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DEVELOPMENT OF CRASH MODIFICATION FACTORS (CMFs) FOR UTAH INTERSECTIONS

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16. Abstract

This research project aims at developing state-specific CMFs at intersections in Utah to quantify the safety impact of the countermeasures. Considering the research needs, data availability, and suggestions from the Technical Advisory Committee, the CMFs of four left-turn-phasing-related treatments, namely converting both-roadway permissive to one-roadway permissive-protected left-turn phasing, converting one-roadway to both-roadway permissive-protected left-turn phasing, converting both-roadway permissive-protected to one-roadway protected left-turn phasing, and converting one-roadway to both-roadway protected left-turn phasing are developed using the cross-sectional study. The results revealed that the conversion from permissive to permissive-protected left-turn signals showed no improvement in safety. However, converting permissive-protected signals to protected signals did result in a reduction of left-turn-related crashes. The CMF estimates for converting to protected left-turn phasing align with findings from other states, but CMFs for converting to permissive-protected phasing are higher than those seen in other states. A survey of other state DOT practices of permissive-protected left-turn phasing indicates that Utah typically uses a shorter protected portion of the permissive-protected phasing compared to other states which may be a possible reason for why Utah's CMFs are higher.

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LIST OF ACRONYMS

CMF	Crash Modification Factor
EB	Empirical Bayes
FB	Full Bayes
FHWA	Federal Highway Administration
FYA	Flashing Yellow Arrow
MCMC	Markov Chain Monte Carlo
SPF	Safety Performance Function
TOD	Time of Day
AADT	Annual Average Daily Traffic
UDOT	Utah Department of Transportation
NB	Negative Binomial
MnDOT	Minnesota Department of Transportation
NCDOT	North Carolina Department of Transportation
HSM	Highway Safety Manual
GIS	Geographic Information System
NB	Negative Binomial
TAC	Technical Advisory Committee

EXECUTIVE SUMMARY

A crash modification factor (CMF) is a multiplicative factor used to compute the estimated number of crashes after implementing a given countermeasure at a specific site. The state-specific CMFs for different countermeasures at intersections have not been thoroughly investigated yet in Utah. Hence, this research project aims to fill this gap by developing state-specific CMFs for signal phasing at Utah's signalized intersections.

Considering the research needs, data availability, and suggestions from the Technical Advisory Committee (TAC), the focus for CMF development is on left-turn phasing treatments. The treatments studied are:

1. Converting from both-roadway-permissive left-turn phasing to one-roadway-permissive-protected (one-roadway-permissive-) left-turn phasing;
2. Converting from one-roadway-permissive-protected (one-roadway-permissive) left-turn phasing to both-roadway-permissive-protected left-turn phasing;
3. Converting from both-roadway-permissive-protected left-turn phasing to one-roadway-protected (one-roadway-permissive-protected) left-turn phasing;
4. Converting from one-roadway-protected (one-roadway-permissive-protected) left-turn phasing to both-roadway-protected left-turn phasing.

Five datasets were used in the study: 1) crash data downloaded from AASHTOWare Safety Powered by Numetric; 2) AADTs provided by UDOT; 3) roadway characteristics collected from Google Street View; 4) demographic factors collected from US Census; and 5) information on left-turn phasing collected from Google Street View and verified with the information provided by UDOT.

A cross-sectional study was used to develop the CMFs. The Safety Performance Functions (SPFs) used to estimate the CMFs are developed using Negative-Binomial (NB) models. The results revealed that for converting from both-roadway permissive to one-roadway permissive-protected left-turn phasing, the CMF of all types of crashes is statistically insignificant, and the CMF of left-turn crashes is statistically significant and its point estimation is 1.416. For converting from one-roadway permissive-protected to both-roadway permissive-protected left-turn phasing,

both the CMF of all types of crashes and the left-turn crash are statistically significant, and the point estimations are 1.330 and 1.288, respectively. For converting from both-roadway permissive-protected to one-roadway protected left-turn phasing, the CMF of all types of crashes is statistically insignificant, and the CMF of left-turn crashes is statistically significant and its point estimation is 0.733. For converting one-roadway to both-roadway protected left-turn phasing, the CMF of all types of crashes is statistically insignificant, and the CMF of left-turn crashes is statistically significant and its point estimation is 0.505. In general, the conversion from permissive to permissive-protected left-turn signals showed no improvement in safety. However, converting permissive-protected signals to protected signals did result in a reduction of left-turn-related crashes. The most effective way to improve safety in terms of reducing the frequency of left-turn-related crashes was found to be the implementation of protected left-turn phasing for both intersecting roadways. The results of the CMF estimates for converting to protected left-turn phasing align with findings from other states. However, the CMF estimates for converting to permissive-protected phasing are estimated to be higher (less safe) in Utah than in other states.

