required, and potential data sources for their extraction. Items highlighted in blue are considered "essential items" and will be part of the core data collection efforts. Note that these items require either "low" or "medium" effort.

Table 3.6 Potential Data Collection Items

Data Collection Item	Required Level of Effort		Potential Data Sources
	Before	After	
Intersection Operation and Geometry			
Signal Phasing operation* (permissive, PPLT, protected only)	Low	Low [†]	Imagery from Google, Bing, UDOT. Field visit to cabinet for phase changes.
Geometric features* (lane configuration, number of lanes, channelization, length of pockets, bike lanes and crosswalks)	Low	Low	Imagery from Google, Bing, UDOT (measurements required)
Signal timing (cycle length, G/C, change date, lead/lag)	Medium**	Low	UDOT ATMS, archived DB
AADT* (major and minor roadway)	Low	Low	UDOT ATMS, studies
Turning and through volumes (opposing through, turning volumes)	High**	Medium	UDOT ATMS, studies
Pedestrian volumes	High**	High	UDOT studies, field data collection
Bicycle volumes	High**	High	UDOT studies, field data collection
Approach speed	High**	High	UDOT studies, field data collection
Posted speed	Medium	Low	Imagery from Google, Bing, UDOT
Sight distance	Medium	Medium	Imagery from Google, Bing, UDOT
Crash Records			
Record search and selection*	Low	Low	UDOT
Crash characteristics (type, vehicle directions, etc.)*	Low	Low	UDOT
Review crash diagram and narrative*	Medium	Medium	UDOT

For intersection operation and geometry items, data collection efforts include an online search for the location and identification and documentation of geometry features.

For crash-related items, estimates include fast initial search and selection of records using an automated script, documentation of crash types (e.g., intersection and left-turn related), direction of vehicles involved (e.g., turning left and opposing through), and a review of the crash diagram and narrative. This process is very labor intensive but ensures accuracy and thoroughness, since every crash record is manually verified by a student who can also document details from open fields that are otherwise difficult to extract.

3.5   Expected Statistical Significance and Adequate Sample Size

Analysis of the data collected in this study will result in assessments of the safety effects of different types of left-turn phasing. However, such assessments need adequate levels of statistical confidence in order to provide reliable results. This section describes the procedure followed to estimate the necessary sample size to achieve such levels of confidence.

Reasonable confidence levels can be obtained from a procedure proposed by Hauer for studies using a comparison group to estimate the safety effects of a treatment [35-37]. The procedure is intended to estimate an index of effectiveness for a treatment (θ, equivalent to a CMF) and its corresponding variance ($\sigma(\theta)$, a measure of confidence). However, we adapted the steps so they could be applied in reverse order to estimate the sample size given a specified confidence level. The following input values were needed:
- "Before" crashes per year on the treated system
- Number of "before" years
- Number of "after" years
- "Before" crashes per year on the comparison system
- Variance of odds ratio (VARk)
- Expected percentage reduction ($1-\theta$)*100

Estimates for these inputs were obtained as described below:

- "Before" crashes per year on the treated and comparison systems:
     Average crashes per year obtained from the 17 locations included in the pilot data collection were used as estimates in the analysis. In addition, intersection-level and approach-level averages for different crash types were also extracted to explore potential analyses on specific groups. For example, left-turn crashes on a particular approach involving only vehicles in opposing directions. This analysis resulted in the following values:
     - At intersection level:
         - Average intersection-related crashes per year = 15.7
         - Average left-turn crashes per year = 5.8
     - At approach level:
         - Average left-turn crashes on approaches per year = 4.0
         - Average left-turn crashes on approaches involving only vehicles in opposing directions per year = 2.0

- Number of "before" and "after" years:
     For the analysis, it was assumed that three years of data were available before and after the left-turn phase was modified.

- Variance of odds ratio (VAR $\{\omega\}$)

  This is a measure of the relative variation of the treated and comparison groups in the before and after periods. The calculation of ω can be obtained as:

$$\omega = (v/u)/(\pi/\kappa)$$

  Where v and u are accident counts in the comparison group in the before and after periods, and π and κ are the same measures for the treatment group, respectively. Since at this point in the study, the actual number of crashes in both groups and their variation from year to year are not known, an estimation of VAR $\{\omega\}$ was obtained using a simulation approach. For this purpose, a simple VBA macro was created in Excel to generate values of VAR $\{\omega\}$ when the number of crashes in both groups varied within a reasonable range from each other, and the resulting values were compared with an assumed threshold for VAR $\{\omega\}$. If the threshold was greater than "most" of the simulated values of VAR $\{\omega\}$, then it was considered a conservative value to be used in our estimation. An image to illustrate the macro inputs and outputs in Excel is shown in Figure 3.1.

Simulated Values			
	Number of Crashes		Individual w values
Year	Treatment	Comparison	
1	535	540.35	0.887593468
2	479	431.1	1.06227117
3	550	528	1.027137706
4	474	469.26	0.925331076
5	465	427.8	
mean	500.6	479.302	

mean	0.975583355
var	6.813380032E-03

Single observation of var (w)	-0.00135456

Input Parameters	
Total crashes per year/group	500
Variation between years	10 %
% Crash variation Treatment Vs Comparison	20 %
Var w threshold	0.005
Output	
% Chances Var (w) theshold is successful	73.8 %

Run Sim

Figure 3.1 VBA macro setup to obtain an approximate value for VAR $\{\omega\}$

As noted from Figure 3.1, input parameters included the total number of crashes per year per group, the percentage variation between years, the variation between treatment and comparison groups, and the VAR $\{\omega\}$ threshold being evaluated.

Results were obtained for different combination of input values, where the percent of success of VAR $\{\omega\}$ was measured from 1,000 random iterations. Simulations showed that for conservative input parameters (10% variation between years and 20% variation between treatment and comparison groups), VAR $\{\omega\}$ values of 0.005 and 0.01 were adequate for not less than 75% and 99% of the cases.

Based on these results, it was decided to perform the analysis of a given confidence level considering a "low variation" (VAR $\{\omega\}$=0.005) and a "high variation" (VAR $\{\omega\}$ =0.01) scenario. It is noted that the values for VAR $\{\omega\}$ are consistent with typical values used in examples in Hauer (2002), providing additional support for the simulation results [35].

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- Expected percentage reduction (1-ω)*100:

    A wide range of potential crash reduction percentages due to a treatment were evaluated and included in the analysis to provide a measure of the sensitivity of the expected results. The range of possible crash reductions varied from 5% to 30%, evaluated in increments of 5%.

Results of the sample size analysis and the corresponding confidence levels are summarized in Figure 3.2. An example to interpret the figures is provided as follows: Assume that the analysis wants to determine the effect of changing the left-turn phasing from permissive to FYA on the overall crash frequency at intersections. First, at the intersection level, shown in Figure 3.2 (a), it is observed that 33 intersection-years were identified from locations that changed from permissive to FYA. With this sample size, we expect to obtain 85% to 90% confidence in our findings, depending on the magnitude of observed crash reductions. If reductions are in the order of 5% to 10%, the expected confidence is 85%; if crash reductions are between 15% and 25%, 90% confidence levels are likely. As expected, for a given sample size, greater effects can be detected with more confidence.

A total of four figures were developed for different treatments when considering the following crash groups:
- All crashes at the intersection level – Figure 3.2(a)
- Left-turn related crashes at intersection level – Figure 3.2(b)
- Left-turn related crashes on treated approaches – Figure 3.2(c)
  - Left-turn related crashes on treated approaches and only involving opposing traffic – Figure 3.2(d)

It is noted that as the analysis became more specific, from the overall intersection crashes [Figure 3.2(a)] to specific approaches and crash types [Figure 3.2(d)], the expected confidence level is significantly reduced. These figures show that the initial sample size identified from UDOT studies may not be adequate for detailed analysis, and additional locations with left-turn changes have to be identified.

Given the need to further expand the sample size for the study, the University of Utah team began a systematic exploration of 520 signalized intersections in Region 2. The analysis involved manual inspection of Google StreetView images from different time periods to identify changes in the left-turn signal heads of the intersection approaches. If changes were observed, the type of phasing before and after were recorded along with the timestamp of the images.

Even though this process was time consuming, it proved to be worthwhile and allowed the University of Utah team to significantly increase the sample size for all treatments, as shown in Table 3.7. In addition, by increasing the sample size using locations from Region 2, the required effort for the University of Utah team to complete field visits and consult cabinet logbooks is minimized.

Table 3.7 Expected Sample Size including Additional Locations from Region 2

Left-turn phase change	Intersections		Approaches	
	UDOT studies only	Including Analysis of Region 2	UDOT studies only	Including Analysis of Region 2
Permissive to protected	7	13	14	25
Permissive to PPLT	18	40	28	69
PPLT to protected	9	40	15	76
Permissive to FYA	15	29	27	54
PPLT to FYA	7	34	15	64
Protected to FYA	10	38	18	75
TOTAL	66	194	117	363

The new sample size for each group was used to obtain a revised estimate of the confidence level based on the analysis from the previous section. The updated estimates are shown in Figure 3.3 (a)-(d), following a similar structure to that described for Figure 3.2. Results show that not only analysis at the intersection level, but also at the approach level and for specific types of crashes, could produce acceptable confidence levels for most treatment combinations.
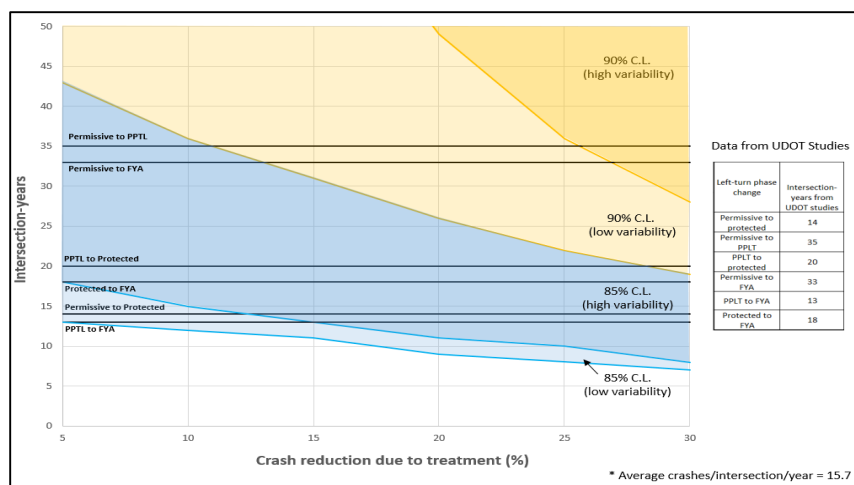
(a) Intersection level – All crashes
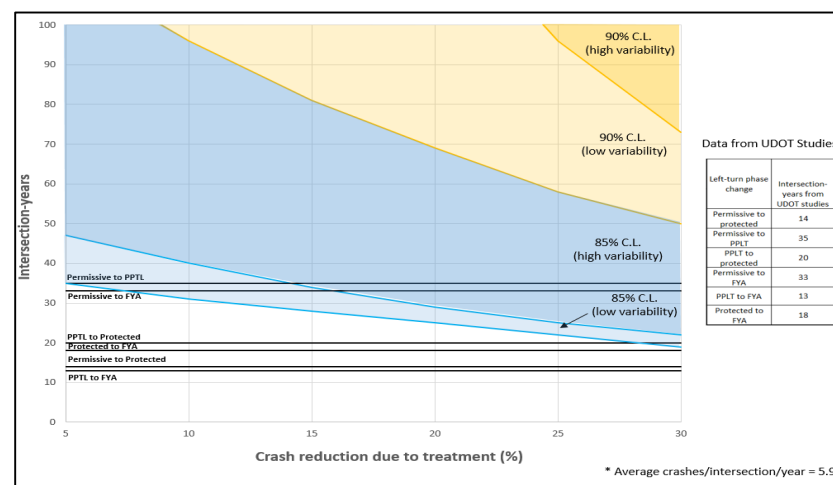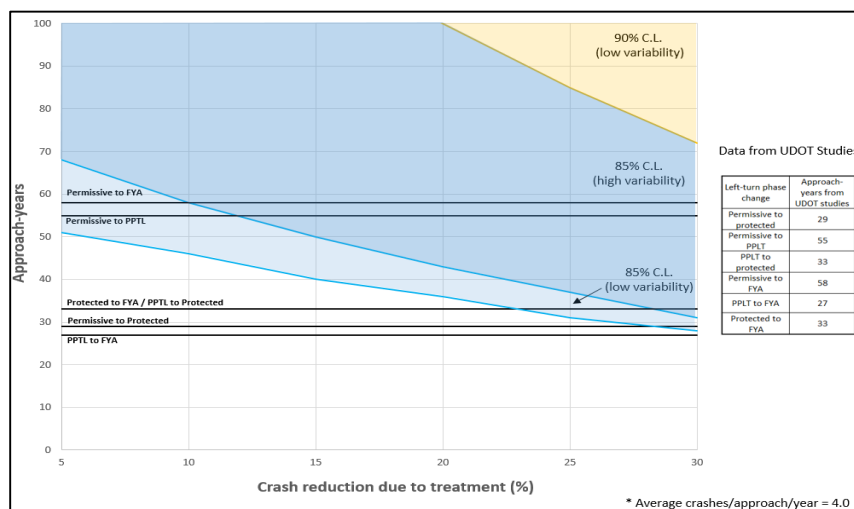
(b) Intersection level – Left-turn crashes

(c) Approach level – LT crashes on modified approaches

(d) Approach level – LT crashes on modified approaches with opposing traffic only

Figure 3.2 Expected confidence levels for different treatments and analysis – locations from UDOT studies
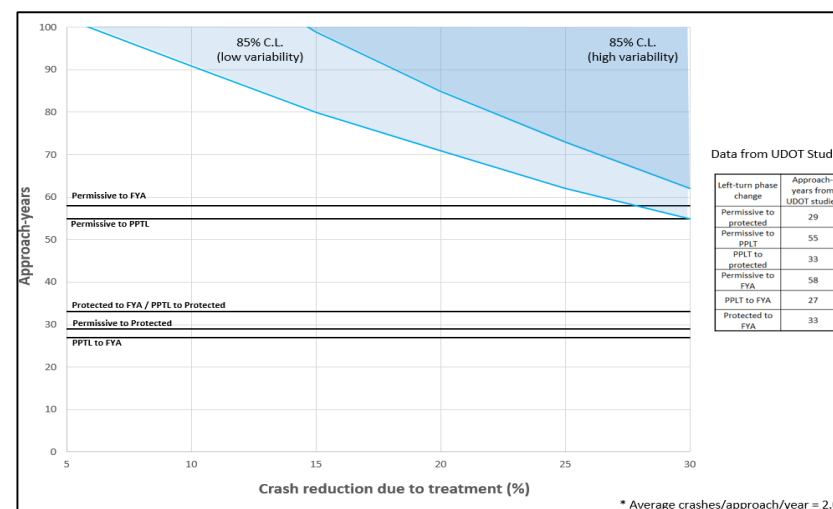
(a) Intersection level – All crashes
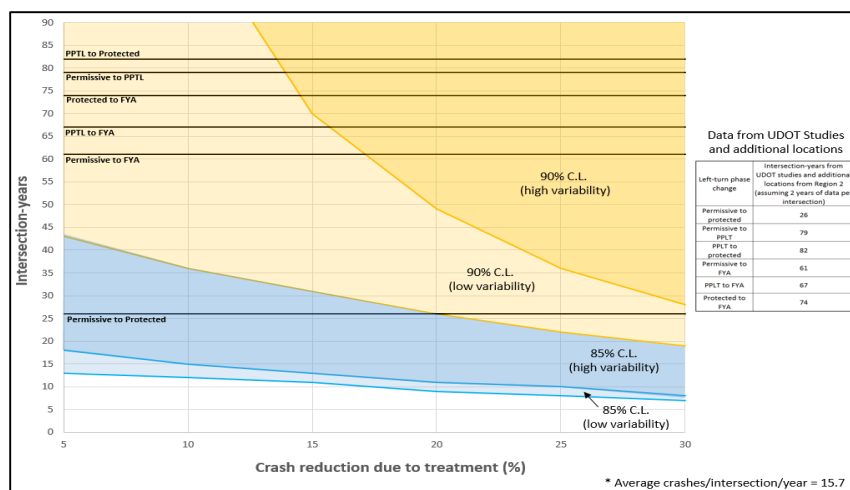

(b) Intersection level – Left-turn crashes

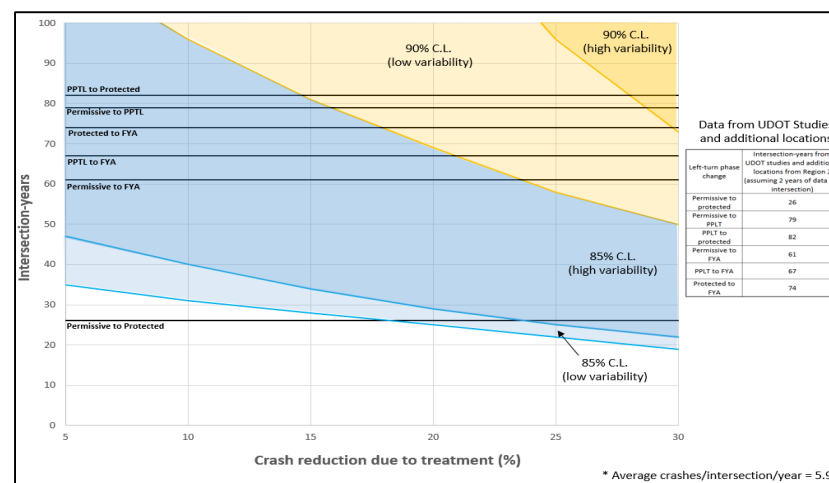(c) Approach level – LT crashes on modified approaches

(d) Approach level – LT crashes on modified approaches with opposing traffic only
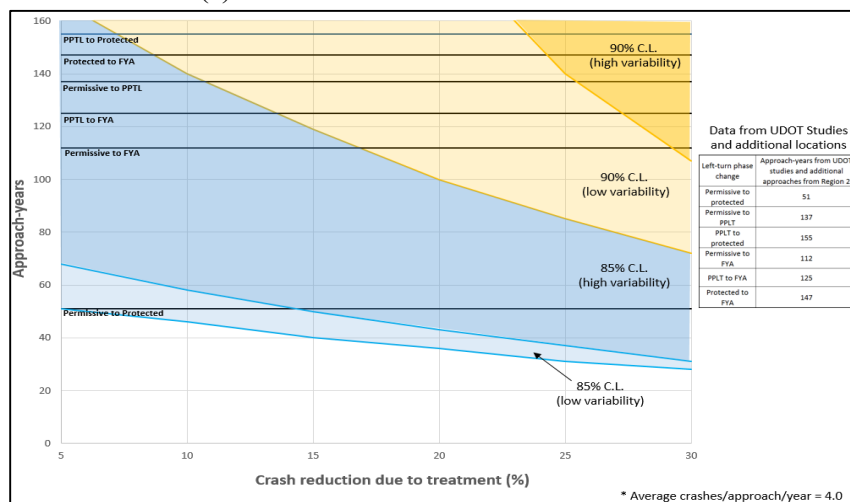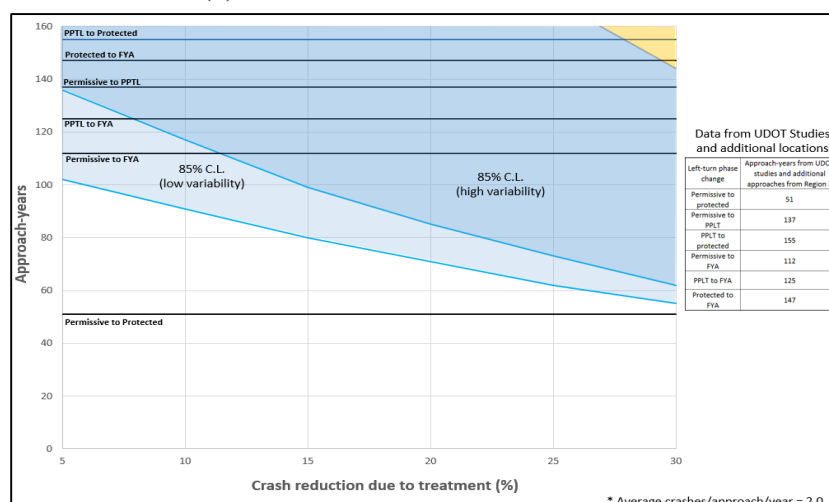
Figure 3.3 Expected confidence levels for different treatments and analysis – Additional locations from Region 2

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3.6   Proposed Data Collection Plan

Based on the results from the pilot data collection and the estimation of efforts required to collect data items at a larger scale, the University of Utah team proposed collecting data for a subset of all possible groups shown in Figure 3.4.
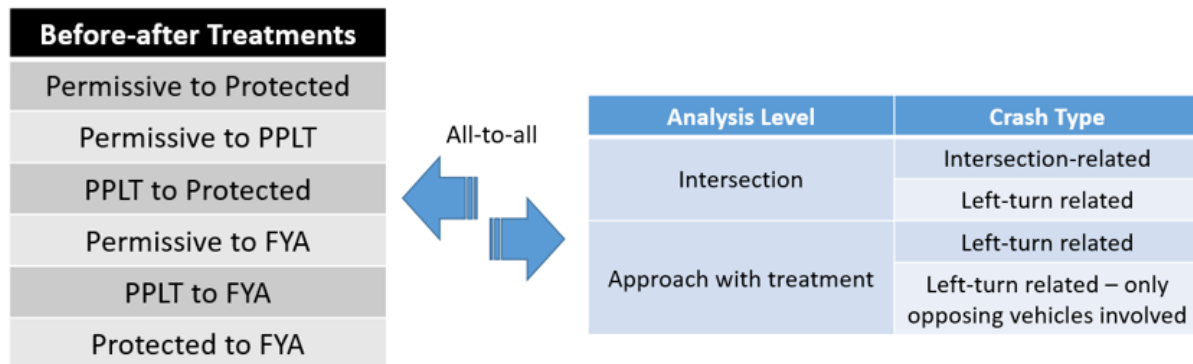

Figure 3.4 All possible combination of treatment groups and analysis levels

Based on the estimations of the required effort level for data collection, the University of Utah team reviewed the budget and the matching funds from the Mountains Plains Consortium UTC (MPC) to determine the required and available resources for the remainder of the study. Considering that about four student-hours are required to gather and prepare the data for one intersection, these resources would be enough for completing up to 275 intersections.