Additionally, the team conducted a survey of other states' practices to understand how UDOT's approach to left-turn phasing may result in different CMFs compared to other localities. A possible reason indicated by the survey is that the left-turn signal operations of UDOT may lead to a shorter protected portion of the permissive-protected phasing compared to states with lower CMFs.

One of the major limitations of this study is the unavailability of data on left-turning volumes, which should serve as the exposure measure of left-turn-related crashes. The absence of this data may lead to a confounding effect in the treatment indicator, which may implicitly account for the higher left-turning volumes at intersections with one-roadway permissive-protected phasing. As a result, there is a possibility of overestimating the CMFs.

1. INTRODUCTION

1.1 Problem Statement

A crash modification factor (CMF) is a multiplicative factor used to compute the estimated number of crashes after implementing a given countermeasure at a specific site. Many states have developed state-specific CMFs for different countermeasures at intersections. These CMFs could benefit practitioners, consultants, and researchers within the practice of transportation safety engineering and for educational purposes. However, the state-specific CMFs for different countermeasures at intersections have not been thoroughly investigated yet in Utah. Hence, this research project aims to fill this gap by developing state-specific CMFs for Utah intersections, based on the currently available data.

Based on the statewide crash records of Utah, a significant portion of crash injuries and fatalities occur at intersections. Therefore, the investigation of potential countermeasures for reducing intersection crash frequency and severity becomes a critical step toward UDOT’s Zero Fatalities strategic direction. Particularly, the development of CMFs can greatly assist the decision-making process of UDOT’s Traffic & Safety division in implementing countermeasures.

Considering the research needs, data availability, and suggestions from the TAC, the focus for CMF development will be on left-turn phasing treatments. Left-turn phasing treatments are widely used by transportation agencies to reduce traffic crashes involving left-turning vehicles (left-turn crashes). Left-turn crash is one of the most frequently occurring types of crashes at intersections since left-turning vehicles at intersections encounter conflicts of various sources. The severity of the injury and the likelihood of fatality in left-turn crashes tend to be high because of the relatively high travel speeds of vehicles involved and the angle of impact. Left-turn phasing treatments intend to reduce the conflicts between left-turning movements from the opposing traffic and crossing pedestrians by providing a separate signal phase for left-turning traffic. They typically convert a permissive left-turn phasing, where left-turns are allowed after yielding to conflicting traffic and pedestrians, to protected. Permissive-protected phasing is intended to do the same but for shorter durations and during specific circumstances. The protected left-turn phasing allows left turns to be made only on a green left-arrow signal indication, while the permissive-protected is a combination of permissive and protected left-turning movements.

1.2 Objectives

The primary objective of this research project is to develop state crash modification factors (CMFs) for several different left-turn phasing treatments at signalized intersections in Utah.

Secondary objectives of this research project are to examine other states' practices to verify how UDOT operations may result in different CMFs than other localities.

1.3 Scope

Task 1: Literature Review

Task 1 focuses on conducting a literature review of existing studies developing CMFs of left-turn treatments and the candidate methods that can be used to develop the CMFs.

Task 2: Data Collection

This task provides a summary of collected data, including left-turning treatments, crash data, traffic data, and roadway geometry. The data will support the development of CMFs and determine the appropriate study sites and methods, given the data availability.

Task 3: CMFs Development

This task begins with the selection of research models for CMF development based on the availability of data. Next, CMFs for various left-turn phasing treatments are developed for intersections in Utah.

Task 4: CMF Comparisons

This task conducts a study of other states' practices to verify how UDOT operations may result in different CMFs than other localities.

Task 5: Final Report

This task prepares the final project report.

1.4 Outline of Report

This report documents the findings of the research and proceeds with the following sections:

- Introduction
- Literature Review
- Data and Study Sites
- CMF Development
- CMF Comparisons
- Conclusions

2. LITERATURE RIVIEW

2.1 Overview

This chapter provides a comprehensive review of existing studies and their methodologies to support the later development of CMFs. It begins with a review of studies that have developed CMFs for various left-turn treatments. Following this, the chapter outlines the candidate methods that can be used for CMF development.

2.2 Crash Modification Factors of Left-Turn Phasing Treatments

In this section, existing studies estimating CMFs related to left-turn phasing treatments are reviewed.

Four treatments that are recommended by the TAC as “treatments with high priority”:

1. Converting from permissive left-turn phasing to permissive-protected left-turn phasing;
2. Converting from permissive-protected left-turn phasing to protected left-turn phasing;
3. Converting from permissive left-turn phasing to protected left-turn phasing; and,
4. Converting from traditional five-head “doghouse” permissive left-turn phasing to flashing yellow arrow permissive left-turn phasing.

The aforementioned high-priority treatments are reviewed in detail, followed by a brief review of other treatments. Note that studies reviewed by the research team are those verified by the Crash Modification Factor Clearinghouse (US Department of Transportation, n.d.) funded by the United States Department of Transportation. The section concludes with a summary of the impact of left-turn phasing treatments on traffic safety.

2.2.1 Converting Permissive Left-Turn Phasing to Permissive-Protected Left-Turn Phasing

Converting a permissive left-turn phase into a permissive-protected one can reduce the probability of the occurrence of conflicts between left-turning vehicles with opposing traffic and crossing pedestrians, especially when the volume of left-turning is sufficiently high to call the "protected" left-turn phase. Over the years, there have been a substantial number of studies on estimating CMFs for this treatment.

The Highway Safety Manual (AASHTO, 2010) (HSM) Part D provides CMF values that show the potential benefits of converting a permissive left-turn phase to a permissive-protected one. According to the HSM, this conversion can reduce the overall crash frequency by 1% (CMF value of 0.99 for all crashes) for each leg that is converted from permissive to permissive-protected, left-turn crashes by 16% (CMF value of 0.84), and injury crashes (K, A, B, C [1])) by 16% (CMF value of 0.84). These findings demonstrate the positive impact this treatment can have on improving the safety of intersections.

Davis and Aul (Davis & Aul, 2007) conducted several studies on different treatments at high-speed intersections in the Twin Cities Metro District, Minnesota. They estimated CMFs for changing permissive to permissive-protected left-turn phasing for minor approaches. Four four-legged right-angle intersections with the major approaches having permissive-protected left-turn phasing were identified as the treatment group, with 16 intersections serving as the reference group. Using the Bayesian method with Markov Chain Monte Carlo (MCMC), the study estimated the CMFs for left-turn crashes and all intersection-related crashes. The results show that the CMF of all intersection-related crashes is not significant while the CMF of left-turn crashes is 0.73. The estimated CMF indicates that converting the permissive left-turn phasing to permissive-protected left-turn phasing could significantly reduce the crash frequency, but the size of the treatment group was relatively small.

Srinivasan et al. (National Academies of Science Engineering and Medicine, 2011) evaluated the safety effects of various treatments at signalized intersections, including the

[1] KABCO Injury Classification Scale. K: Fatal; A: Incapacitating Injury; B: Non-incapacitating Injury; and C: Possible injury

conversion from permissive to permissive-protected left-turn phasing. Seventy-one intersections in Toronto, Canada, and North Carolina, United States were used as the treatment group, but the size of the reference group was not mentioned. The Empirical Bayes (EB) before-after study was employed. The results indicate that the CMF of all types of crashes is 1.033, the CMF of left-turn crashes is 0.858, the CMF of crashes with injury or fatality is 0.958, and the CMF of rear-end crashes is 1.063. Therefore, the conversion reduces the frequency of targeted left-turn crashes but increases the frequency of rear-end crashes even more, which then leads to an increase of total crash frequency. The injury severity tends to decrease. A possible reason is that the increased rear-end crashes are likely to be less severe.

Chen et. al (Chen et al., 2015) employed a quasi-experimental design accompanied with regression modeling to assess the impact of several different left-turning phasing treatments in New York City. Fifty-nine intersections with the conversion from permissive to permissive-protected were used as the treatment group and a reference group consisting of 991 intersections was used. The estimated CMF of all crash types is 0.67 while the estimated CMF of left-turn crashes is 0.83. The CMFs imply that the conversion can reduce the crash frequency, but its effect on the target crash type, left-turn crashes, is not as satisfactory as other types of crashes, which is not consistent with the HSM. This could be due to the randomness or the lack of consideration of traffic volume in the analysis.

Some studies focus on the conversion to one specific type of permissive-protected left-turn phasing, which is the flashing yellow arrow (FYA). Simpson and Troy (Simpson & Troy, 2015) estimated the CMF using EB before-after study. The study used 30 intersections as the treatment group and found that the CMF for all crashes was 0.935, for left-turn crashes was 0.598, for injury crashes (K, A, B, C) was 0.654, and for severe injury left-turn crashes (K, A, B, C) was 0.592. These CMFs show similar trends to those CMFs of all kinds of permissive-protected left-turn phasing.

Medina et al. (Medina et al., 2018) evaluated the safety impact of converting different left-turn phasing into FYA in Utah using the EB before-after method. The study focused on 54 approaches that underwent the conversion from permissive to FYA and were used as the treatment group. The results showed that the CMF of left-turn crashes is 1.16 but is not statistically significant. The authors suggest that the conversion might have increased conflicting traffic demands/volumes, resulting in increased crash exposure, but not necessarily increasing crash risk. While the results suggest a potential increase in crash frequency, further investigation is needed to make a definitive conclusion.