On the other hand, the University of Utah team identified a total of up to 194 intersections during the pilot data collection, as shown in Table 3.7. Even though this estimate is very conservative, the allocation of resources should be prioritized not only to maximize the confidence in the results, but also to optimize the utilization of resources.

A number of strategies to improve efficiency in the data collection will be explored, including:
- Reduced number of unique comparison groups, taking advantage of multiple groups with the same untreated left-turn phase (i.e., permissive, protected, and PPLT).
- Increased/reduced number of locations analyzed based on the confidence level analysis. For example, in some cases, it may be more beneficial to invest more resources analyzing additional treated sites; whereas, in others, increasing the number of locations in the comparison groups is more convenient.
- Optimization of site visit scheduling and routing to increase the number of intersections that can be visited per field trip.
- Careful selection of comparison groups to obtain low variability scenarios while ensuring representativeness with respect to the treated group.

The University of Utah team began the evaluation of treatments giving priority to groups related to FYA, given the increasing utilization of this type of left-turn indications in Utah. A detailed account of the data collection and analysis is presented in the next chapter, followed by the models and final results.

4. DATA COLLECTION AND METHODOLOGY

Identification of signalized intersections, suitable for this study, used manual inspection of the mast arm signal heads to obtain a set of candidate intersections with LT phase changes occurring between 2011 and 2017. The 2011 cutoff year was selected due to limited crash data and quality in earlier years; the 2017 cutoff date was selected to maximize the number of months included in the after period for phase changes at each intersection. It is noted that initial efforts included crash data through 2016, but at some point during spring 2018, the time period covered in the study was re-evaluated with the addition of more recent crashes from 2017.

UDOT operates over 1,300 signalized intersections statewide, with approximately 550 operational in Salt Lake County and an additional 270 in Utah County. Signal phase changes are evaluated for individual intersections and based on signal warrant requirements to accommodate operational needs, including LT phasing, using engineering studies. A phase change will typically occur when an engineering study warrants modification to the signal. When a phase change occurs, a signal head is added (such as changing from a permissive only phase) or a signal head is changed from the doghouse to a protected arrow or FYA, or even changed from protected to a doghouse or FYA. Any change in phasing requires changing the signal head, allowing for a visual indication that a phase change had occurred. It is noted that UDOT does not utilize the three-section head for FYA indications, so all three-section heads with arrows are used for protected only LT phasing.

Intersections with at least one approach that changed LT phasing were included in the initial dataset. Google Maps street viewer provided a general historic record of each intersection; phase changes were identified by scrolling through different years of pictures and identifying which signals changed among the three-section head with solid balls, four-section FYA arrows, five-section doghouse, or three-section arrow. The month and year of the before and after Google Map images were recorded to provide a range of dates for when the signal had changed, sometimes spanning several years. However, the exact date of the phase change was found by consulting the maintenance record logbook inside the traffic cabinet onsite at each location; in some cases, an old logbook was filled up or replaced, but the original books were archived and accessed at UDOT's regional facilities. The maintenance logbook would indicate a change in signal heads on a specific date, and often would indicate signal phase changes. Some logbooks did not contain the exact date the LT phasing took place, or the date could not be determined, which resulted in those intersections being excluded from the final dataset.

Selected intersections identified with an LT phase change were mainly in UDOT Region 2 (i.e., Salt Lake City area), which includes the largest urbanized area in the state and a significant number of intersections with an LT phase change. However, the number of applicable intersections during the initial data search within UDOT Region 2 was deemed insufficient to provide all required data, prompting the research team to gather supplemental intersection locations in Region 3 (i.e., Provo, Orem, and American Fork Cities).

It is noted that some of the left-turn phase changes included adding a lagging left phase, which quickly showed signs of safety concerns for the FYA operation. In the field, a lagging left created a "perceived yellow trap" among some drivers; wherein the left-turning driver interpreted the signal cycle change for through traffic in the same direction as an indication of the opposing through traffic also changing phases, creating the need to clear the intersection. In such cases, the perceived yellow trap resulted in left-turning vehicles not yielding to opposing through vehicles. UDOT removed all lagging left-turn phases from FYA operations as a safety measure, and a supplemental FYA sign indicating "Left Turn Yield on Flashing Arrow" was also installed at all intersections as a standard practice (UDOT Standard Sign RS10-21ex). Intersections with lagging phase operations were removed from the dataset as a precaution due to the apparent significant increase in crashes. A case example showing the effects of adding and then removing the lagging FYA operation is included in the data analysis chapter.

Selected intersections had site-specific characteristics gathered. Relevant geometric data included annual average daily traffic (AADT), vehicle movement counts, posted speed, and number of travel lanes. AADT traffic data were extracted from UDOT's open data portal, and an AADT was determined for the years in the analysis. Turning movement counts were obtained from UDOT's Automated Traffic Signal Performance Measures (ATSPM) website [38]. Some intersections in ATSPM do not have turning movement counts, so in those cases the team consulted UDOT historic traffic studies to extract manual traffic counts that warranted the LT phase change. The ATSPM website was preferred over the traffic study counts, as ATSPM provides daily counts over extended time periods, while the available traffic study provides only peak hour counts and only during the days of the study. In those cases that required the traffic counts from the traffic studies to be used, the ratio of each turning movement to the total peak hour traffic was multiplied by the AADT to obtain an expected daily demand for each movement.

Also, Google Maps and Google Earth were used to explore aerial/street views and gather the number of lanes and posted speed limit. Each intersection approach had the site-specific geometry and movement counts for that approach identified and assigned accordingly, allowing for an approach level analysis of the effects of specific phase changes.

The final dataset did not contain intersections with major construction during the study years, significant geometric differences to a typical four-way signalized intersection, or locations with limited vehicle data.

Crash history, obtained from UDOT's crash database gathered between 2011 and 2017, identified all LT-related crashes within 250 feet of the intersections. Utah transitioned to an electronic crash data reporting system in 2011, so crash history prior to 2011 provided less detailed information and did not have crash diagrams and narratives, which are essential for an approach-level crash analysis, readily available to the research team.

Soon after the crash data extraction began, it was clear that an approach-level analysis required detailed verification of the vehicles' travel direction using crash diagrams and narratives from the crash reports. The recorded direction of travel for left-turning maneuvers is inconsistent between the direction of the originating movement (direction the vehicle is turning from) and the direction of travel after the turning movement, wherein the vehicle direction was sometimes recorded prior to the turn and sometimes after the turn. Each vehicle in every crash was checked against the crash narrative and/or diagrams to verify the vehicle direction prior to turning left.

The crash verification process corrected nearly one-third of the recorded vehicle directions to reflect the direction of the originating movement. Therefore, without this extensive verification process, results could have been highly inaccurate. Also, the crash verification process showed that about one-third of all left-turn related crashes occurred during the yellow-red transition phase.

The before period was calculated as the total of months that passed from January 2011 until the phase change month; the after period was calculated as the total months that passed from the phase change month through the end of 2017. The number of months in the before and after periods were divided by 12 to create a total portion number of years for each period. The assigned crashes by approach were then identified as either occurring in the before or in the after period for the phase change. The total number of before crashes were then related to the before years, and the number of after crashes were related to the after years to get average annual crash frequencies.

A breakdown of the number of approaches, total number of approach-months, and the total number of LT-related crashes for the before and after periods is shown in Table 4.1. Only LT-related crashes were included in the analysis, and the frequency of LT opposing through traffic is also indicated.

It is important to highlight that the data collection was quite extensive and required continual refinement to reach the final dataset. The level of effort to obtain and verify the dataset, along with data availability itself, are likely strong reasons for most studies not pursuing such approach level analysis.

After gathering data from the sources mentioned above—including left-turn demands, date of change to FYA, geometric characteristics, and crash data—a dataset with all approaches and those suitable for final analysis was created. Unfortunately, the number of approaches suitable for analysis was significantly reduced due to incomplete information, the left-turn demands being the main limiting factor, but primarily due to data with short time periods or no available turning count data from ATSPM. However, other factors, such as unusual geometry, construction, and configuration changes, also played a role. Initially, a set of 86 intersections with at least one FYA approach was identified in the Salt Lake Valley, for a total of 171 potential FYA approaches. This sample was then enhanced with 16 additional intersections in Region 3, representing a total of 51 FYA approaches, for a total of 222 approaches with potential to be included in the analysis. The final dataset, after processing all collected data and making a careful selection of approaches with complete and reliable data, comprised 74 approaches in the main three groups to be analyzed, as shown in Table 4.1. Attempts were also made to construct a reliable group for signals changing from permissive only to protected-permissive (doghouse), but data from only eight approaches had complete and suitable before-after information.

Table 4.1 Summary Final Dataset for Analysis

Group (before – after)	Number of Approaches	Before Period		After Period	
		Approach-months	LT Crashes	Approach-months	LT Crashes
Permissive – FYA	23	981	66	951	72
PPLT – FYA	34	1501	196	1355	268
Protected – FYA	17	731	15	687	126

4.1　Description of Geometric and Traffic Characteristics

A summary of descriptive statistics related to geometric and traffic characteristics from the selected approaches is provided in the tables below. Approaches are presented based on the LT indication during the analysis period, whether before or after a signal change, resulting in four main groups: 1) Permissive Only (Table 4.2), 2) PPLT – Doghouse (Table 4.3), 3) FYA (Table 4.4), and 4) Protected (Table 4.5).

Table 4.2 Descriptive Statistics for Approaches with a Permissive Indication

Permissive LT Indication					
Variable	Obs	Mean	Std. Dev.	Min	Max
Total LT Crashes	23	2.87	3.65	0.00	15
Exposure Years	23	3.55	1.00	1.67	4.83
LT Daily Traffic	23	935	706	264	2,819
Opposing Through Daily Traffic	23	7,707	5,237	2,069	23,000
Ln Cross Product	23	15.09	0.99	13.42	17.86
LT Receiving Lane	23	1.91	1.08	1	4
Posted Speed	23	40.87	11.35	30	60

Table 4.3 Descriptive Statistics for Approaches with a PPLT (Doghouse) Indication

PPLT (Doghouse) Indication					
Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Total LT Crashes	34	5.76	4.42	1	20
Exposure Years	34	3.68	0.84	2.17	4.67
LT Daily Traffic	34	1,664	1,132	516	6,414
Opposing Through Daily Traffic	34	10620	4009	3713	24,743
Ln Cross Product	34	16.36	0.59	14.76	17.49
LT Receiving Lane	34	1.88	0.91	1	4
Posted Speed	34	38.38	7.56	30	60

Table 4.4 Descriptive Statistics for Approaches with a FYA Indication

FYA Indication					
Variable	**Obs ***	**Mean**	**Std. Dev.**	**Min**	**Max**
Total LT Crashes	74	6.30	5.93	0	30
Exposure Years	74	3.37	0.98	2.17	6.67
LT Daily Traffic	74	1,451	1,013	147	6,681
Opposing Through Daily Traffic	74	11086.7	5314,9	2,289	28,285
Ln Cross Product	74	16.1	0.96	13.69	17.75
LT Receiving Lane	74	1.82	0.9	1	4
Posted Speed	74	39.32	8.41	30	60

* Includes approaches in the after period from permissive, PPLT, and protected groups

Table 4.5 Descriptive Statistics for Approaches with a Protected Indication

Protected Indication					
Variable	**Obs**	**Mean**	**Std. Dev.**	**Min**	**Max**
Total LT Crashes	17	0.88	0.99	0	3
Exposure Years	17	3.58	1.31	0.33	4.75
LT Daily Traffic	17	1,233	553	133	2,167
Opposing Through Daily Traffic	17	12,000	3,777	6,205	18,223
Ln Cross Product	17	16.41	0.74	14.45	17.59
LT Receiving Lane	17	1.59	0.51	1	2
Posted Speed	17	39.12	4.76	30	45

4.2   Description of Crash Data

In addition to the geometric and traffic characteristics above, this section presents a summary of the crash data, and annual crash rates are described for the same groups. These data can also be contrasted with initial estimates used in the pilot data collection to improve future data collection efforts.

Table 4.6 Descriptive Statistics for Crashes per Year by LT Indication

LT Indication	Crashes per Year			
	Mean	**Std. dev.**	**Min**	**Max**
Permissive	0.72	0.79	0.00	3.10
PPLT – Doghouse	1.59	1.14	0.23	4.90
FYA	1.81	1.54	0.00	6.51
Protected	0.25	0.29	0.00	0.82

A comparison of the final dataset with the assumptions made in the pilot data collection suggests that initial estimates on the length of exposure per approach were in line with the expectations, but the total number of approaches with fill data and the final crash rates in the field were lower than anticipated. Crash rates were expected to be in the order of four left-turn crashes per year, with at least two of them occurring between left-turning vehicles and opposing through traffic. From Table 4.6, field data indicate much lower crash rates for all groups.

4.3   Methodology

This section describes the development of safety performance functions (SPFs) used to predict expected crash frequencies for each left-turn phase.

4.3.1   Crash Frequency Modeling

The relationships left-turn phasing and the expected frequencies of left-turn crashes were explored in this study using a negative binomial regression modeling approach. In these negative binomial models, the expected number of crashes (μ_i) was expressed as:

$$\mu_i = e^{(X\beta)} \tag{1}$$

where:

μ_i = the expected number of crashes of left-turn phase type i;
X = a set of traffic and geometric variables characterizing each intersection;
  β = regression coefficients estimated with maximum likelihood that quantify the relationship
    between μ_i and variables in X;

The negative binomial regression analysis of site-specific characteristics to observed crashes creates a safety performance function (SPF) for the predicted number of crashes (*Npredicted*).

4.3.2 Empirical Bayes Modeling

This research used an empirical Bayes before-after analysis to quantify the safety effects, in terms of left-turn related crashes, of changing left-turn phasing operations. The benefit of an empirical Bayes analysis is that it accounts for changes in traffic volume over time, as well as the regression-to-the-mean tendency for crash frequency analysis. The methodology followed recommended steps from the FHWA's Guide to Developing Quality Modifications Factors [39].

The empirical Bayes methodology estimates crash frequency in a comparison group had the treatment not occurred ($N_{expected, after}$) against the observed crash frequency of that group with the treatment ($N_{observed, after}$). The empirical Bayes method calculates N expected, after using the following equation:

$$N_{expected,after} = N_{expected,before} \left(\frac{N_{predicted,after}}{N_{predicted,before}} \right) \quad (2)$$

Where,

$N_{expected, before}$ = the unadjusted empirical Bayes estimate of the before period crashes

$N_{predicted, after}$ = the predicted number of crashes in the after period using an SPF

$N_{predicted, before}$ = the predicted number of crashes in the before period using an SPF

The SPF for the expected number of crashes in the before period ($N_{predicted, before}$) is then multiplied by the weighted average (SPF weight) of the number of observed crashes in the before period. The observed before period crashes ($N_{observed, before}$) are also multiplied by the remaining percentage weight, as shown in equation 3. The following equation calculates the N expected, before crash estimate:

$$N_{expected,before} = SPF \; weight \left(N_{predicted,before} \right) + (1 - SPF \; weight)\left(N_{observed,before} \right) \quad (3)$$

And

$$SPF \; weight = \frac{1}{1 + \dfrac{N_{predicted,before} \times (\#yrs)}{\alpha}} \quad (4)$$

Where,

α = the over-dispersion parameter of the SPF

Approximate the crash modification factor (CMF) by the ratio of the observed in the after period to the expected after period crashes, as shown in Equation 5.

$$CMF = \frac{N_{observed,after}}{N_{expected,after}} \quad (5)$$

5.   DATA ANALYSIS AND MODELING

Traffic volume is a primary decision point in left-turn phasing implementation. Higher traffic volumes warrant greater left-turn phasing control for operational needs; consequently, greater control results are expected to reduce crashes. Intersections with permissive only left-turn phasing are strategically allowed to increase in traffic volume without changing LT phasing until it becomes advantageous to improve operations or decrease crash frequency. Typically, higher volumes reduce opportunities for permissive maneuvers, prompting the need to change a permissive phase to a PPLT phase, and even higher demands result in a protected phase. When crash frequency reaches a certain warrant level, the intersection is also expected to change operations from a permissive phasing. Figure 5.1 shows distributions of the opposing through volumes of the approaches in the final dataset during the period before being converted to FYA, and a clear shift from left to right when comparing permissive, PPLT, and protected phases. Similar trends for left-turn volumes of the same approaches were also found, as expected, and are shown in Figure 5.2.

It is noted that traffic demands were explored in different forms and combinations, including left-turn and opposing through volumes as individual variables, their natural logarithmic transformation, and the natural logarithm of the cross product between the two competing volumes.

The safety performance of the FYA indication in the after periods, and the permissive, PPLT, and protected phases in the before periods are described below.