Storm et al. (Storm et al., 2020) also estimate the CMF of the conversion to FYA for Minnesota. A naïve before-after study was conducted. Nine intersections were selected as the treatment group. The estimated CMF of all types of crashes is 0.467, the CMF of left-turn crashes is 0.527, the CMF of all injury crashes (K, A, B, C) is 0.389, and the CMF of rear-end crashes is 1.023. The CMFs indicate that the conversion reduces the frequency of all crashes, injury crashes, and targeted left turn, but it might increase the frequency of rear-end crashes. However, it should be noted that the study's use of a naïve before-after method is limited in accounting for confounding factors, reducing the reliability of the estimated CMFs.

Table 1 CMFs of Converting Permissive Left-Turn Phasing to the Permissive-Protected Left-Turn Phasing

Study	Jurisdiction	Crash Type	CMF
HSM	N/A	All	0.99
		Left-Turn	0.84
Davis and Aul (Davis & Aul, 2007)	Twin Cities, Minnesota	All	0.85
		Left-Turn	0.73*
Srinivasan et al. (National Academies of Science Engineering and Medicine, 2011)	Toronto, Canada North Carolina	All	1.033
		Left-Turn	0.858*
		Injury	0.958
		Rear-End	1.063
Chen et. al (Chen et al., 2015)	New York City	All	0.67
		Left-Turn	0.83
Simpson and Troy (Simpson & Troy, 2015)	North Carolina	All	0.935
		Left-Turn	0.598*
		KABC	0.654*
		KABC Left-Turn	0.592*
Medina et al. (Medina et al., 2018)	Utah	Left-Turn	1.16
Storm et al. (Storm et al., 2020)	Minnesota	All	0.467*
		Left-Turn	0.527*
		KABC	0.389*
		Rear-End	1.023

* Statistically significant at the 0.05 level

Table 1 presents a summary of the reviewed crash modification factors (CMFs) for the conversion of permissive left-turn phasing to permissive-protected phasing. Overall, the conversion has a positive impact on reducing the frequency of its target crash type, left-turn crashes. However, the effects on other types of crashes may vary depending on the jurisdiction. In some areas, it can also reduce the overall number of crashes, while in others, it may increase it by increasing the frequency of other crash types, such as rear-end crashes. Despite this, the severity of crashes tends to decrease with the conversion, even if the number of crashes increases, making the conversion a beneficial measure for intersection safety.

However, it should be noted that many CMFs reviewed are not statistically significant at 0.05 level due to large standard errors associated with the estimated CMFs. This does not necessarily mean that these CMFs are unreliable, but it highlights the potential for error. It is crucial for users to be aware of these limitations when interpreting the results.

2.2.2 Converting Permissive-Protected Left-Turn Phasing to Protected Left-Turn Phasing

Converting a permissive-protected left-turn phase to a fully protected one is expected to further improve the safety of left-turning vehicles. Several studies have been conducted to estimate the corresponding CMFs in different states.

The HSM (AASHTO, 2010) Table 14-23 does not provide CMFs for converting either permissive or permissive-protected to protected left-turn phasing. Instead, it provides CMFs for converting to protected phasing on a specific leg. The CMF value is 0.99 for all crashes and 0.01 for left-turn crashes. Although these CMFs serve as references only, it can be concluded that protected left-turn phasing can significantly reduce targeted left-turn crashes.

Davis and Aul (Davis & Aul, 2007) estimated the impact of converting permissive-protected left-turn phasing to full protection in the Twin Cities Metro District, Minnesota. For minor approaches, only two four-legged right-angle intersections with the major approaches having protected left-turn phasing were identified as the treatment group, while 17 intersections were used as the reference group. For major approaches, only one intersection was identified, and 233 intersections were in the reference group. The Bayesian method using MCMC was used to estimate the CMFs. The results show that the CMF of all intersection-related crashes is 0.99 for minor approaches and 0.58 for major approaches respectively, while the CMF of left-turn crashes is 0.04 for minor approaches and 0.01 for major approaches. Although the CMFs estimated indicate that converting the permissive-protected left-turn phasing to protected left-turn phasing is able to reduce the crash frequency, the limited size of the treatment group undermines the reliability of the CMFs.

Srinivasan et al. (Srinivasan et al., 2008) conducted a study in Winston-Salem, North Carolina to estimate the effect of converting permissive-protected left-turn phasing to protected left-turn phasing. The study used four intersections as the treatment group and compared the results with a reference group of 60 untreated intersections. The results show that the CMF of all intersection-related crashes is 1.02 but is not statistically significant. The authors state that the introduction of a protected left-turn phase may increase rear-end crashes due to the increase in the number of phases (and thus, dilemma zone opportunities) and the increase in queue length that results from reduced green time available for other traffic not protected by the introduced phase. However, the CMF of angle crashes was found to be zero, which suggests that angle crashes could be eliminated.

Asaduzzaman et al.(Asaduzzaman et al., 2021) employed a cross-sectional framework to develop CMFs of converting permissive-protected left-turn phasing to protected left-turn phasing in Louisiana. Twenty-one four-leg intersections served as the treatment group and another twenty-one intersections with similar geometry, traffic volume, and roadway classification were used as the control. The estimated CMF of all types of crashes is 1.001 and that of left-turn crashes is 0.66, which implies that the conversion might slightly increase the total crash frequency but does reduce the number of targeted left-turn crashes. As for the crash severity, the conversion tends to reduce the injury (K, A, B, C) crashes (CMF of all crash types is 0.567 and CMF of left-turn crashes is 0.309) but increase the property-damage-only crashes (CMF of all crash types is 1.367, and CMF of left-turn crashes is 1.096). In conclusion, the conversion demonstrates positive safety benefits.

Table 2 summarizes the reviewed CMFs for converting permissive-protected left-turn phasing to protected phasing. In general, the treatment is able to reduce the frequency of its target type of crash, which is the left-turn crash. In some jurisdictions or under certain conditions, the treatment can eliminate left-turn crashes. However, similar to the conversion from permissive to permissive-protected, the effect on other crash types may vary depending on the jurisdiction. On the positive side, the treatment tends to reduce the severity of crashes. Hence, converting the permissive-protected left-turn to the protected one has positive impacts on intersection safety. Again, the users should be aware of the issues related to the statistical significance of CMFs indicated in Table 2.

Table 2 CMFs of Converting the Permissive-Protected Left-Turn Phasing to the Protected Left-Turn Phasing

Study	Jurisdiction	Crash Type	CMF
Davis and Aul (Davis & Aul, 2007)	Twin Cities, Minnesota	All & Major	0.99
		All & Minor	0.58
		Left-Turn & Major	0.04*
		Left-Turn & Minor	0.01*
Srinivasan et al. (2008)	Winston-Salem, North Carolina	All	1.02
		Left-Turn	0*
Asaduzzaman et al.(Asaduzzaman et al., 2021)#	Louisiana	All	0.67
		Left-Turn	0.83
		All (KABC)	0.567
		Left-Turn (KABC)	0.309
		All (O)	1.367
		Left-Turn (O)	1.096

* Statistically significant at the 0.05 level
# Unable to determine the statistical significance due to the lack of original material

2.2.3 Converting Permissive Left-Turn Phasing to Protected Left-Turn Phasing

Though not very common in the State of Utah, there exist conversions directly from a permissive left-turn phase into a fully-protected one. Several studies provide CMFs for the conversion in other states.

Davis and Aul (Davis & Aul, 2007) estimated CMFs of changing permissive left-turn phasing to protected for minor approaches in Minnesota. Only one intersection was identified, and 16 intersections served as the reference group. Similarly, the Bayesian method using MCMC was used. The results show that the CMF of all intersection-related crashes and left-turn crashes are 0.83 and 0.01 respectively. While the study suggests that converting to protected left-turn phasing can effectively reduce crashes, the sample size of just one treatment intersection limits the reliability of the findings. Srinivasan et al. (Srinivasan et al., 2008) used eight intersections in North Carolina that underwent conversions from permissive to protected to estimate the CMF. The same reference group for estimating the CMF of converting the permissive-protected to protected left-turn phasing is used. The results show that the CMF of all intersection-related crashes is 0.975 and the CMF of angle crashes is 0.021. Therefore, the conversion benefits intersection safety, especially by reducing left-turn crashes.

Chen et. al (Chen et al., 2015) used the quasi-experimental design accompanied by regression modeling to estimate the CMF of converting a permissive left-turn to a protected one. Nine intersections with the conversion were used as the treatment group, and the reference group was the one used for estimating the CMF of converting a permissive left-turn to a permissive-protected one (991 intersections). The estimated CMF of all crash types is 0.45 while the estimated CMF of left-turn crashes is 0.23. The CMFs indicate that the conversion can reduce the crash frequency, especially for the target crash type, left-turn crashes. Moreover, compared with the CMF of the conversion from permissive to permissive-protected estimated from the same study, it can be concluded that full-protected left-turn phasing can improve intersection safety more than the permissive-protected one, aligning with the theoretical expectation.

Table 3 CMFs of Converting the Permissive Left-Turn Phasing to the Protected Left-Turn Phasing

Study	Jurisdiction	Crash Type	CMF
Davis and Aul (Davis & Aul, 2007)	Twin Cities, Minnesota	All & Minor	0.83
		Left-Turn & Minor	0.01*
Srinivasan et al. (2008)	Winston-Salem, North Carolina	All	0.975
		Left-Turn	0.021*
Chen et. al (Chen et al., 2015)	New York City	All	0.45
		Left-Turn	0.23*

* Statistically significant at the 0.05 level

Table 3 shows a summary of reviewed CMFs of converting the permissive left-turn phasing to the protected phasing. The treatment has been proven to be effective in reducing both the overall crash frequency and the frequency of its target crash type, left-turn crashes. The impact on left-turn crashes is more significant compared to other crash types, similar to the outcomes of converting permissive-protected left-turn phasing to protected. However, it is important to note the level of statistical significance indicated in Table 3.