5.1   Safety Performance of Approaches with FYA Indication

Unlike other signal indications, approaches in the three main selected groups transitioned from one of the standard LT phasing indications (i.e., permissive, PPLT, or protected) to FYA. Therefore, the sample size for FYA was significantly larger than each of the other groups, as it comprised the "after" period from the three groups combined, producing more robust estimations of safety performance used in the empirical Bayes evaluations presented in later in this chapter.
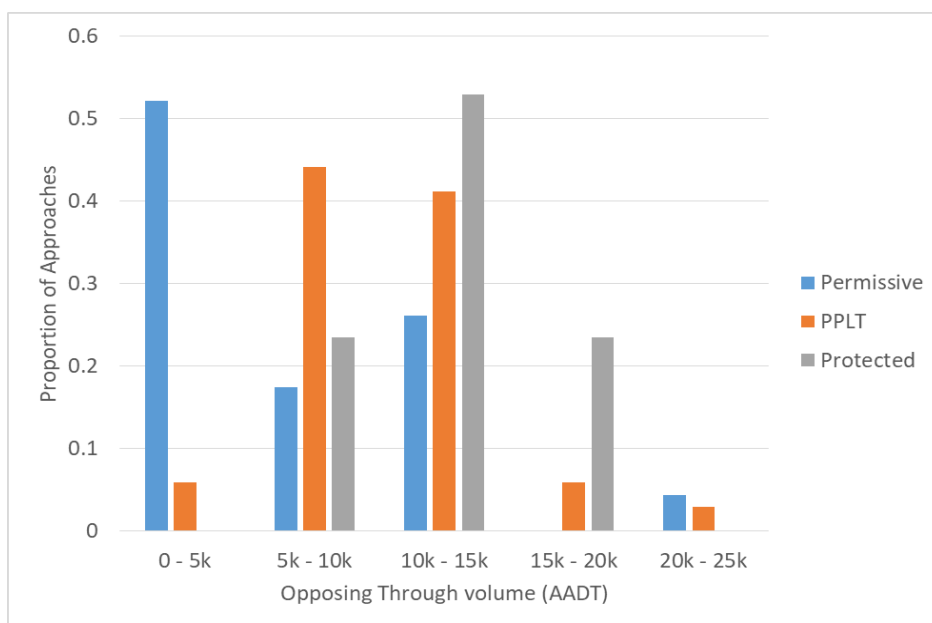

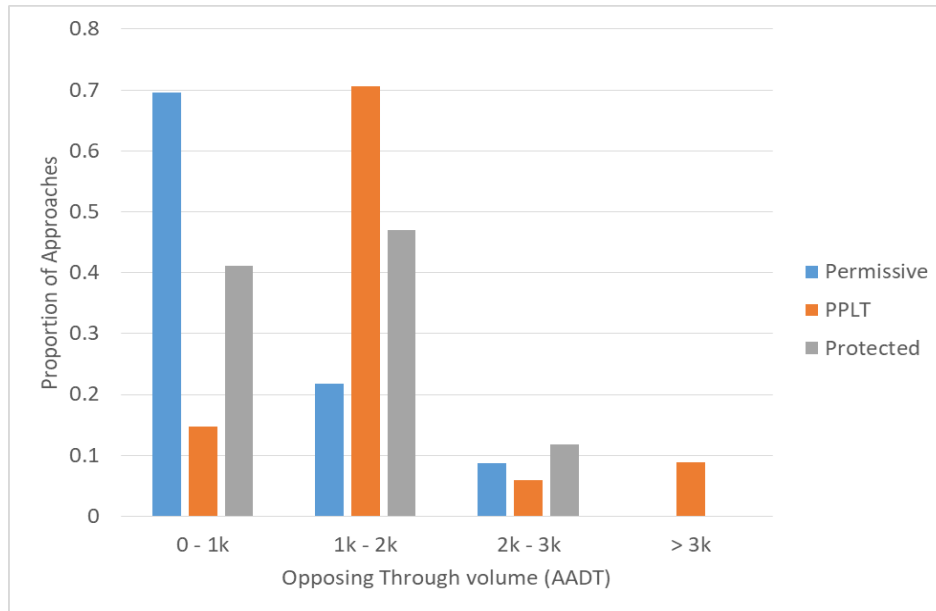**Figure 5.1** Comparison of opposing through volumes for approaches with different LT indications

Figure 5.2 Comparison of left-turn volumes for approaches with different LT indications

Figure 5.3 shows the observed crash frequencies of all FYA approaches, where each symbol indicates the type of left-turn phase in the before period. The shapes superposed over the points indicate regions with a high concentration of permissive approaches (blue ellipse) and protected approaches (green ellipse), highlighting their different cross product values and their annual crash frequencies. However, it is noted that a number of locations are observed away from the shape boundaries and deviate from cross-product or crash frequency values typical of their group, as expected. Locations from the PPLT group were found across all range of values and constituted the strongest group from a sample size perspective.
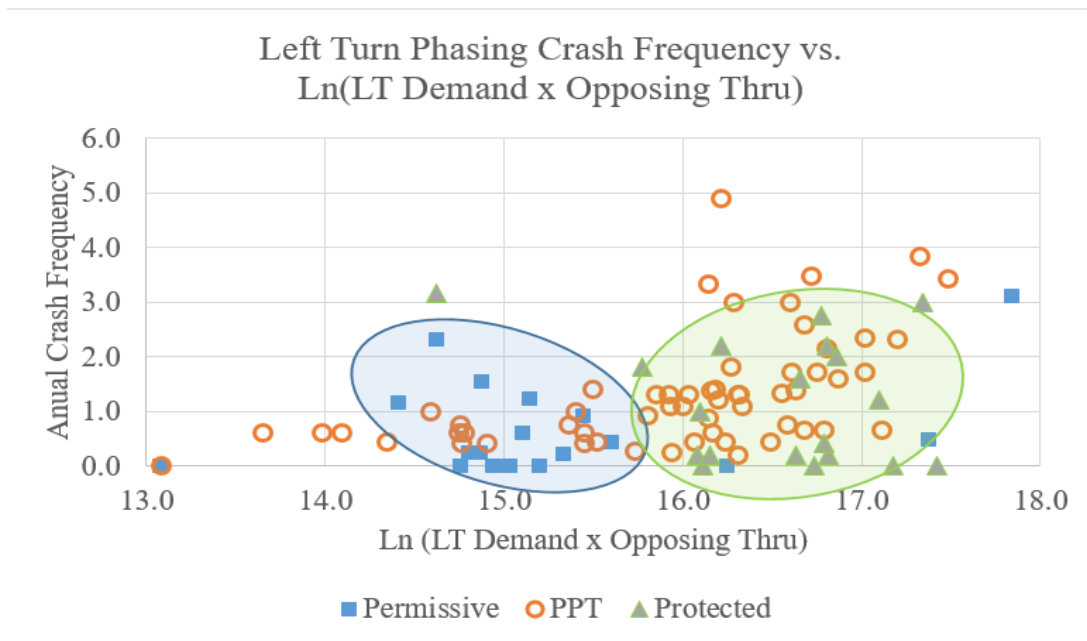

Figure 5.3 Selected approaches by group and crash frequencies during the "after" (FYA) periods

As mentioned above, initial explorations of model forms included different combinations of independent variables to predict crash frequencies. Some of these models are shown in Table 5.1, along with the corresponding log-likelihood and R^2.

Table 5.1 Sample Exploratory Models for FYA Approaches

Model	Independent Variables	Significant? (Pvalue<0.1)	Number Obs	Log likelihood	Pseudo R^2
1	Left-turn volume	Y	74	-212.20	0.0481
	Opposing through volume	Y			
2	Ln (Left-turn volume)	Y	74	-207.04	0.0713
	Ln(Opposing through volume)	Y			
3	Ln (cross product of left-turn and through volumes)	Y	74	-207.20	0.0705
4	Ln (Left-turn volume)	Y	74	-201.43	0.0964
	Ln (Opposing through volume)	Y			
	Number of receiving lanes	N			
	Posted speed limit	Y			
5	Ln (cross product of left-turn and through volumes)	Y	74	-201.86	0.0945
	Number of receiving lanes	N			
	Posted speed limit	Y			
6*	Ln (cross product of left-turn and through volumes)	Y	57	-138.58	0.1256
	Number of receiving lanes	Y			
	Posted speed limit	Y			

* Model without approaches that transitioned from a protected phase

From Table 5.1, it is observed that the addition of explanatory variables different from traffic demands, including the number of receiving lanes and the posted speed limit, enhanced the ability of the model to capture variability in the crash frequency. Also, it is noted that the FYA model that excluded approaches transitioning from a protected phase (i.e. Model 6) had a higher R^2 value than other models with all three groups (permissive, PPLT, and protected) combined. This highlights some of the inherent differences of approaches with different left-turn phases in the before condition, and suggesting that care needs to be taken when making comparisons across groups.

Based on negative binomial regressions applied to the final dataset, the two SPFs for FYA (with and without approaches from the protected groups) are shown in the equations below. The corresponding P-values for each of the variables in the regressions are included in Table 5.2.

$$FYA_{all\ groups} = e^{[0.693 \times LnCrossProductAADT + 0.096 \times LTReceivingLane + 0.0429 \times PostedSpeed - 12.459]}$$

$$FYA_{no\ protected} = e^{[0.621 \times LnCrossProductAADT + 0.1964 \times LTReceivingLane + 0.0409 \times PostedSpeed - 11.536]}$$

Table 5.2 Results of NB Regression for Approaches with an FYA Indication

Variable	All Groups		No Protected	
	Coefficient	P-Value	Coefficient	P-Value
Ln Cross Product	0.693	0.00	0.621	0.00
LT Receiving Lanes	0.096	0.402	0.1964	0.065
Posted Speed Limit	0.0429	0.002	0.0409	0.001
Constant	-12.459	0.00	-11.536	0.00

A representation of the two SPFs using the coefficients from the NB regressions above is shown in Figure 5.4. To construct the figure, the average number of receiving lanes (value=1.82) and posted speed limit (value=39.3) from the whole sample was used, and the horizontal scale follows actual range of ln (cross product) observed in the field.
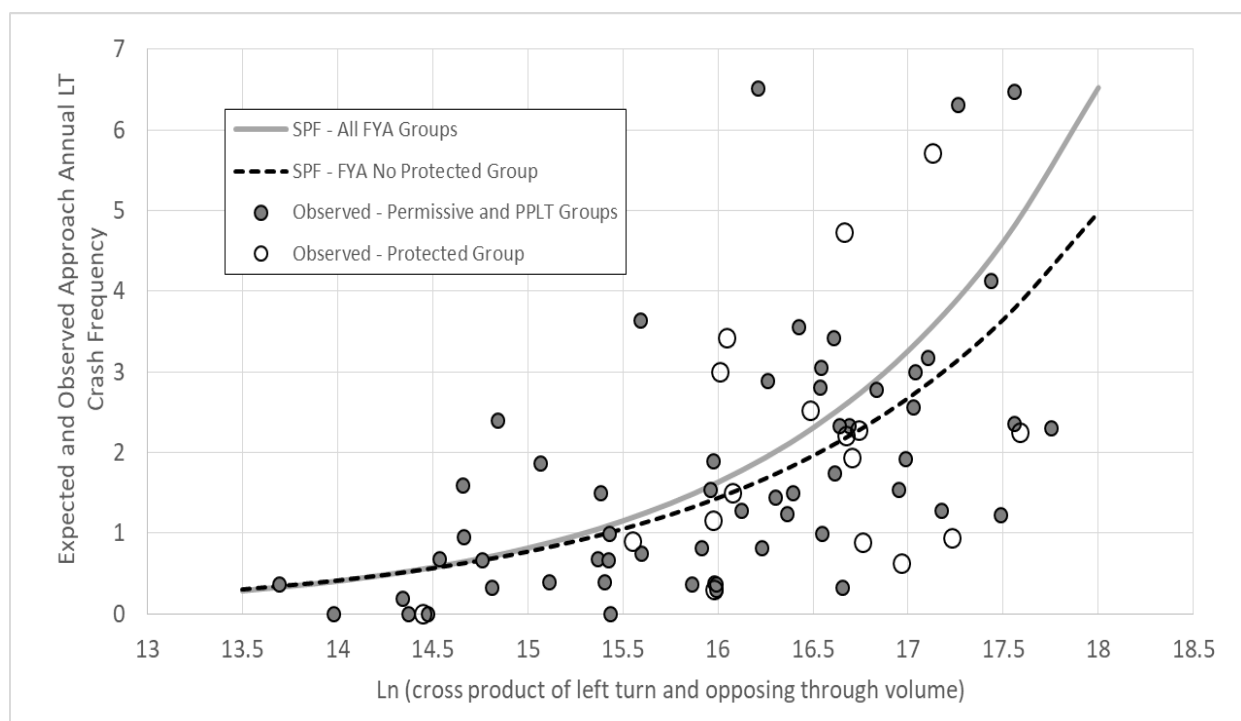
Figure 5.4 SPFs for left-turning movements at approaches with an FYA indication

From Figure 5.4, it is noted that the models produce a central tendency line to represent the expected safety performance of an average FYA approach. The model without the FYA approaches coming from a protected phase (dashed line) resulted in slightly lower crash frequencies compared with that including all FYA groups (continuous line), with greater differences observed for larger values of ln (cross product). However, these small nominal differences in the models may or may not result in actual significant differences when annual crash frequencies are collected from the field. For example, for an average ln (cross product) with a value of 16, the model suggests average differences in crash rates of less than 0.2 crashes per approach per year.

5.2   Approaches Changing from Permissive to FYA Indication

After data preparation and cleaning, a total of 23 approaches that changed LT phasing from permissive to FYA were included in the final dataset. A summary of this group is provided in Table 5.3.

Table 5.3 Summary Data for Permissive to FYA Analysis

LT Phase	Total Crashes per Approach				Time Period (Approach-years)				Average Crashes per Year *
	Mean	Min	Max	Total (sum)	Mean	Min	Max	Total (sum)	
Permissive	2.87	0	15	66	3.55	1.67	4.83	81.75	0.81
FYA	3.13	0	9	72	3.45	2.17	5.33	79.25	0.91

* This value is a direct average of crashes over time and does not account for changes in traffic volumes

A closer examination of the change in yearly crash frequencies for each of the 23 approaches showed that the effects of the FYA indication resulted in slightly higher values as the cross product of the opposing demands increased, as shown in Figure 5.5. Moreover, the FYA indication had a tendency to slightly reduce crash frequencies for low cross product values, but also to produce slightly higher crash frequencies for higher cross product values. These results also suggest that an evaluation of the effects of FYA when changing from a permissive phase could produce different results (increase or decrease of crashes) depending on the distribution of the cross products in the selected sample. The sample in this study had a distribution of ln (cross product) with an average value of 15.22, which is above the point where the FYA effects were approximately zero, as shown in Figure 5.6. Thus, the overall result comparing FYA vs. permissive indications would show a slight increase of crashes. On the other hand, had the average value of ln (cross product) in our sample been in the order of 14.5 or so, the comparison of FYA vs. permissive indications could have shown similar crash rates for before and after periods. In fact, after accounting for traffic growth in such a case, the overall effect of the FYA would float around a similar crash rate with more confidence.
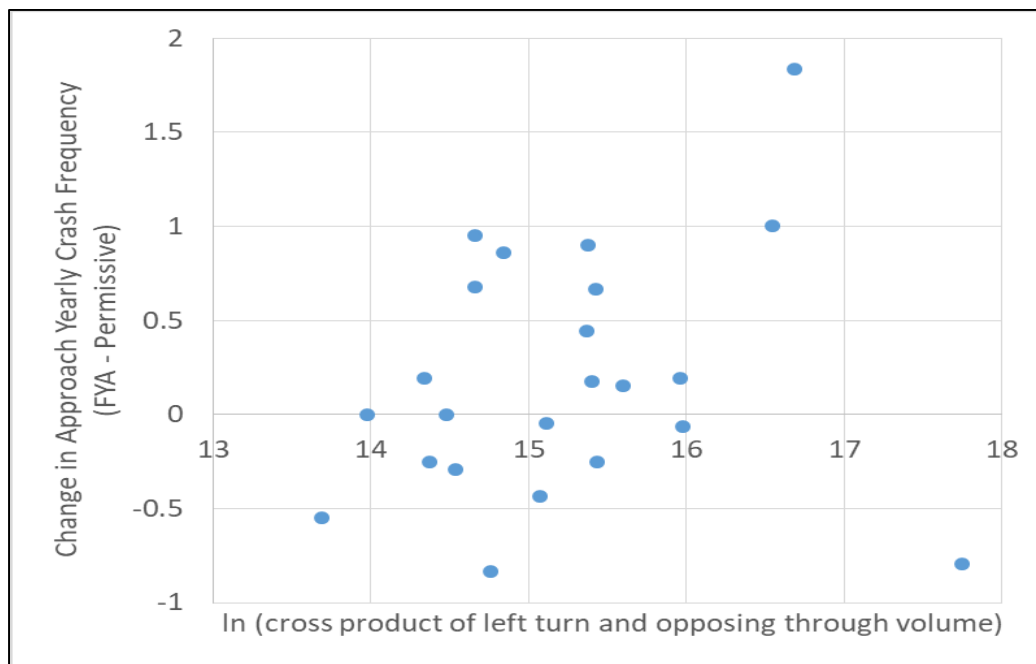

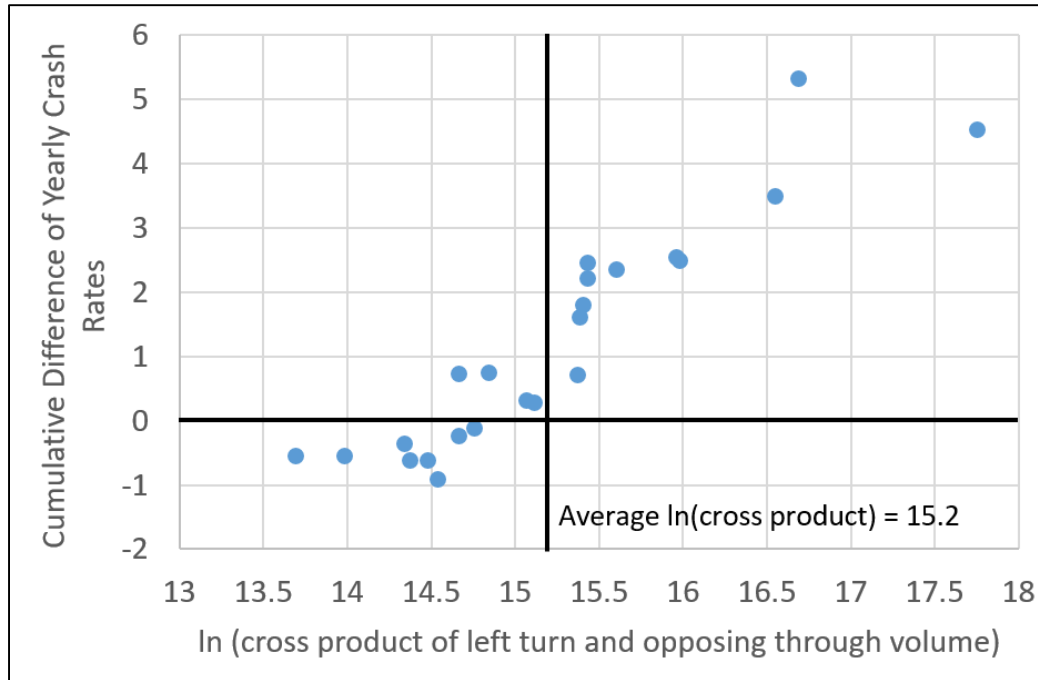**Figure 5.5** Change in yearly crash frequency from permissive to FYA

Figure 5.6 Cumulative change in yearly crash frequency from permissive to FYA

Results above indicate that the safety effects of converting a left-turn indication from permissive to FYA (in terms of left-turn crashes) could be better characterized by also providing the range of conflicting traffic demands in the sample being analyzed. For our particular sample, an overall slight increase in crash frequency was observed for approaches with a range of ln (cross product) values between 13.69 and 17.75 and with an average of 15.22. The quantification of such an increase is approached more carefully as follows, using the empirical Bayes before-after method described in Chapter 4.