2.2.4 Converting Five-Head ("Doghouse") Permissive Left-Turn Phasing to Flashing Yellow Arrow Permissive Left-Turn Phasing

The traditional permissive-protected left-turn phasing uses a five-head signal. In the last two decades, many transportation agencies, including UDOT, started converting the five-head to FYA due to potential safety and operational benefits (Brehmer et al., 2003; United States Department of Transportation, 2006). Recently, after years of implementations, a growing body of literature has explored the safety impacts of this conversion.

Among several safety-related treatments at signalized intersections, Srinivasan et al. (National Academies of Science Engineering and Medicine, 2011) estimated CMFs of the conversion doghouse to FYA using the EB before-after study. Thirteen intersections in Toronto, Canada, and North Carolina, United States were used as the treatment group. The results show that the CMF of all types of crashes is 0.922, and the CMF of left-turn crashes is 0.806. However, both CMFs are not statistically significant at the 0.05 level. Therefore, although the CMFs might imply that the conversion has positive safety effects, they should be interpreted with caution.

Simpson and Troy (Simpson & Troy, 2015) estimated the CMFs also using the EB before-after study. One hundred and five intersections were selected as the treatment sites. The estimated CMF of all types of crashes is 0.934, the CMF of left-turn crashes is 0.777, the CMF of all injury crashes (K, A, B, C) is 0.853, and the CMF of injury left-turn crashes (K, A, B, C) is 0.676. These CMFs illustrate that the conversion has significant safety benefits in the reduction of total crash frequency, frequency of targeted left-turn crashes, and injury severity.

Medina et al. (Medina et al., 2018) also employed sixty-four treatment approaches to conduct an approach-level EB before-after study to estimate the CMF of converting "Doghouse" to FYA permissive left-turn. The results show a CMF of 1.33 for left-turn crashes, which indicates that the conversion increased the crash frequency. The authors believe that the increase is due to the increase in conflicting traffic demands/volumes (exposure).

Appiah et al. (Appiah et al., 2018) employed both full Bayes and empirical Bayes before-after methods to estimate CMFs of the conversion from "doghouse" to FYA permissive left-turn in Virginia. Twenty-two intersections were used as the treatment group and another thirty-nine untreated intersections were used as the reference group. The model estimates a CMF of 0.88 for all types of crashes and a CMF of 0.70 for left-turn crashes. The CMFs indicate that the conversion can reduce both total crash frequency and the number of targeted left-turn crashes, and thus it is beneficial to intersection safety.

Storm et al. (Storm et al., 2020) also estimate the CMF of converting “doghouse” to FYA for Minnesota using naïve before-after method. Forty intersections were used as the treatment group. The estimated CMF of all types of crashes is 0.740, the CMF of left-turn crashes is 0.792, and the CMF of all injury crashes (K, A, B, C) is 0.577. The CMFs indicate that the conversion reduces the frequency of all crashes, injury crashes, and targeted left-turn crashes. Again, since the study uses a naïve before-after study that cannot account for many confounding factors, the reliability of estimated CMFs is limited.

Srinivasan et al. (Srinivasan et al., 2020) conducted a comprehensive analysis of the safety effects of converting different left-turn phasing to FYA. The study examined hundreds of intersections across four states (Nevada, North Carolina, Oklahoma, and Oregon). The study evaluated three different conditions of conversions from three different conditions “doghouse” to FYA: occurred on one road of a three-leg intersection (category one, 46 sites), occurred on one road of a four-leg intersection (category two, 136 sites), occurred on both roads of a three-leg intersection (category three, 64 sites). For category one, the CMF of all types of crashes is 0.849, the CMF of left-turn crashes is 0.804 (not statistically significant), and the CMF of injury crashes (KABC) is 0.791. For category two, the CMF of all types of crashes is 0.889, the CMF of left-turn crashes is 0.746, and the CMF of injury crashes (KABC) is 0.801. For category three, the CMF of all types of crashes is 0.818, the CMF of left-turn crashes is 0.624, and the CMF of injury crashes (KABC) is 0.782. In general, converting the “doghouse” to FYA improves intersection safety in terms of reducing crash frequency and severity. The more conversions that occurred at an intersection, the larger safety benefits could be expected.

The results of converting the traditional five-head "doghouse" to FYA permissive-protected left-turn phasing, as shown in Table 4, suggest that it generally improves intersection safety by reducing crash frequency and severity. However, in Utah, the conversion may result in an increase in crash frequency, which requires further investigation. It is important to note that the statistical significance of the CMFs presented in Table 3 should be considered when interpreting the results.