First, a similar process to that used for FYA approaches was also followed to model the SPF for permissive indications. These efforts explored a number of variables as possible explanatory factors in addition to the conflicting demands (i.e., left-turning and opposing through volumes), including the number of opposing lanes, the number of lanes receiving the left-turning movement, and the posted speed limit. The equation below and Table 5.4 show the results of the final NB regression that provides the SPF for approaches with permissive indications.

$$Perm = e^{[0.4327 \times LnCrossProductAADT + 0.0436 \times LTReceivingLane + 0.0236 \times PostedSpeed - 7.827]}$$

Table 5.4 Results of NB Regression for Approaches with a Permissive LT Indication

Variable	Coefficient	P-Value
Ln Cross Product	0.4327	0.042
LT Receiving Lanes	0.0436	0.850
Posted Speed Limit	0.0236	0.204
Constant	-7.827	0.046

A comparison of the SPFs for permissive and FYA is shown in Figure 5.7. This figure was constructed using the model in Table 5.4 and the same average values used in Figure 5.4 for the left-turn receiving lanes (value=1.82) and posted speed limit (value=39.3), so the SPF for the approaches with a permissive indication is directly comparable to one shown previously for FYA. As expected, and in agreement with the discussion above, the curves meet at a value of ln (cross product) near 14.5 and suggest slightly smaller yearly crash frequencies with permissive indications for higher cross product values. However, also as noted above, the majority of the intersections with permissive indications had values of ln (cross product) that lie in regions where FYA and a permissive indication would result in similar crash frequencies.
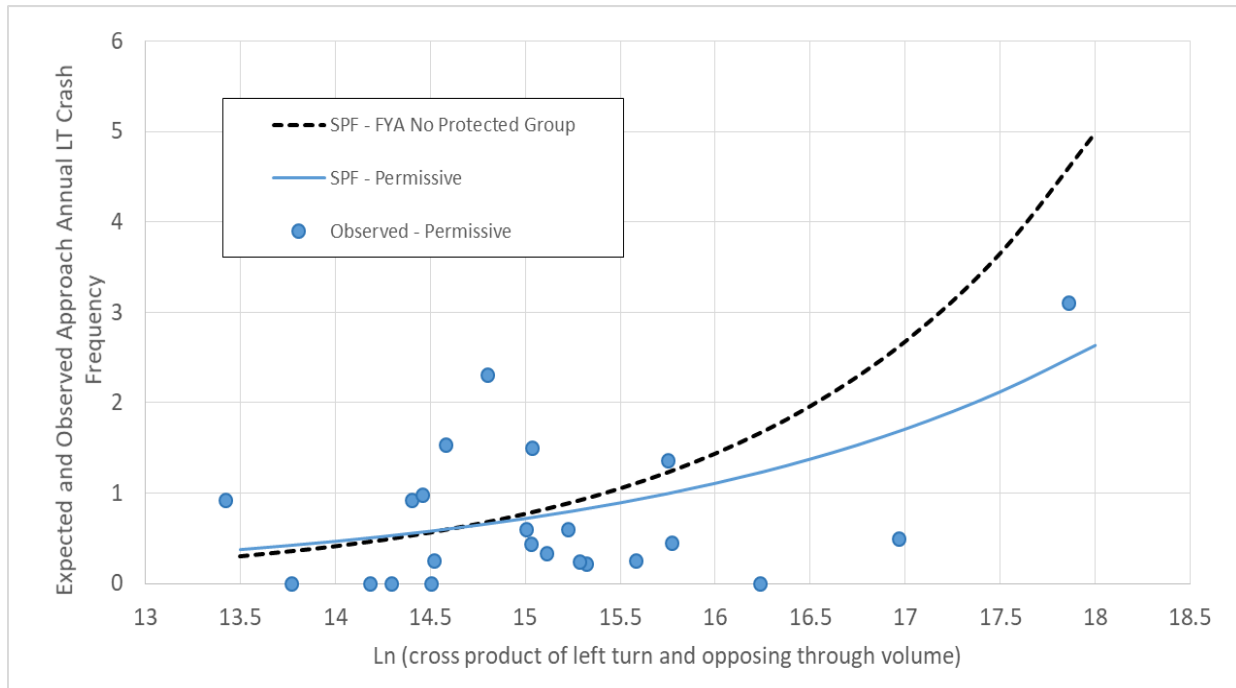

Figure 5.7 SPF for left-turning movements at approaches with a permissive and comparison with FYA indication

The application of the empirical Bayes before-after method using the SPF above, and the data for 18 of the approaches in this group without zero crash frequencies in the before period, showed a corresponding CMF of 1.16, with a wide confidence level given the small sample size suitable for the analysis, as shown in Table 5.5. It is noted that the predicted crash rates in the after period had the approaches not been changed to FYA were expected to be 3.3% higher due to increases in conflicting traffic demands [more specifically the ln (cross product)], which is taken into account in the CMF value. Once again, as described above, the CMF is expected to increase or decrease depending on the distribution of the ln (cross product) values in the sample analyzed.

Table 5.5 CMF and Confidence Interval for Permissive to FYA

Lower Bound	CMF	Upper Bound
0.77	1.16	1.54

5.3   Approaches Changing from Protected-Permissive (doghouse) to FYA Indication

A total of 34 approaches were in the final dataset regarding changes for PPLT to FYA left-turn indications. A summary of the final data in this group is provided in Table 5.6.

Table 5.6 Summary Data for Protected-Permissive to FYA Analysis

LT Phase	Total Crashes per Approach				Time Period (Approach-years)				Average Crashes per Year*
	Mean	Min	Max	Total (sum)	Mean	Min	Max	Total (sum)	
PPT	5.76	1	20	196	3.67	2.17	4.67	125.1	1.57
FYA	7.88	1	20	268	3.32	2.33	4.83	112.9	2.37

*This value is a direct average of crashes over time and does not account for changes in traffic volumes

An inspection of the change in yearly crash frequency for the 34 approaches shows that, in general, approaches with FYA generated higher yearly crash frequencies compared with the same approaches using a PPLT indication. However, the significance of such change depends on the value of the ln (cross product), with crash frequencies having a higher increase as the cross product increases. This is shown in Figure 5.8 and Figure 5.9 for individual changes and for cumulative values, respectively. It is noted that, different from the case described above for permissive approaches, changes in crash frequencies seem to have larger magnitudes and are present for the whole range of available ln (cross product) values. Nonetheless, a general representation of the actual before-and-after yearly crash frequencies is shown in Figure 5.10 to provide a different perspective, which indicates a similar spread of values and overall range.
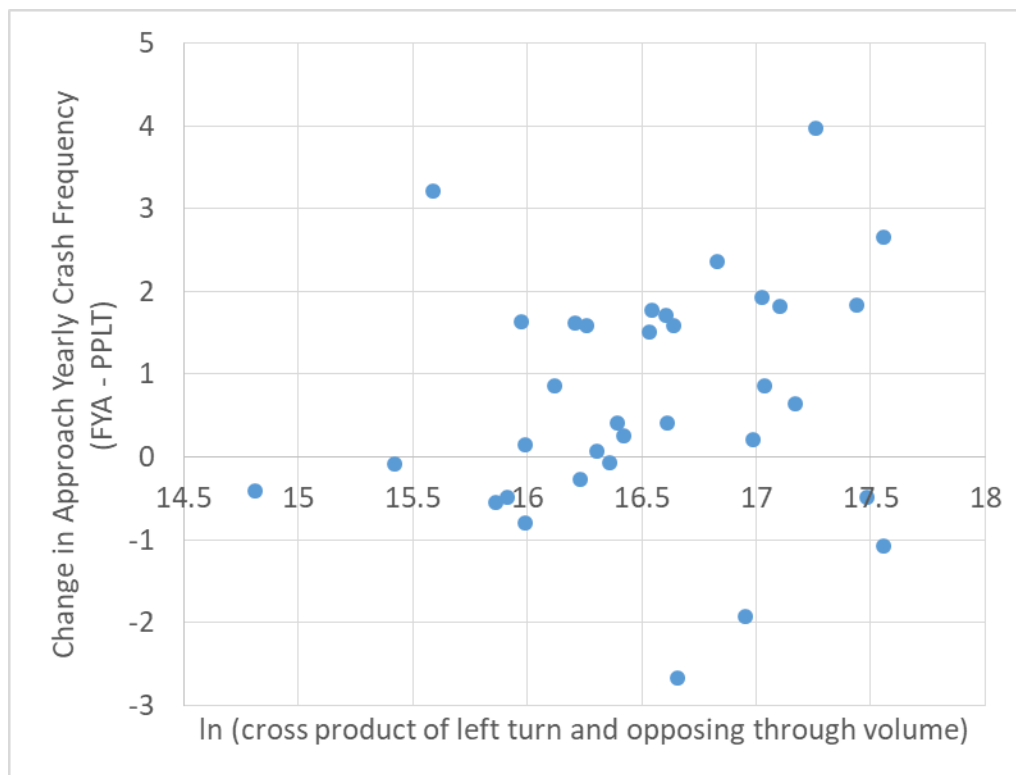

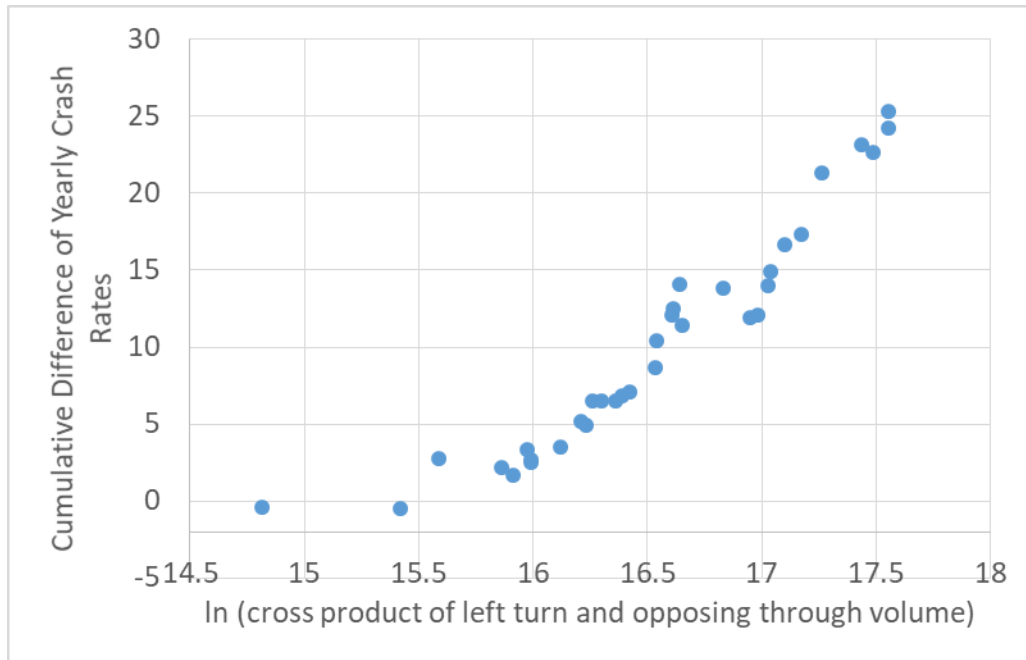**Figure 5.8** Change in yearly crash frequency from protected-permissive to FYA

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Figure 5.9 Cumulative change in yearly crash frequency from PPLT to FYA
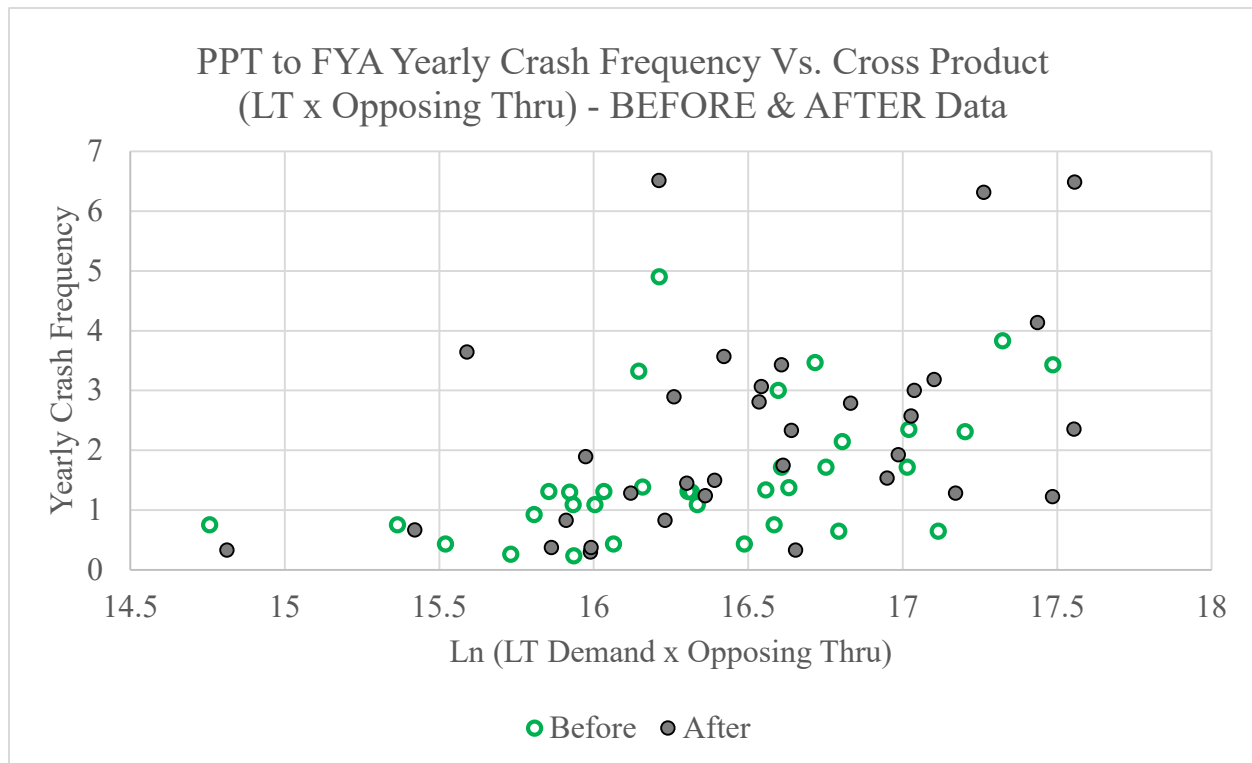

Figure 5.101 Annual crash frequency before and after for the PPT-FYA group

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In preparation for the empirical Bayes before-after method, modeling efforts similar to those described above were completed for the PPLT approaches, resulting in the equation below and model coefficients shown in Table 5.7.

$$PPT = e^{[0.5251 \times LnCrossProductAADT + 0.2108 \times LTReceivingLane + 0.0215 \times PostedSpeed - 9.404]}$$

Table 5.7 Results of NB Regression for Approaches
with a PPT LT Indication

Variable	Coefficient	P-Value
Ln Cross Product	0.5251	0.000
LT Receiving Lanes	0.2108	0.037
Posted Speed	0.0215	0.132
Constant	-9.404	0.000

A comparison of the SPF from the model above for PPLT approaches and the SPF for FYA previously presented is shown in Figure 5.11. Note that the range of values for the ln (cross product) in this group was smaller than for permissive approaches and the figure also reflects this range. Expected differences for the average ln (cross product) value of 16.35 is in the order of 0.28 crashes per approach per year.
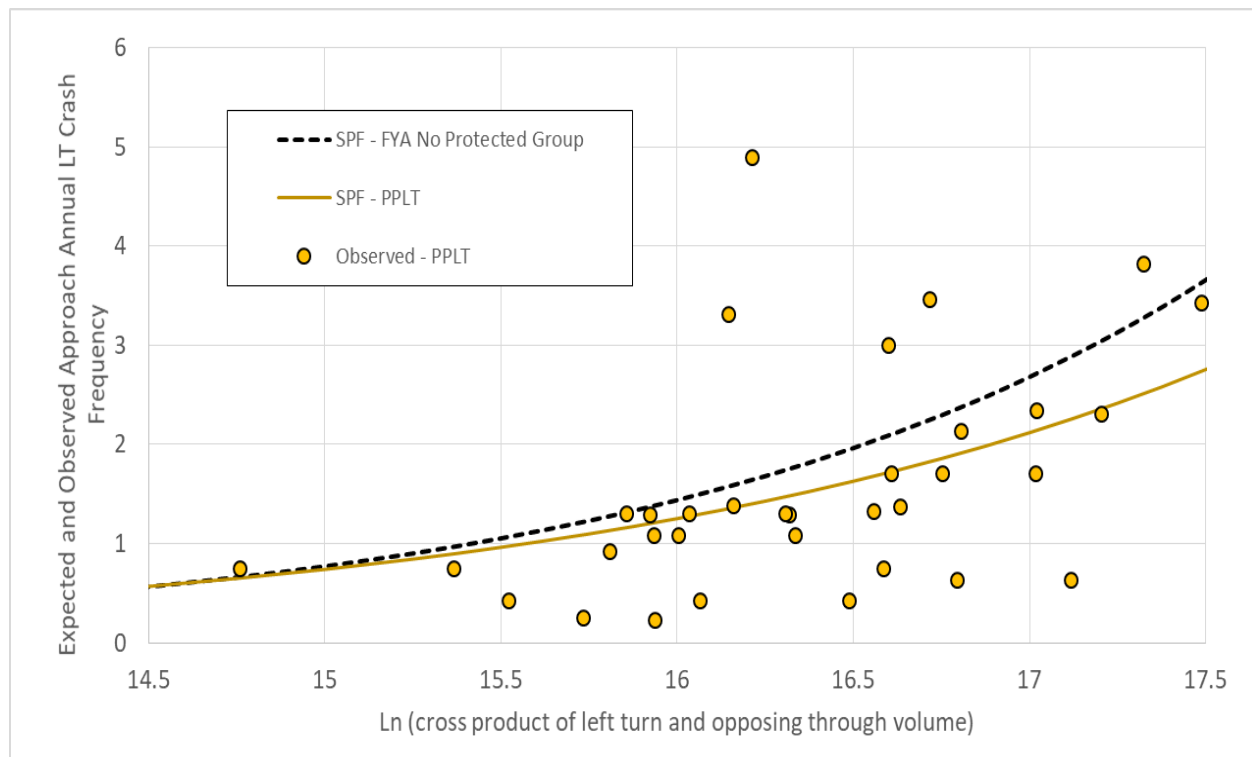

Figure 5.11 SPF for left-turning movements at approaches with PPLT and comparison with FYA indication

In addition, the empirical Bayes before-after method was applied to quantify the actual differences in the PPLT and the FYA group accounting for changes in traffic conflicts over time. The CMF results and the corresponding confidence interval are shown in Table 5.8. It is necessary to highlight that even though increases in yearly crash rates were estimated to be in the order of 33% with FYA compared with PPLT,

this amount corresponded to, at most, 0.9 crashes per approach per year for the highest crash rate of 2.76 in the before period with a PPLT indication.

Note that using a simple difference of the average crashes per year in Table 5.6 (2.37-1.57 = 0.8 crashes per approach per year) could be misleading in this case because that value does not account for a 9.9% expected increase in crash rate as a result of increasing volumes, and the fact that the average approach in terms of conflicting volumes would be located in the mid-point of the ln (conflict product) range resulting in a much lower average increase of 0.28 crashes per approach per year, as mentioned above.

Similar to caveats provided for the group changing from permissive to FYA, the actual increase in crash rate measured for FYA when changing from PPLT is expected to be dependent on the range and average values of ln (cross products) in the sample being analyzed, as discussed from Figure 5.8; thus, care needs to be exercised when trying to transfer the CMF results presented here to locations with different ranges of conflicting volumes and overall yearly crash rates. Further data collection is needed before these results can be extended to locations with higher crash rates in the before periods, considering that even at the highest ln (cross product) from this study, the difference between PPLT and FYA is an increase in 0.9 crashes per approach per year.

Table 5.8 CMF and Confidence Interval for Protected-
Permissive (Doghouse) to FYA

Lower Bound	CMF	Upper Bound
1.21	1.33	1.45

5.4   Approaches Changing from Protected to FYA Indication

After data preparation and cleaning, a total of 17 approaches that changed LT phasing from protected to FYA were included in the final dataset. A summary of the final data in this group is provided in Table 5.9.

Table 5.9 Summary Data for Protected to FYA Analysis

LT Phase	Total Crashes per Approach				Time Period (Approach-years)				Average Crashes per Year *
	Mean	Min	Max	Total (sum)	Mean	Min	Max	Total (sum)	
Protected	0.88	0	3	15	3.58	0.33	4.75	60.9	0.25
FYA	7.41	0	30	126	3.37	2.25	6.67	57.3	2.2

* This value is a direct average of crashes over time and does not account for changes in traffic volumes

As expected, Table 5.9 indicates a clear increase in crashes when allowing permissive movements with an FYA indication from a previous phasing with protected movements only. However, it is noted that average crash frequencies with FYA resulted in similar values as those obtained for the previous group (from PPLT) in the after period. The actual magnitude of the change in yearly crash frequency by ln (cross product) is shown in Figure 5.12. As it should be expected, based on previous groups, the numeric value of the change increases with the corresponding conflicting volumes, as the increase in crashes is expected to be proportional to the initial crash rate in the before period, resulting in the trends discussed here and in previous groups.
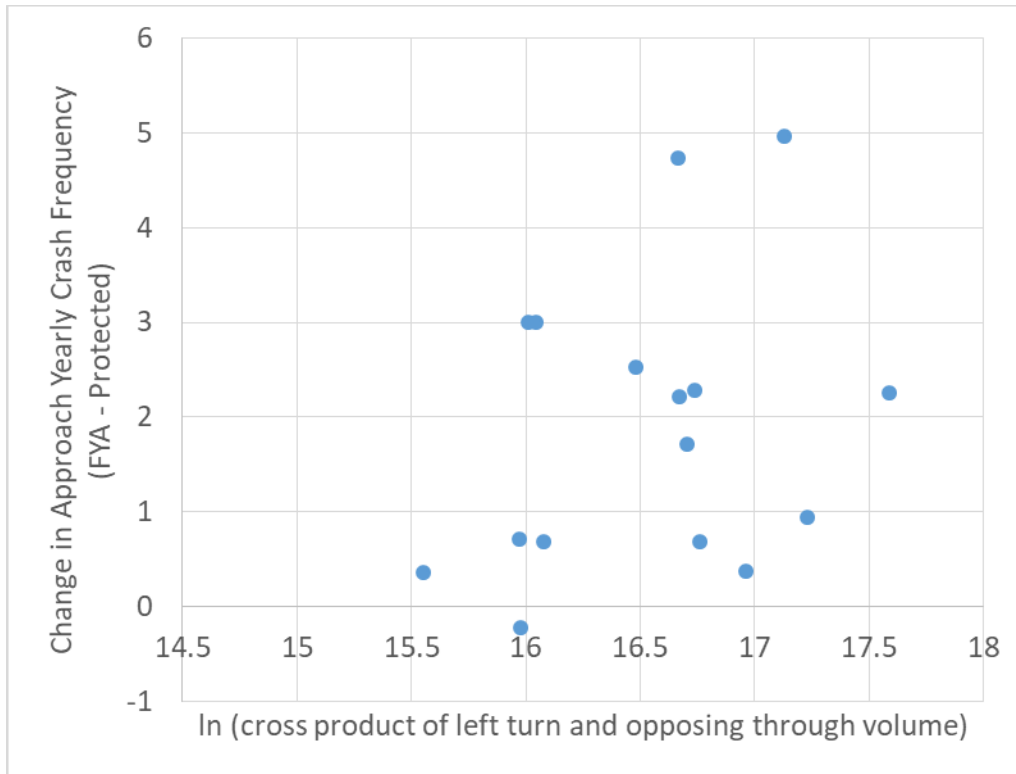
Figure 5.12 Change in yearly crash frequency from protected to FYA

Additional comparisons between protected LT phases and FYA were not pursued due to the low crash frequency in the before period. The protected signal also provides complete separation of conflicting movements, leaving only crashes due to unexpected situations, traffic violations, and other external factors (e.g., weather) not inherent to signal operation as contributors to crash events. An attempt at generating an SPF with such low crash frequencies and without a clear relationship between demands (in the absence of conflicts) and crash events would be misleading. The group of protected left-turn phasing crashes serves a different purpose of enhancing the sample size and sites in the evaluation of the after periods with FYA.

5.5   Summary of Findings from Models

Sections 5.1 through 5.4 provide a summary on the efforts to model and understand the safety performance of different left-turn indications, including permissive, PPLT, and FYA, with limited results for protected-only phases due to the absence of conflicting volumes during normal operation and very low crash rates.

Statistical models from NB regressions were developed and served as a basis for SPF for permissive, PPLT, and FYA approaches, with consistent results for each set of approaches and when comparing the safety performance in the before and after periods.

For models using the cross product of conflicting volumes, comparisons of before and after periods need to consider how the actual value of the cross product (and the natural log transformation) affects the CMF. In the samples analyzed, the CMF is expected to vary for the comparison of permissive vs. FYA, depending on the range and distribution of values for ln (cross product). This is because on the low end of the range of ln (cross product), the FYA indication tended to have similar/lower expected crashes, but higher on the other. Therefore, reasonable CMF values for this group are difficult to generalize, but similar overall performance of the two groups is a reasonable expectation for an average ln (cross products) of about 14.5.

For the comparison of PPLT vs. FYA, data showed that the CMF is not expected to vary as a function of ln (cross product), but the magnitude of the changes is. Results from the empirical Bayesian before-after method for the range of ln (cross product) values obtained in the field resulted in a CMF of 1.33 ± 0.12. However, within the same range observed in the field, the overall change for the maximum value of ln (cross product) did not exceed an increase of 0.76 crashes per approach per year, and represented, on average, an increase of 0.28 crashes per approach per year.

5.6   Temporal Analysis of Crashes and Safety Considerations

Analysis of left-turn crashes at an individual crash level explored crash occurrence throughout the year, within 24-hour periods, and as a function of the time after a new FYA indication was installed. The after period served as a metric for a possible driver adjustment period or a novelty effect. Seasonal and intra-day distributions can provide a measure of potential differences between left-turn phasing indications and may offer insights to understand operational or mechanistic characteristics that may be important in predicting crash events.

5.6.1   Seasonal (month-to-month) Variations

Seasonal estimates using individual groups (permissive, protected-permissive, or protected) may not be representative of typical left-turn crashes in the Salt Lake Valley due to their small sample size, biasing the analysis in directions difficult to assess. However, the FYA group represents a stronger sample as it combines approaches from the three groups altogether in the after period, and thus may provide a valid estimation of month-to-month crash proportions for FYA signals. The complete FYA group for the analysis contains 466 selected crashes covering 250 approach-years.

To construct the monthly crash distribution of crashes, it was necessary to take into account the actual number of months of exposure from each approach by reflecting exposure differences resulting from the month when installing FYA. For example, for the after FYA period, if an FYA indication was installed on October 10, the first calendar year will include two-thirds of the month of October and a complete period for November and December, in addition to the remaining full calendar years until the end of the collection period (Dec. 31). The added exposure for October, November, and December with respect to other months is taken into account in the normalization.

The actual observed monthly crash distribution of all left-turn crashes and the expected upper and lower bounds were obtained from a simulation exercise using 5,205 left-turn crashes from the Salt Lake Valley in 2016 and 2017, which is a time period similar to that covered by the FYA installations. The simulation was created based on the distribution of random selections of 450 crashes from the 5,205 crashes, where the averages and standard deviation of 100 samples were found, and their maximum distance between $\mu+2\sigma$ and $\mu-2\sigma$ was measured. Here, μ represents the mean and σ the standard deviation of each sample. A conservative estimate of +0.02 and -0.02 was found to encompass 100% of the simulated cases and was used for the comparison.

Figure 5.13 shows the monthly proportion of crashes from the FYA sample, the average proportion of left-turn crashes in the Salt Lake Valley, and the upper and lower bands where proportions from a sample of 450 crashes are expected to fit. The overall trend from the FYA sample seems to fall within the expected bounds, with the exception of January and April, where small deviations from the expectation are noted. However, given the small sample size of the FYA group, it is difficult to provide evidence of different seasonal effects for the FYA crashes compared with the population of left-turn crashes in the entire valley.

While these results may be expected, and there was no a priori assumptions on particular seasonal effects related to FYA crashes, this exercise serves to gain further confidence on the adequacy of the final dataset as a representative sample of FYA safety performance.
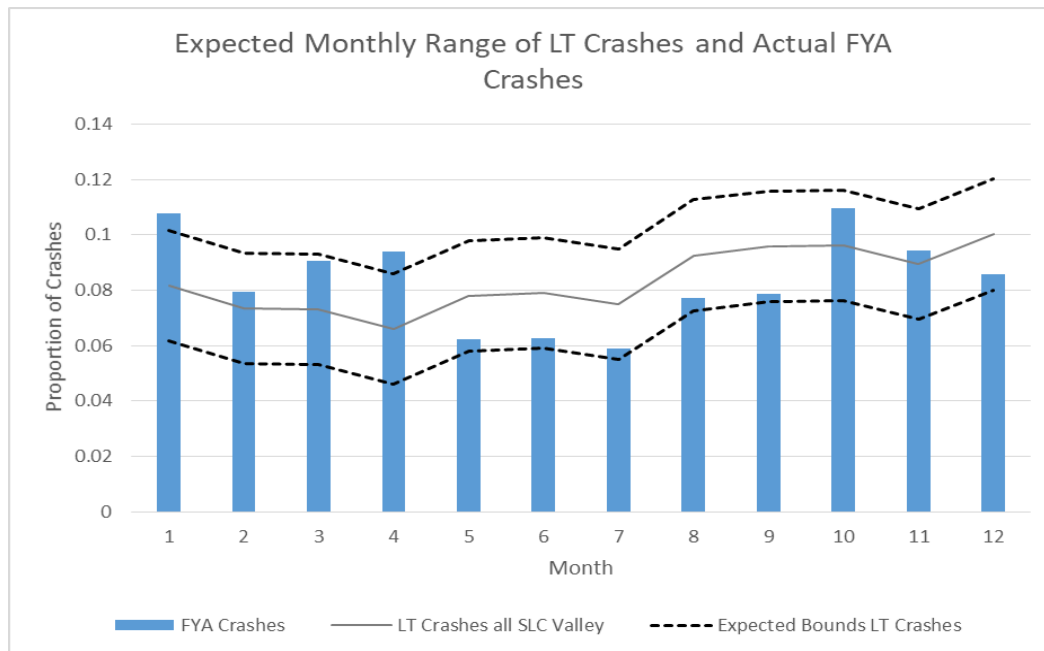

Figure 5.13 Average month-to-month variation of LT crashes at locations with FYA and for all LT in the Salt Lake Valley

5.6.2 Intra-day (hour-by-hour) Variations

A separate analysis was also conducted to explore possible time-of-day (TOD) effects of left-turn indications on crash frequency. Comparisons of the proportion of crashes by TOD for two groups, permissive to FYA and PPLT to FYA, are shown in Figure 5.14 and Figure 5.15. These figures also highlight crash distributions at peak and off-peak times, where peak times in this case were defined as 6 am to 9 am and 4 pm to 7 pm, and the afternoon off-peak period included the two hours between 2 pm and 4 pm.
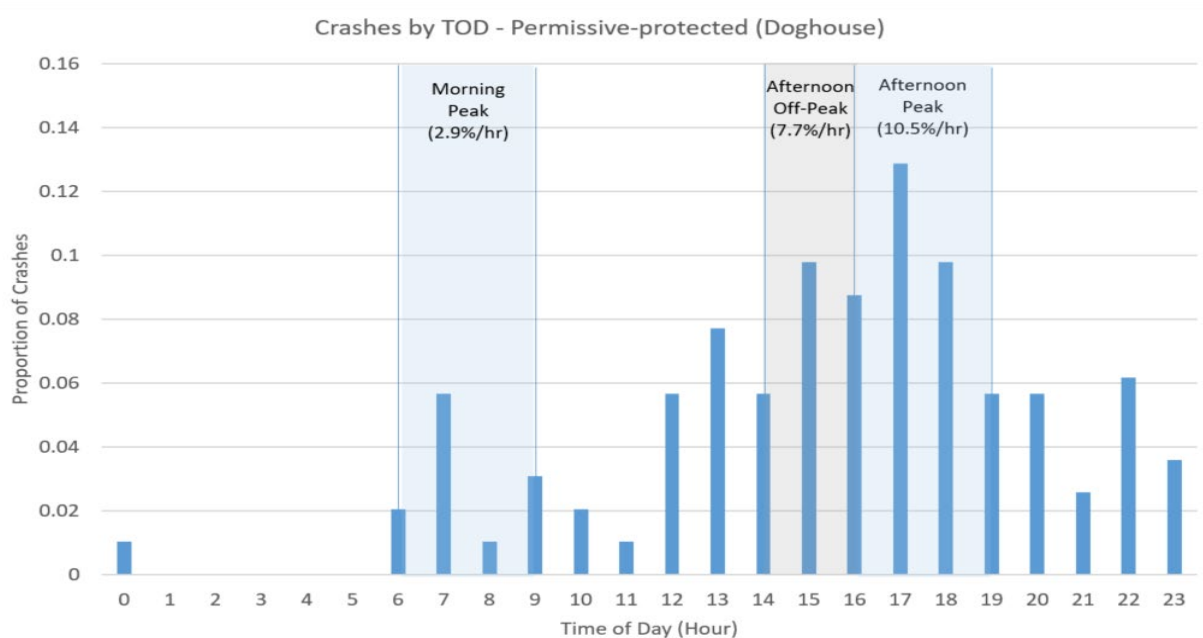
Figure 5.14 LT Crashes by time-of-day at approaches with protected-permissive LT indication
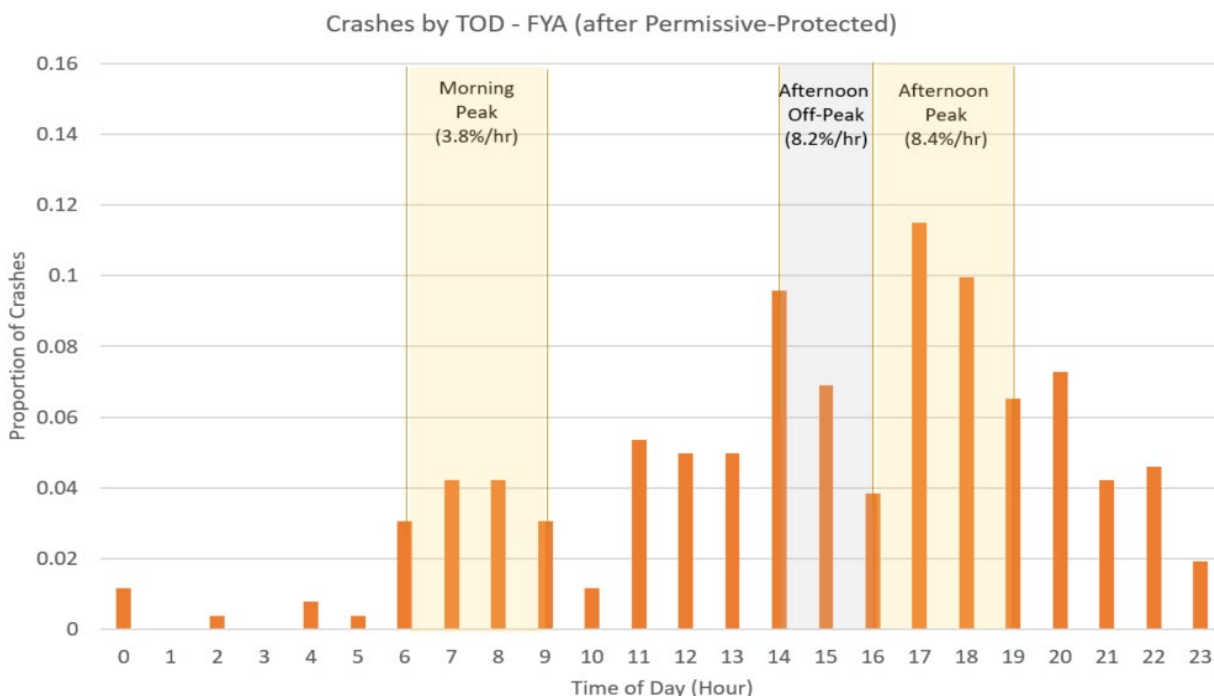

Figure 5.15 LT Crashes by time-of-day at approaches that changed from a protected-permissive to an FYA indication

From Figure 5.14 and Figure 5.15, at first there does not seem to be a clear shift between TOD patterns at approaches displaying a protected-permissive (doghouse) indication in the before period compared to the after period with an FYA indication. However, there are higher crash concentrations during peak hours and lower during morning peak hours with the doghouse indication and a flatter distribution with the FYA. Also, under the FYA indication there is a clear reduction of crashes at the beginning of the afternoon peak period (4 pm to 5 pm), suggesting a change in crash patterns possibly due to signal

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operational changes introduced in the after period. Fewer crashes at the beginning of the peak period also creates an apparent peak in the afternoon off-peak period (2 pm to 4 pm). Crashes in this off-peak period are not significantly higher for the FYA compared with the doghouse, but in contrast they are now closer to crashes during the peak period. This suggests an opportunity to target such crashes by considering extending operational measures that reduce crashes at the beginning of the afternoon period (4 pm to 5 pm) to off-peak afternoon periods (2 pm to 4 pm), wherever possible.