Table 4 CMFs of Converting the "Doghouse" to FYA Permissive-Protected Left-Turn Phasing

Study	Jurisdiction	Crash Type	CMF
Srinivasan et al. (National Academies of Science Engineering and Medicine, 2011)	Toronto, Canada North Carolina	All	0.922
		Left-Turn	0.806
Simpson and Troy (Simpson & Troy, 2015)	North Carolina	All	0.934*
		Left-Turn	0.777*
		KABC	0.853*
		KABC Left-Turn	0.676*
Medina et al. (Medina et al., 2018)	Utah	Left-Turn	1.33*
Appiah et al. (Appiah et al., 2018)	Virginia	All	0.88*
		Left-Turn	0.70*
Storm et al. (Storm et al., 2020)	Minnesota	All	0.740*
		Left-Turn	0.792*
		KABC	0.577*
Srinivasan et al. (Srinivasan et al., 2020)	Nevada, North Carolina, Oklahoma, and Oregon	3-Leg/One Road	0.849*
		3-Leg/One Road/Left-Turn	0.804
		3-Leg/One Road/KABC	0.791*
		4-Leg/One Road	0.889*
		4-Leg/One Road/Left-Turn	0.746*
		4-Leg/One Road/KABC	0.801*
		4-Leg/Both Road	0.818*
		4-Leg/Both Road/Left-Turn	0.624*
		4-Leg/Both Road/KABC	0.782*

* Statistically significant at the 0.05 level

2.2.5 Other Treatments

There are also other left-turn treatments that occurred at intersections. The most common one is converting protected ones into permissive or permissive-protected ones (including traditional five-head and FYA). All studies (Medina et al., 2018; National Academies of Science Engineering and Medicine, 2011; Simpson & Troy, 2015; Srinivasan et al., 2020; Storm et al., 2020) show that these types of conversion have negative safety effects on intersections by increasing crash frequency and severity. The possible reason is that converting the protected to permissive to some degree increases the conflicts between the left-turn vehicles and opposing traffic.

Some studies estimate the CMFs of converting other types of left-turn phasing to FYA with Time-of-Day (TOD) operation. Most sites with TOD operation employed FYA during off-peak hours (in general, 9 p.m. to 6 a.m.) and operated fully protected for the remainder of the day. Simpson and Troy (Simpson & Troy, 2015) found that converting the protected left-turn phasing to FYA with TOD reduced the total crash frequency by 9.9% (CMF is 0.901). And Srinivasan et al. (Srinivasan et al., 2020) estimated a CMF of 0.974 but not statistically significant. Both studies do not explain the reason. Both studies also found that the conversion increased the frequency of left-turn crashes, although neither of these findings was statistically significant.

There is a study (Schultz et al., 2013) conducted in the state of Utah estimating CMFs associated with the modification of left-turn phasing. Thirty-one intersections that underwent the modifications were chosen as the study sites. A hierarchical Bayesian model was used. The results show that the CMF of all types of crashes is 1.15, and the CMF of left-turn crashes is 1.55, which implies that the effectiveness of these treatments in Utah is not satisfactory. Although the authors state that the majority of the treatments are the installations of a 5-section left-turn signal head (permissive to permissive-protected), it is unclear what the other treatments are. Different types of treatments can have opposite effects, such as converting from permissive-protected to protected and from protected to permissive-protected, which makes the results of this study inconclusive.

2.2.6 Summary

This chapter reviewed existing studies developing CMFs for different kinds of left-turn phasing treatments. Four major types of treatments are reviewed, namely:

1. converting permissive left-turn phasing to permissive-protected left-turn phasing;
2. converting permissive-protected left-turn phasing to protected left-turn phasing;
3. converting permissive left-turn phasing to protected left-turn phasing; and,
4. converting traditional five-head “doghouse” permissive left-turn phasing to flashing yellow arrow permissive left-turn phasing.

Table 5 provides statistics of the reviewed CMFs for readers' reference. On average, providing protected left-turn phasing to any degree can improve intersection safety, but the safety benefits of protected phasing are more than those of the permissive-protected one. Protected left-turn phasing is expected to reduce or almost eliminate the targeted left-turn crashes. The use of FYA has typically been found to have a positive impact on safety, however in certain circumstances it may result in an increase in crashes.

Table 5 Statistics of Reviewed CMFs Related to Left-Turn Phasing

Treatment	Crash Type	Mean	Range
Permissive to Permissive-Protected	All	0.824	0.467-1.033
	Left-Turn	0.792	0.527-1.160
Permissive-Protected to Protected	All	0.815	0.580-1.020
	Left-Turn	0.220	0.000-0.830
Permissive to Protected	All	0.752	0.450-0.975
	Left-Turn	0.087	0.010-0.230
Five-Head "Doghouse" to FYA	All	0.862	0.740-0.934
	Left-Turn	0.822	0.624-1.330

2.3 Methodology for Developing CMFs

Various methods can be used for developing CMFs, including the naïve before-after study, the before-after study with the comparison group, empirical Bayesian before-after study, full Bayesian before-after study, cross-sectional study, case-control study, and cohort study. The Federal Highway Administration (FHWA) provides a comprehensive guide (Gross et al., 2010) to assist practitioners in selecting the most suitable methodology and in understanding the related issues and data considerations (see Figure 1) as well as issues and data considerations related to the methodologies. The methods used by the studies reviewed in section 2.2 are summarized in Table 6.