The second group includes approaches changing from a permissive-only to an FYA indication, as shown in Figure 5.16 and Figure 5.17. In this group, there was a large proportion of afternoon peak-hour crashes with the permissive-only indication, even larger than the proportion observed for doghouse approaches. This is somewhat expected considering the limitation of a permissive indication to protect some of the left-turning movements, resulting in a direct increase in crash frequency under higher conflicting volumes at peak times. In the after period, the crash distribution during the FYA indication significantly shifted crashes, resembling the FYA distribution observed in the previous group, and in turn also highlighting the dependence between left-turn crash patterns by time of day and the left-turn signal indication. With the FYA, the proportion of crashes during peak periods was similar to that in the previous group, but the contribution of off-peak afternoon crashes was even higher and surpassed afternoon peak crashes. Thus, data suggest similar opportunities to improve safety by extending operating strategies applied in the afternoon peak hours to some of the afternoon off-peak periods wherever possible.
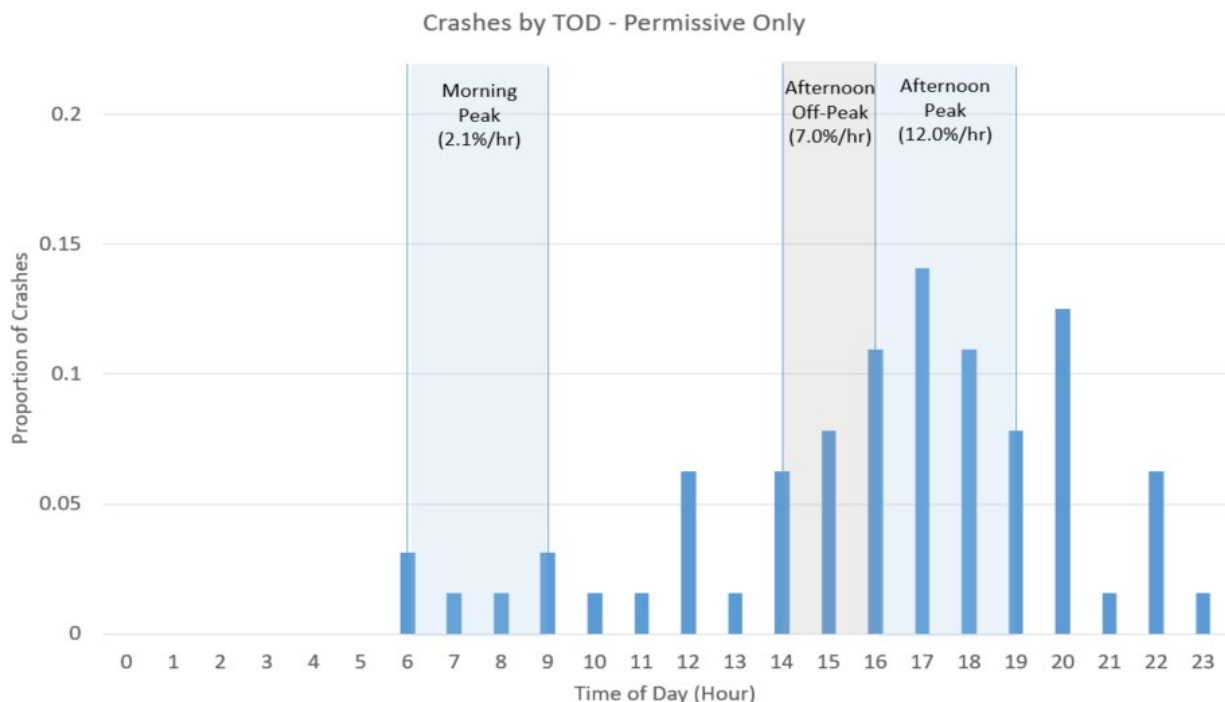

Figure 5.16 LT Crashes by time-of-day at approaches with permissive-only LT indication
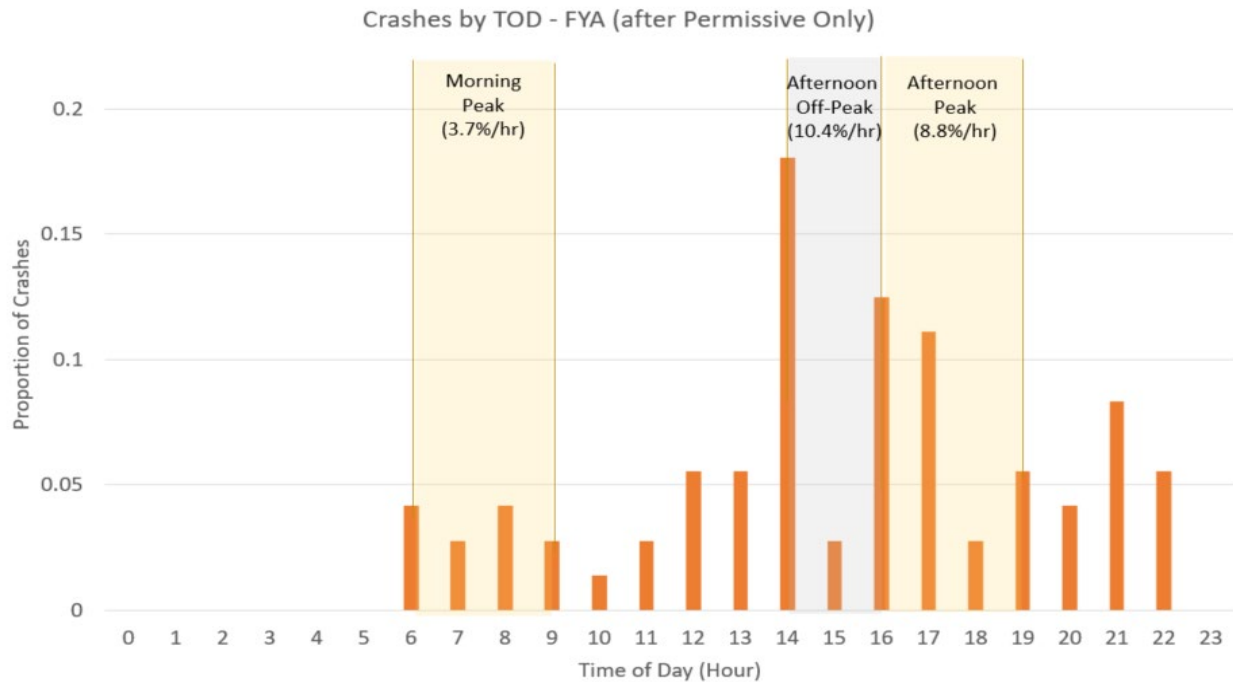
Figure 5.17 LT Crashes by time-of-day at approaches that changed from a permissive-only to an FYA indication

The last group included approaches changing from a protected left-turn indication to FYA. As mentioned above, crashes under the protected indication were mostly the result of signal violations and were rather sporadic, with only 15 crashes in 61 combined approach-year periods. On the other hand, when changed to an FYA indication and allowing permissive movements, crash frequencies increased, and trends by time-of-day could be explored in a manner similar to the previous two groups. The results are shown in Figure 5.18.
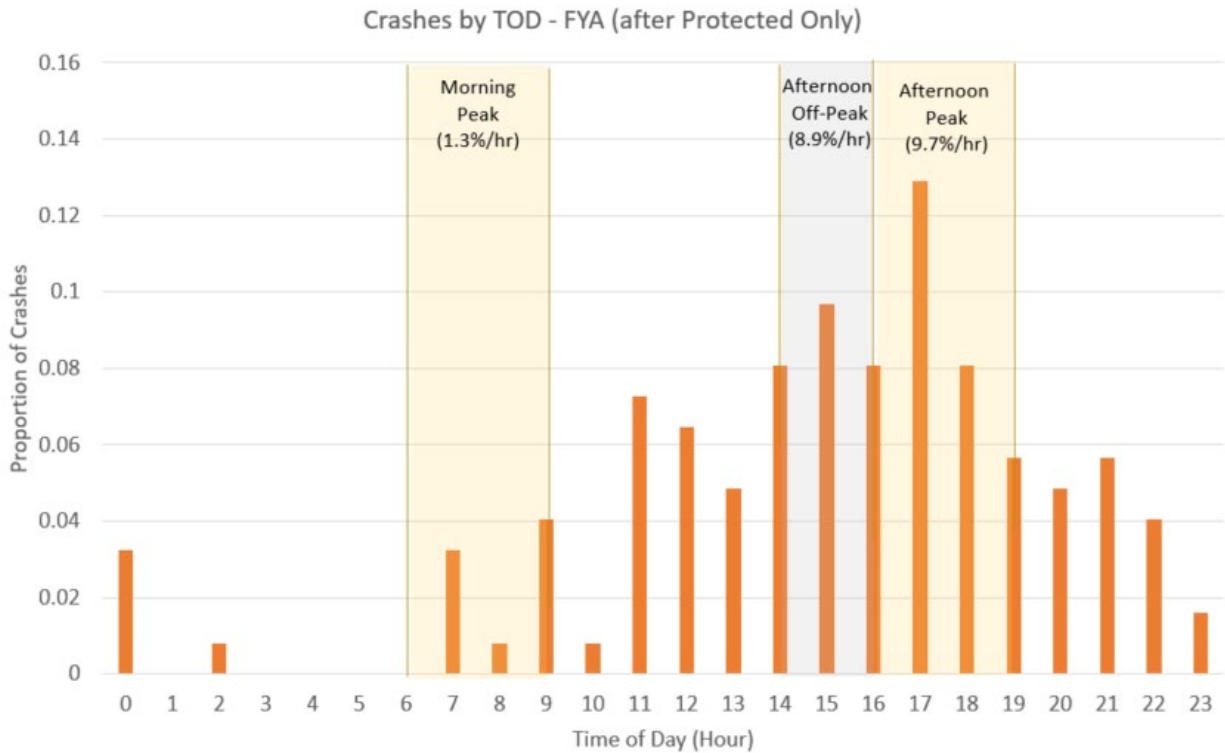
Figure 5.18 LT Crashes by time-of-day at approaches that changed from a protected to an FYA indication

Similar patterns with high afternoon off-peak hours were observed in this group, followed by an afternoon peak with similar proportions. Unlike the previous groups, morning peaks has a much lower crash contribution, and late-night crashes were also observed.

An alternative perspective with all available FYA approaches combined regardless of the previous indications is shown in Figure 5.19. This can be considered the most comprehensive sample, encompassing all 74 approaches and thus a more representative picture of an average approach with FYA. Overall, the average afternoon peak hours (4 pm to 7 pm) had the same contribution of crashes as average off-peak hours (2 pm to 4 pm), whereas the morning peak contributed to less than half the number of crashes per hour. Once again, crashes with lower sustained volumes during the off-peak hours could be curbed by exploring signal alternatives applied during peak hours, and perhaps increasing the frequency of protected left-turn phases whenever possible.
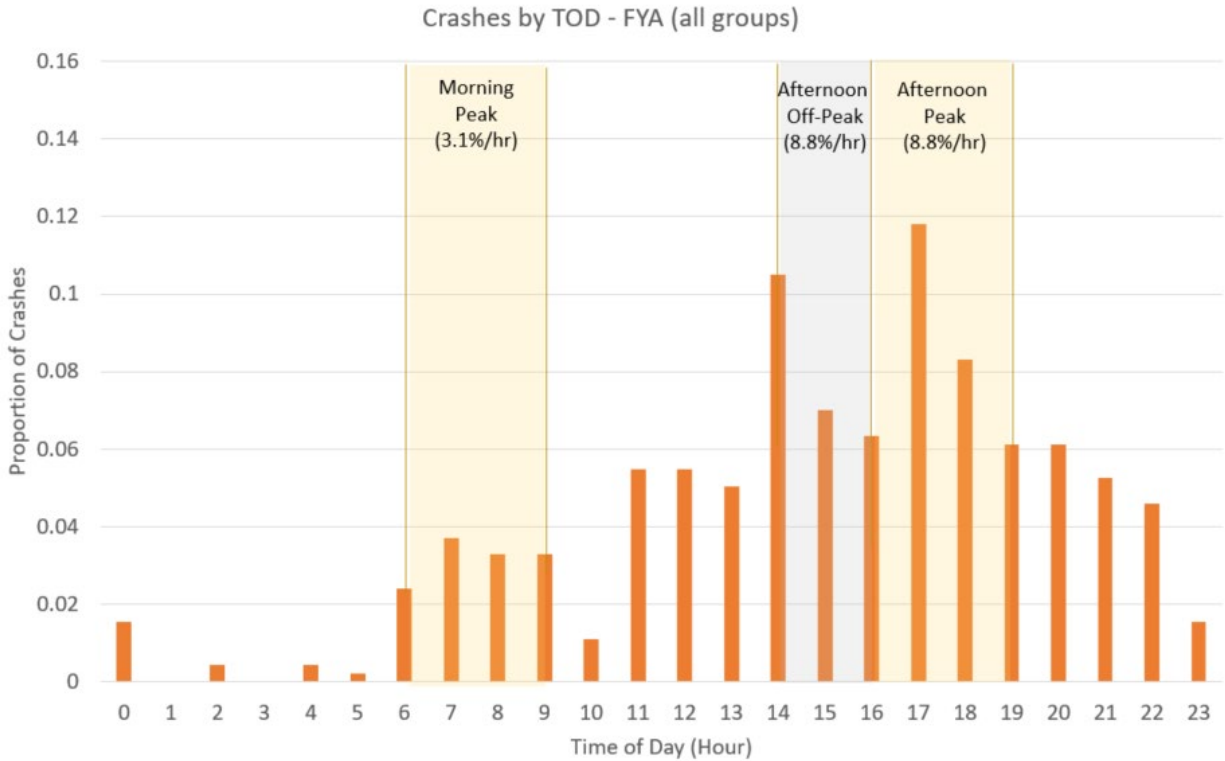
Figure 5.19 LT Crashes by time-of-day at all approaches with an FYA indication

5.6.3   Driver Adjustment Period or Novelty Effect after FYA Installations

This section examines the cumulative frequencies of left-turn crashes immediately after the installation of an FYA indication, testing for possible negative effects due to a driver adjustment period or a novelty effect.

To construct the plot, crashes are sorted based on the elapsed time between the installation of the FYA and the crash occurrence, creating a cumulative distribution where the slope from the origin represents the number of crashes per unit of time. Figure 5.20 shows the cumulative distributions for the three main groups together (permissive, protected-permissive, and protected) for the first two months following an FYA installation. Data show no increase in the number of crashes per unit of time during the first month of FYA operation when compared with the second month. Thus, for the selected approaches, there is no evidence of novelty effect or driver adjustment factor following the FYA installation.
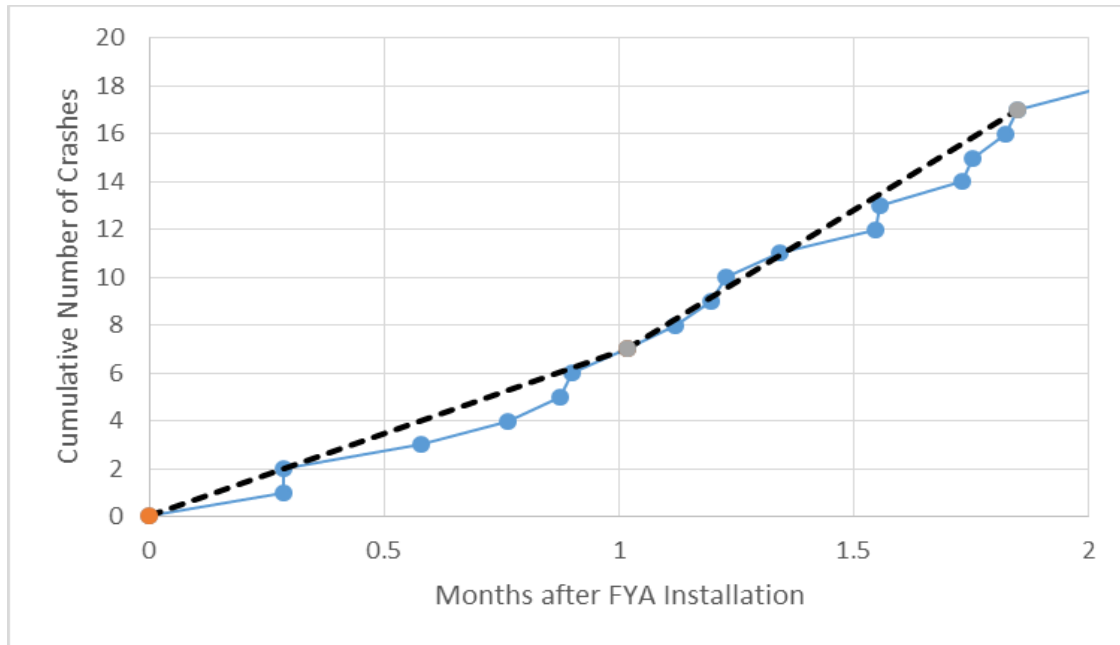
Figure 5.20 Cumulative distribution of crashes after FYA indications were installed

5.7   Case Study Lagging FYA Operation

An interesting case to illustrate the potential adverse effects of a "perceived yellow trap" indication was found at the intersection of Redwood Rd and 3500 S in West Valley City, UT. At this intersection, an FYA indication was initially deployed in a "lagging" mode, allowing the permissive phase to continue even after the same direction through traffic had transitioned from green to yellow and red. General geometric characteristics and traffic volumes at the subject intersection are shown in Table 5.10.

Table 5.10 Geometric Characteristics and Traffic Volumes at Redwood Rd and 3500 S

Approach	Northbound	Southbound	Eastbound	Westbound
Through Lanes	3	3	3	3
Left-turn Lanes	1	1	1	1
Right-turn Lanes	0	0	0	0
Approx. AADT Through (2015)	16,000	12,000	16,000	15,000
Approx. AADT Left-turn (2016)	2,200	1,600	1,800	2,200

The FYA indication in the lagging mode entered into operation on October 26, 2014, replacing a protected-only left-turn operation in all four approaches. An increase in crash frequencies is generally expected when allowing left-turning movements on a permissive fashion, but the addition of a lagging operation resulted in higher than expected crash rates, as shown in Figure 5.21.

During the protected-only phases, left-turn-related crashes were limited to traffic violations and resulted in low crash frequencies. Soon after the lagging FYA indications were installed, crash rates increased to a rate of about one crash every 3.6 days. This rate did not appear to change during a period of about four months, until changes were introduced to the intersection. The first change included the installation of a supplemental plate next to the flashing yellow arrow signal head with the message "left turn yield on

flashing yellow arrow" (UDOT Standard Sign RS10-21ex). This change occurred sometime in May/June 2015, where the first deviation from the sustained crash rate is observed in Figure 5.21. The second change was introduced on June 10, 2015, with the removal of the lagging FYA operation, resulting in the permissive portions of the phase leading the through phases.
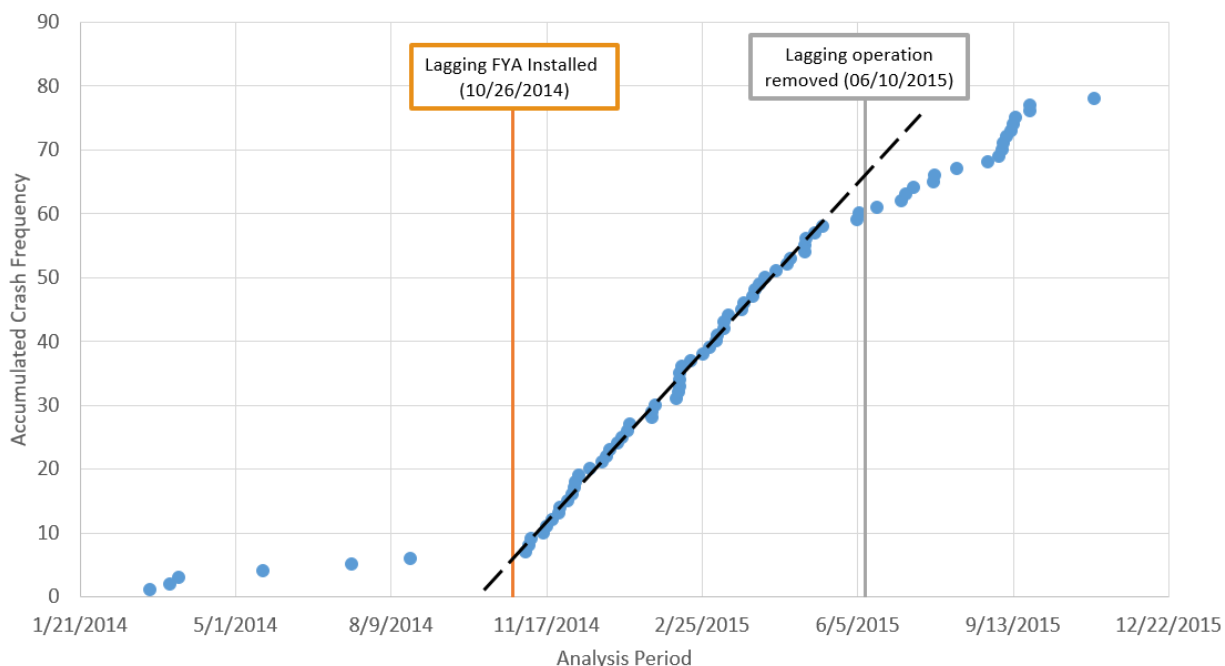

Figure 5.21 Effect of adding and removing a "lagging FYA" operation at selected intersection (all approaches had FYA)

From the crash data, it is clear that the combination of both adding the supplemental plate and removing the lagging operation provided significant reduction in crash rates. Further examination of the crash records indicated frequent confusion regarding the FYA operation, mostly at the end of the green phase for the through movement, effectively showing signs of a "perceived yellow trap."

Such effects of the lagging FYA operation for this particular intersection do not necessarily indicate this type of operation should always be avoided, but point out possible challenges, particularly at locations with similar geometric configurations and traffic demands.

5.8 New Proposed Estimation of Left-Turn Crash Risk Using High-Resolution Data

In addition to traditional approaches for crash analysis using standard statistical models, the research team developed a new measure of risk using high resolution data from ATSPM. The intent of this approach is to leverage the large amounts of data currently being collected by UDOT using an event-based metric that accounts for conflicting movements at fine resolutions. The approach is demonstrated in this section using 5-minute turning and opposing through counts from vehicle detectors.

It is noted that even though statistical models responded more favorably to expressions using the cross product between left-turning and through volumes, this implies that the two movements contribute equally to crash frequencies. Thus, an increase in one left-turning vehicle is expected to have the same effect as an increase in one through vehicle. While at the macro-level (i.e., daily volumes) this relation is

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widely accepted, this section shows by an analysis this is not the case when high-resolution data (e.g., 5-minute counts) is used.

The proposed event-based metric is an estimation of risk due to competing demands occurring within 5-minute time intervals. Different from standard approaches and safety performance functions, a full historical account of 5-minute data is taken into account, for cases both with and without crash events. A standard definition of risk is used, so the number of crash events is divided by the long-term history of conflicts (total exposure) to estimate a probability of crash or risk. As data continue being collected, estimates become more reliable and converge to stable values, improving their usability. For a complete description of the proposed procedure, background, and full details of the data collection and analysis, the reader is directed to Azra [40], who is a member of the research team and included the efforts in a thesis as part of her master's degree. Excerpts and a partial account of results from the thesis are included in the remainder of this section with the objective of introducing the methodology and provide initial pointers on risk estimation and high-resolution data.

The dataset used for the analysis includes 22 intersections where permissive left turns are allowed, and volume and crash data were analyzed from January 2015 until December 2017. Figure 5.22 shows the location of the 22 intersections. The geometric information was collected from Google Earth, the volume information from the ATSPM website, and the crash information from the Department of Public Safety.

The crash occurrence and exposure are used to measure crash rates as follows:

$$risk = \frac{number\ of\ crash\ causing\ conflict\ volumes\ within\ the\ cell * 1000}{number\ of\ conflicting\ volumes\ within\ the\ cell\ over\ the\ period\ of\ study}$$

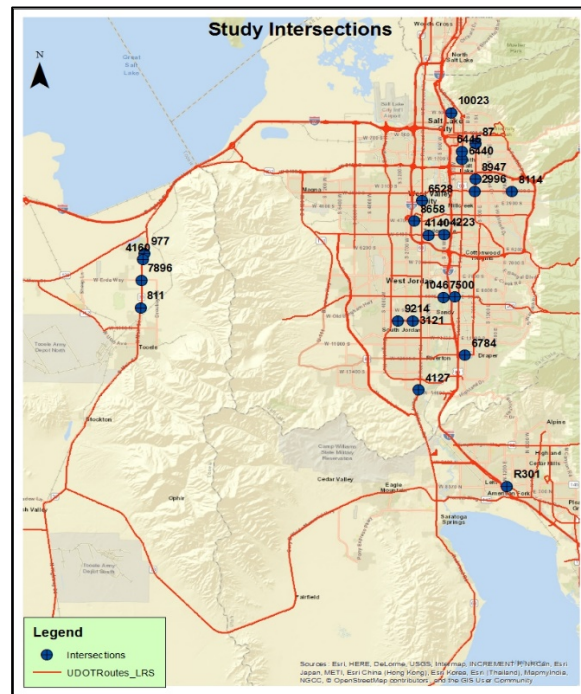**Figure 5.22** Location of 22 intersections selected for risk analysis

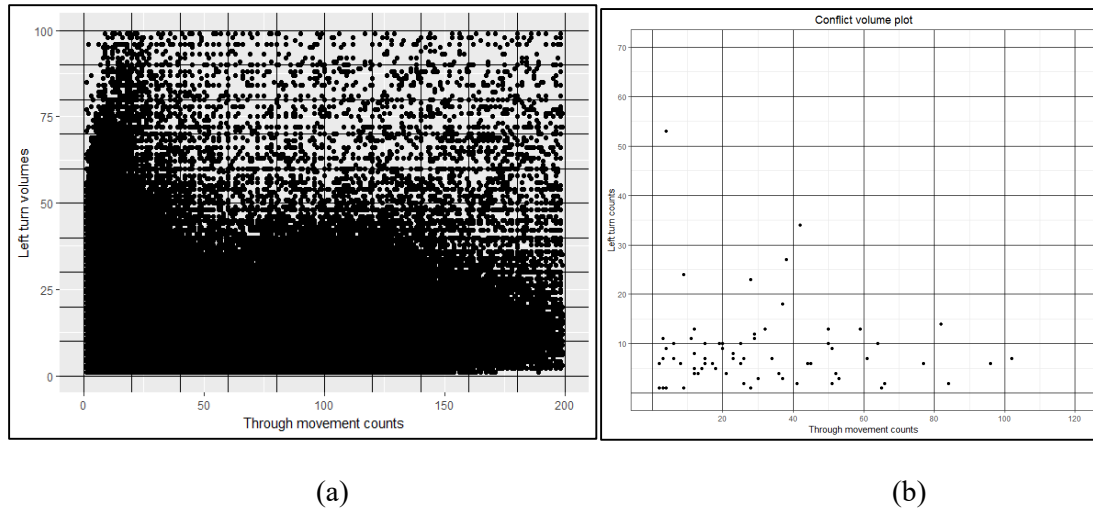| (a) | (b) |

Figure 5.23 Summary of a) 5-minute conflicting volumes and
b) corresponding conflicts when crash events occurred

Figure 5.23 shows the volume and crash data from three complete years with the through volume on the x-axis and the left-turn volume on the y-axis. Section a) includes every single conflicting volume pair in the three-year period and represents the risk estimation in the equation above; whereas b) shows the 151 crash events at the same locations and represents the numerator in the risk equation. However, in order to build a risk measure for a given set of conflicting volumes, volume pairs were defined using a grid size of 20 x 10 vehicles, where through volumes were grouped in increments of 20 and left-turn volumes in increments of 10.

For example, in Figure 5.23, the cell between left-turn volume 50-60 and through volume 120-140 contains 259 conflict volume points, and one of them is associated with a crash. Whereas, the cell between left-turn volume 0-10 and through volume 140-160 has 19,410 conflict volume points, and three of them are associated with crashes. Although the first cell has a lower crash frequency, the combination is considered to be of higher risk with higher crash rate of 3.86, as opposed to a 0.155 crash rate in the later cell. The resulting risk matrix for individual cells with risk values greater than zero using the 5-minute data is shown in Table 5.11, where LTmin, LTmax, Thmin, and Thmax denote the minimum and maximum boundaries for left-turn movement and through movements.

It is noted that, given the large number of 5-minute observations extracted from ATSPM, an automated script was written in the R platform to read files from the ATSPM API in batches, consolidate them, and store them in a workstation.

The risk values developed follow the hypothesis of a hyperbolic risk function, with the amount of exposure (the number of events of a given type experienced per unit of time) and the risk of accident (the number of accidents per unit of exposure) having a negative relation, as shown in Figure 5.24 and discussed by Elvik [41].

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Table 5.11 Risk Matrix for Volume Combinations with One or More Crashes

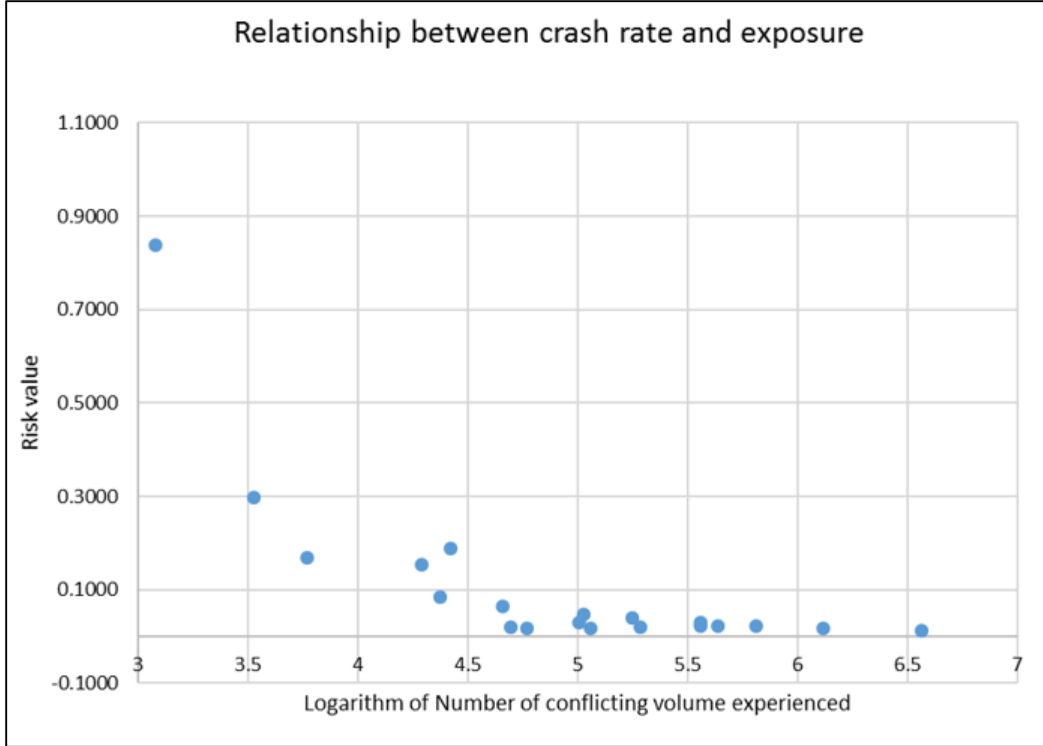| LT_{min}	LT_{max}	Th_{min}	Th_{max}	Total frequency of volumes within cell	Frequency of crash occurring volumes within cell	Risk
0	10	0	20	3681394	43	0.0117
10	20	0	20	434045	10	0.0230
20	30	0	20	114651	2	0.0174
40	50	0	20	23788	2	0.0841
60	70	0	20	1193	1	0.8382
0	10	20	40	1309924	24	0.0183
10	20	20	40	362230	11	0.0304
20	30	20	40	45613	3	0.0658
30	40	20	40	26438	5	0.1891
0	10	40	60	649834	14	0.0215
10	20	40	60	178293	7	0.0393
30	40	40	60	5897	1	0.1696
0	10	60	80	363025	8	0.0220
10	20	60	80	105948	5	0.0472
0	10	80	100	192509	4	0.0208
10	20	80	100	58956	1	0.0170
30	40	80	100	3364	1	0.2973
0	10	100	120	101863	3	0.0295
50	60	100	120	259	1	3.8610
0	10	120	140	49677	1	0.0201
0	10	140	160	19410	3	0.1546
40	50	160	180	259	1	3.8610

Figure 5.24 Inverse relation between exposure and risk

Further analysis was performed to check the individual effect of left-turn volumes and through movement volumes, and new risk values were generated. A normalization process was designed for this purpose, resulting in the relations in Figure 5.25. It is noted that these changes in risk are completely based on field data, and no assumptions of any kind were made to obtain the risk points in the figure. However, a more formal expression derived from a statistical model was used to develop the relationships of left-turning (Lt) and through (Th) volumes, as shown in the figure by the dotted lines and the equations below:

$$LT\ risk = \ e^{(-3.2709+0.085*LT\ volume)}$$

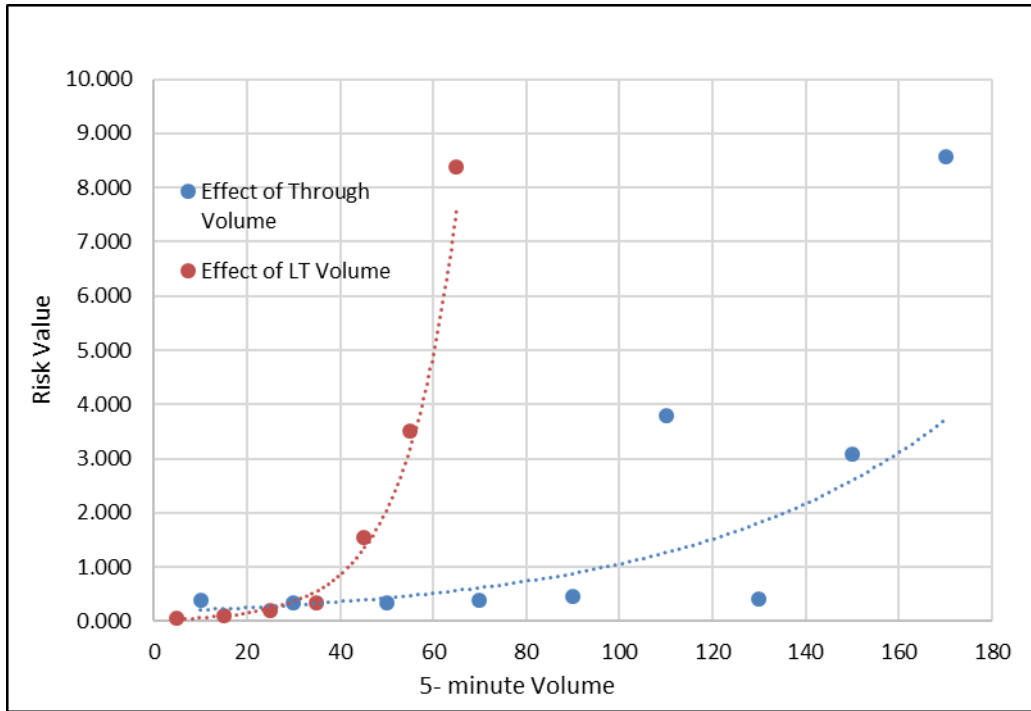$$Th\ risk = \ e^{(-1.3053+0.0085*Th\ volume+0.0692*Opposing\ Lanes)}$$

Figure 5.25 Increase in expected risk as a function of increasing left-turn or through volumes

However, it would be difficult to implement the models above as they require normalization of the competing volume. A more complete model incorporating both left-turning and through demands is shown in the equation below:

$$Risk = e^{(-4.937+0.100*LT\ volume+0.02*Th\ volume+0.0822*Opposing\ Lanes)}$$

It is noted that the model above also includes the number of opposing lanes being used by the through volume, as this variable also showed significance in the model. This model can be directly implemented to estimate risk and risk changes as a direct function of the left-turn and opposing through volumes. An example of this application is the monograph shown in Figure 5.26.
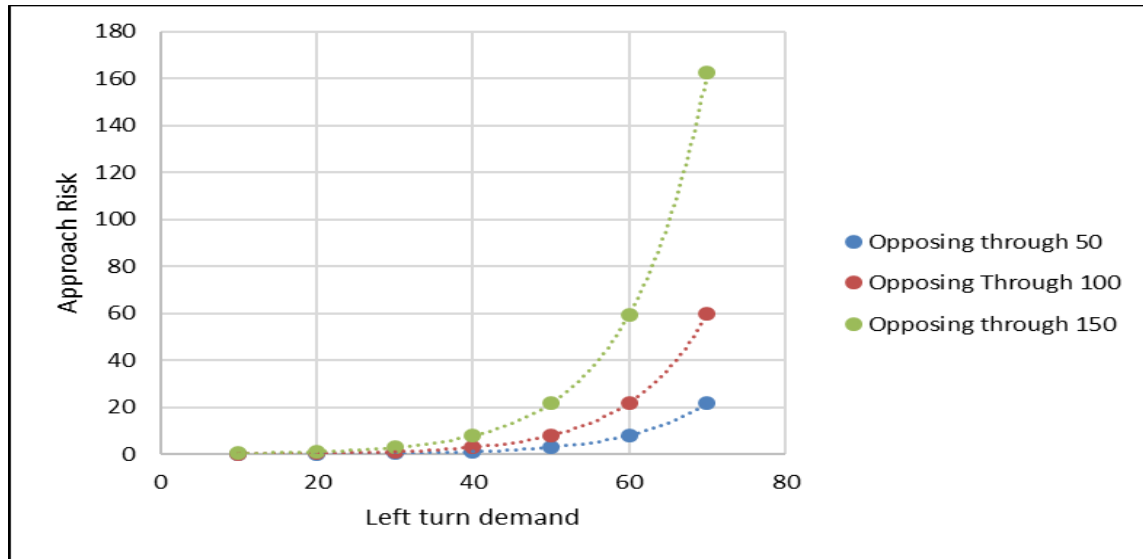
Figure 5.26 Relative approach risk values as a combination of left-turn and opposing through volume

Risk values introduced in this section are based on a relatively small sample size, but they provide a good picture of a risk-based approach to assess left-turn safety as a function of competing demands. As mentioned above, as the number of observations and crashes within each 20 x 10 cell increases, the confidence in the risk value also increases. An example of the risk value for the cell at the origin of Figure 5.23 is shown in Figure 5.27, where 43 crashes were observed. The figure is constructed by updating the risk value every three months, with a cumulative number of crashes and a cumulative number of observed volume combinations with 0-20 vehicles in the opposing through direction and 0-10 left-turning vehicles for a given 5-minute period. The evolution of the actual risk value is shown in the left portion of the figure; whereas, the change in risk from one estimation to the next is shown in the right portion of the figure. Note that as the data collection time increases, and the exposure and crashes increase, the deviation between consecutive points becomes smaller, indicating that the risk value is converging to a stable number.
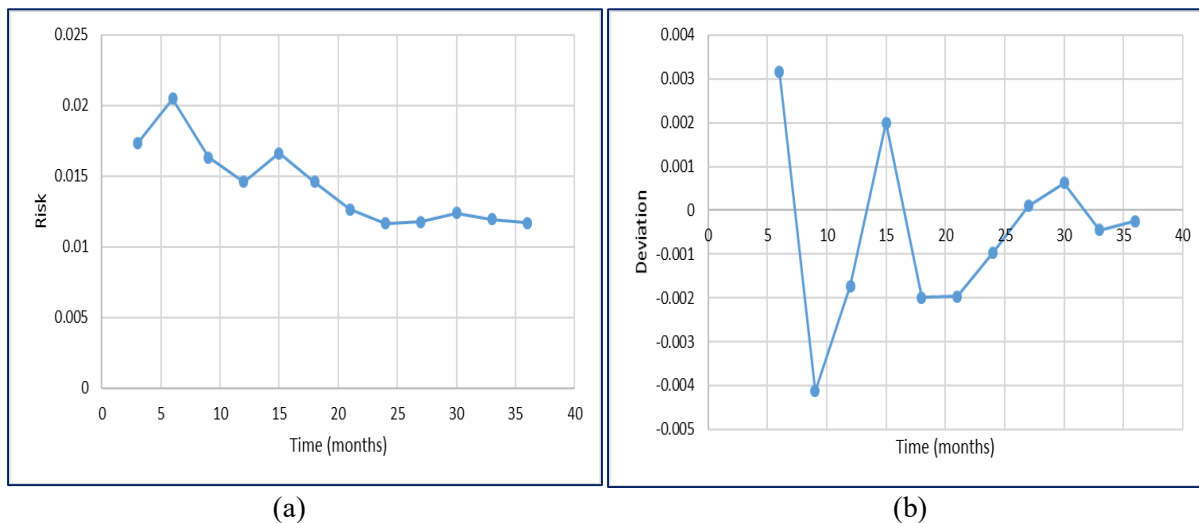

(a) (b)

Figure 5.27 Changes in risk and convergence of risk value over time

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Overall, the risk estimation presented here is an innovative and model-free approach to evaluate left-turn safety. The use of a standard risk definition allows simple calculations using the ratio of the number of crash events over the number of times such a volume combination has occurred. Different from traditional approaches, the complete history of events at the intersection (both with and without crashes) is taken into account. Calculations and data processing required for the risk estimation are also ideal for real-time applications without the need of significant processing power or data storage.

An example of an actual implementation for the intersection of 700 E and 3300 S in South Salt Lake is illustrated in Figure 5.28 and Figure 5.29 using 365 days of volume data. In Figure 5.28, the eastbound left-turn and opposing through volumes are shown together with the risk value for the same approach. It is noted that significant risk values are not found exclusively during peak hours, but also at various other times of the day, including afternoon off-peak and early night hours. The risk estimation is based on actual 5-minute readings during a full year and uses the risk values described in the risk matrix in Table 5.11 and the risk model above.

From section 5.6.2, recall that the expected crashes per hour for FYA approaches had similar magnitudes during afternoon peak and off-peak hours, so it is not surprising to observe high risks at similar hours at 700 E and 3300 S.

In addition, Figure 5.29 shows risk values when the two opposing left-turning movements at EB left and WB left are combined, since these movements will occur simultaneously during protected and also permissive portions of the signal cycle. In practice, such risk values could be useful to fine-tune phase timing plans and target periods with high potential for safety improvements by time of day and/or day of the week.

For a more complete description of the methodology, background, and applications, the reader is referred to Azra [40].
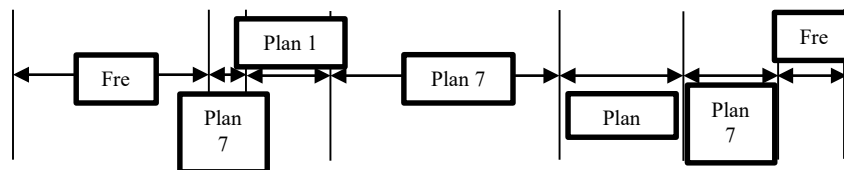
Figure 5.28 Risk values for eastbound LT at the intersection of 700 E and 3300 S – from top to bottom: average LT and through volumes, average risk, and sample phase plan
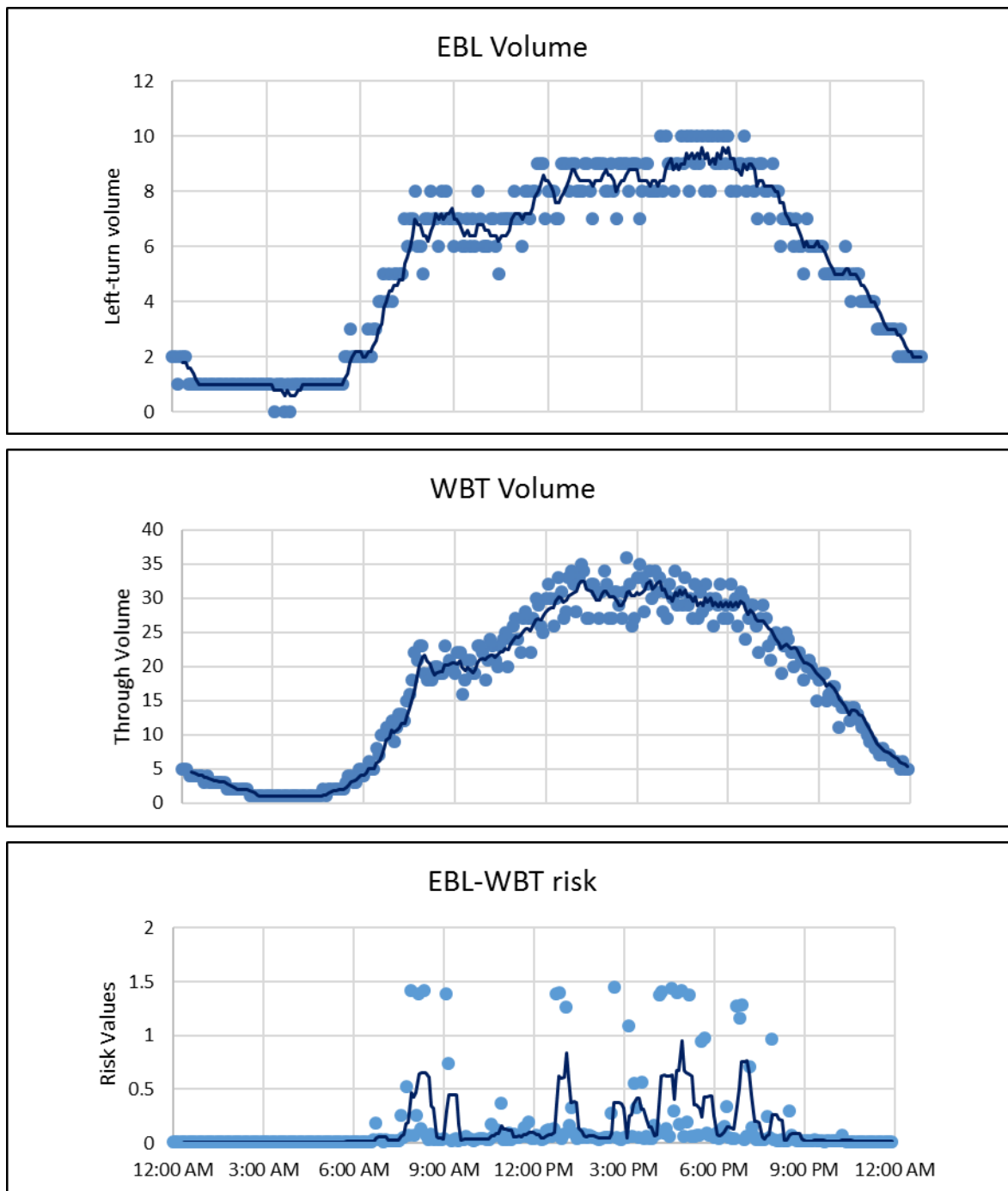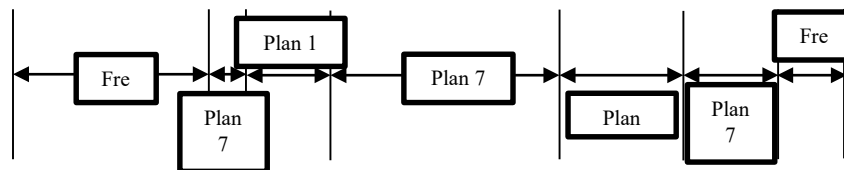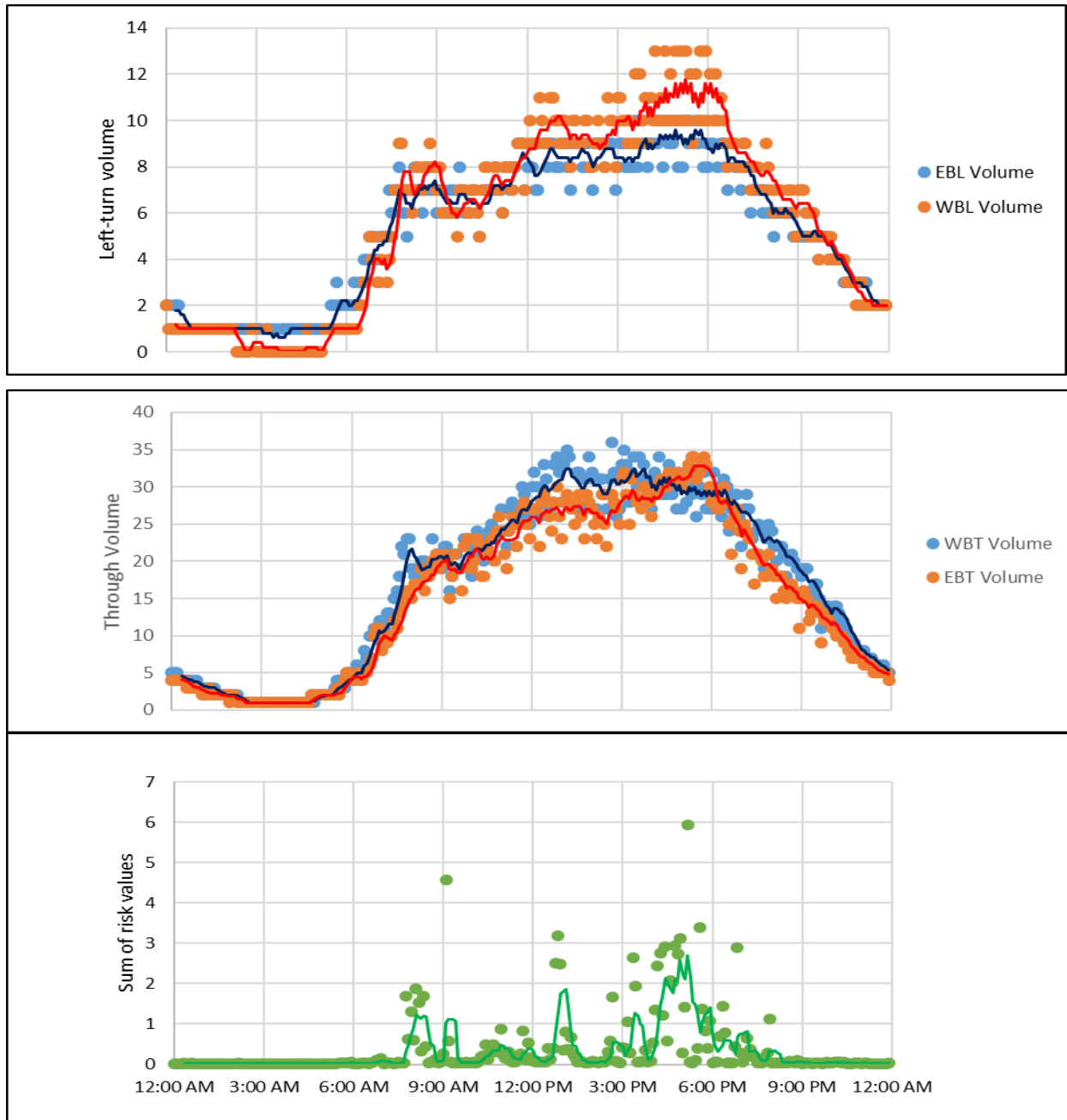
Figure 5.29 Risk values for EB and WB LT at the intersection of 700 E and 3300 S – from top to bottom: average LT and through volumes, average risk, and sample phase plan

6. CONCLUSIONS, RECOMMENDATIONS, AND FUTURE WORK

6.1 Conclusions and Recommendations

This study presented an evaluation of the safety performance of different left-turn phases, including permissive, protected-permissive (PPLT), protected, and flashing yellow arrow. The evaluation used statistical models to develop SPFs and CMFs to compare different left-turn phases, and also explored individual crash occurrences for seasonality effects (month-by-month), time-of-day trends, and evidence of safety changes due to novelty effects or driver adjustment periods right after an FYA was installed.

An extensive data collection with careful crash coding verification proved essential to obtain reliable final datasets. Performing manual data collection and verification for some of the intersection and crash datasets required more hours of work than anticipated, but it was a worthwhile effort to achieve consistency in the results.

The safety performance of left-turn phases is traditionally evaluated on a macro scale using intersection-level data, and more recently using approach-level data. Difficulties in data collection at the approach level quickly arise from common inaccuracies or lack of key crash and intersection information. From crash records, about one-third of all crashes verified at selected approaches needed corrections in the vehicle direction of travel, where the direction in the crash report indicated the direction of the receiving approach for a left-turning vehicle and not the approach of the originating movement. For example, a vehicle turning left from the northbound approach, facing the southbound through traffic, might have been coded as turning left traveling in the westbound direction (the receiving lane direction); therefore, this crash could be attributed to the westbound approach (and phase) if not manually verified. Incorrect assignment of one-third of the crashes would likely result in large misrepresentations of safety performance, which would render the study unreliable.

Difficulties in obtaining intersection data were mostly related to separate estimations of volumes for through and left-turn movements. UDOT's ATSPM service was a key source for accurate left-turning and through volumes, but previous left-turn studies conducted/contracted by UDOT were also used in a limited number of approaches in an effort to increase the availability of movement-level data. Continuous data recording from ATSPM was invaluable for the safety performance evaluation, and was the main source of data for a proposed event-based risk estimation suitable for real-time applications. Past left-turn studies mainly focused on short-term peak hour counts, and thus required further processing to find estimates of daily left-turn and through demand.

Results from the safety evaluation using statistical models produced consistent trends among the three main groups being evaluated using an empirical Bayes (EB) before-after methodology. SPFs were developed for permissive, PPLT, and FYA indications. The SPFs followed a similar structure, using the natural log of the cross product [ln (cross product)] as the independent variable describing demands and conflicts. An SPF for protected phases was not pursued, given the low crash frequency resulting from a complete separation of conflicting movements. In our case, an attempt at generating an SPF with such low crash frequencies and without a clear relationship between demands and crash events (volumes were not significant in an NB model) would be misleading.

The comparison of safety performance between permissive and FYA indications showed a slight reduction in expected yearly crash frequencies for lower ln (cross product) values when using FYA, but a slight increase as the ln (cross product) increased. Thus, a CMF value will be dependent on the range of ln (cross product) used in a given comparison. For the sample evaluated, the CMF showed a slight increase

(1.16 ± 0.38), although not statistically significant. Such a wide range in the CMF was the result of a small sample size after applying the EB method only for crash rates with a value different than zero. In our setting, zero values do not provide any information on the crash-generating process at a given approach and are not conducive to correct approximations.

Similarly, SPFs were generated for PPLT and FYA, and their performance was compared using the EB method. Overall, an increase in yearly frequencies of left-turn crashes was observed throughout the range of ln (cross product). Estimates for this group were more robust than the permissive-FYA group, given the increased sample size, resulting in a CMF of 1.33 ± 0.12. While this increase is significant, the actual magnitude for the average ln (cross product) value was equivalent to an increase in 0.28 LT crashes per approach per year, and for the highest value in the range it represented an increase of 0.9 LT crashes per approach per year. From the data, higher ln (cross product) values are expected to result in similar CMFs but higher nominal values for the increased number of crashes. Similarly, on the low end of the ln (cross product) range (e.g., lower than 15.5) the differences were negligible.

A simple comparison of the average yearly crash frequency for approaches that changed from protected to FYA phasing showed an increase in crashes, as expected. However, their average crash frequency with FYA showed values in similar ranges to those observed in the after period of the PPLT to FYA group, albeit with some differences in the upper end of the ln (cross product) range, as it can be quantified by the provided SPFs for FYA. In other words, the magnitude of the increase in crash frequency for the protected-FYA group was within expectation and as a direct result of allowing permissive movements at intersections that only had a protected phase.

An important caveat to direct and strict comparisons between FYA and PPLT arise from differences in their operational capabilities, with FYA indications having greater flexibility to improve traffic operations over traditional PPLT. As an example, FYA indications may allow an increasing number of vehicles to complete a left-turn maneuver under a permissive indication. This is because PPLT operations allow left-turn vehicles to make a permissive turn only when the adjacent and opposing through vehicles have a green light. FYA operations, in turn, allow left-turn vehicles to make a permissive turn only requiring the opposing through vehicles having a green light. Thus, under the same conflicting demands this operational benefit of FYA can improve mobility, but it also creates greater opportunity for permissive conflicts, and therefore also for crashes.

On the other hand, improving operations using FYA may also contribute to indirect safety improvements not observed as changes in left-turn crashes. For example, fewer vehicles needing a protected phase will result in shorter protected phase durations, which in turn can lead to longer through phases, fewer phase transitions over time, and therefore a lower risk of other crash types such as rear-end collisions. This research focused on safety effects in terms of left-turn crashes as a direct reflection of LT phases; however, FYA indications introduce additional flexibility that may result in additional indirect benefits. Previous research has identified overall improvements to all crash types when increasing protection on left-turn phasing [3, 9, 42], thus considering such indirect impacts of the flexibility of an FYA may help explain some of the apparent increase in left-turn crashes, particularly when comparing FYA with PPLT.

Additional analyses conducted at the single crash level, specifically considering their month of occurrence, time-of-day, and time elapsed since the FYA installations, provided insights, which are often hidden under overall crash frequencies alone. Whereas there were no special seasonal effects due to FYA indications, or any measurable novelty effect or safety adjustment period soon after the FYA installation, time-of-day distributions did show significant shifts. With an FYA indication, flatter crash distributions were found by time-of-day, indicating smaller crash increases during peak hours, but higher crash concentrations during off-peak periods. In particular, the two-hour period between 2 pm and 4 pm was observed to have a similar number of crashes per hour as the afternoon peak hours (from 4 pm to 7 pm).

Shifts in the distribution of crashes by time of day when using an FYA indicate there are opportunities to reduce unexpected peaks in crash frequencies during off-peak afternoon times, particularly from 2 pm to 4 pm. Operational strategies used during peak hours with FYA have curbed crash frequencies during such periods and could be also explored (with modifications) to reduce off peak crashes.

This study also introduced a new metric for estimating the risk of left-turn crashes at a given approach using high-resolution data from ATSPM and an event-based method. The method calculates a true measure of risk accounting for the complete history of conflicting volumes using 5-minute counts. For a particular set of conflicting volumes, the ratio of events (crash frequency) to all observed events (total number of times such volumes were observed) represent the risk, which can be shared with many locations with similar characteristics. Results are very encouraging, producing consistent trends and safety estimates ready for implementation. Moreover, the proposed method is ideal for real-time applications given the robustness and ease of calculation, only requiring to read data streams without storage requirements. Such a real-time risk monitoring system also allows for more proactive strategies that can target intra-day periods with high risk potential by adjusting phase and timing plans for a specific time of day, day of the week, or even preemptively upon unexpected risk changes.

Lastly, this study presented an evaluation of the safety effects of left-turn phases and quantification and comparisons of their safety performance using reliable field data from Utah. Such results are intended to provide insight and decision support in the process of evaluating alternatives from a safety standpoint. As mentioned above, operational differences between indications may not only produce operational advantages, but also indirect safety benefits in terms of other types of crashes; thus, these differences should also be considered when assessing the overall effects of a given left-turn indication.

6.2 Future Work

Future work is recommended to target limitations and natural extensions of this study. From a data collection point of view, SPF curves and CMF values will benefit from larger sample sizes and continual updates to locations already included in this study.

Also, the inclusion of operational details in the evaluation of protected-permissive phases could reduce uncertainty in modeling and allow direct comparisons. Such details could include: percentage of skip left-turn phases by time of day; percentage of left turns completed during the permissive, protected, and clearance portions of the left-turn phase; and classification of operational settings that affect the onset of a protected or a permissive period, for example, criteria to provide a protected phase at the beginning of green (e.g., number of vehicles in queue needed to trigger a protected phase).

Extensions related to the proposed risk estimation are also recommended. This method leveraged the existing high-resolution data and showed consistent estimates in this study, offering a promising alternative to evaluate safety performance in real time and greater detail (intra-day risk variations). Moreover, there could be direct operational applications derived from the risk estimations worth exploring, such as signal phasing and timing modifications to target high risk periods. Along with the use of a risk metric, monitoring crash frequencies by time of day is also recommended to update risk results. Paired with signal timing settings, time-of-day information from crash reports can provide additional key pointers for left-turn safety improvements.

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