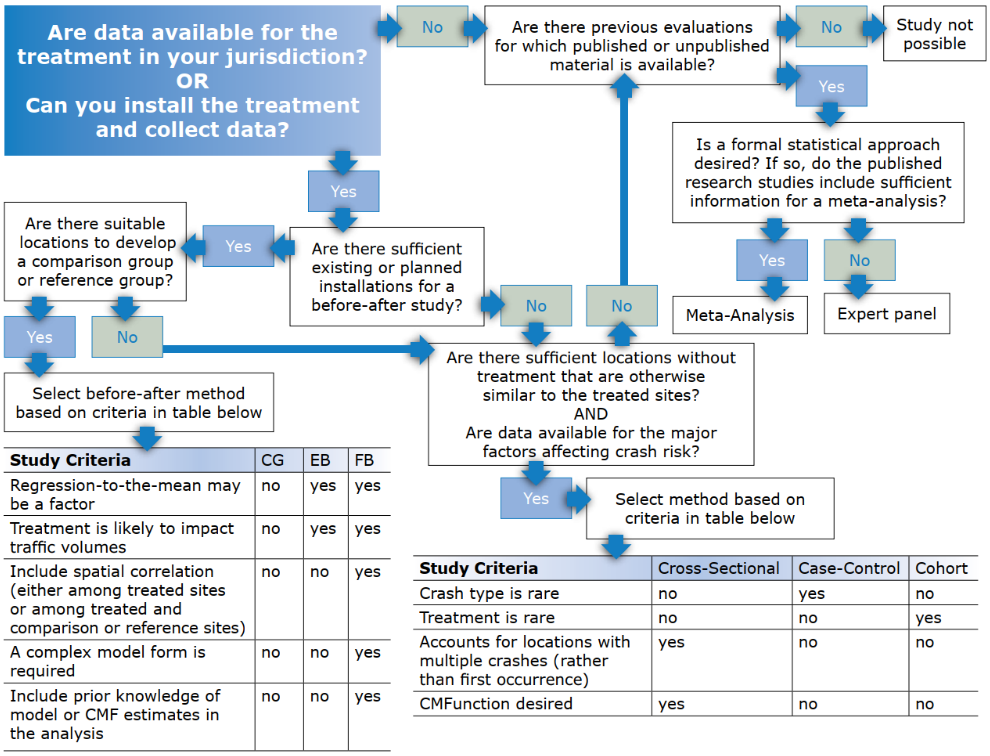


Figure 1 Flow Chart for Identifying CMF Development Methodology (Source: (Gross et al., 2010))[2]

Table 6 Methods Used by the Studies Reviewed

Method	Number of Studies	Study
Empirical Before-After	6	Davis and Aul (2007), Srinivasan et al. (Srinivasan et al., 2008), Srinivasan et al. (National Academies of Science Engineering and Medicine, 2011), Simpson and Troy (Simpson & Troy, 2015), Medina et al. (Medina et al., 2018), Appiah et al. (Appiah et al., 2018)
Full Bayes Before-After	1	Appiah et al. (Appiah et al., 2018)
Cross-Sectional	1	Asaduzzaman et al.(Asaduzzaman et al., 2021)
Other	2	Chen et. al (Chen et al., 2015) (Quasi-experimental design with regression modeling), Storm et al. (Storm et al., 2020) (naïve before-after)

[2] Flow Chart Legend: CG = Comparison Group; EB = Empirical Bayes; FB = Full Bayes

According to Table 6, the majority of previous studies regarding left-turn phasing treatments employ the EB before-after study. Hence, the research team considers it to be the preferred methodology. However, according to Figure 1, the EB before-after study requires sufficient existing installations of the treatments, suitable locations to develop a reference group, and sufficient crash data. If these prerequisites were not met, a cross-sectional study would be considered as an alternative.

The next sections will provide a brief overview of the two selected study methodologies. The mathematical equations for each method will not be included in this section, but rather will be presented once the final methodology is determined based on available data.

2.3.1 Empirical Bayes Before-After Study

For a before-after design, the CMF is estimated from the change in crash frequency before and after the implementation of the treatment. A naïve before-after study simply compares the crash counts between before-and-after periods. However, it fails to account for the changes unrelated to the treatment (compounding factors).

Therefore, in the EB before-after study, a reference group of sites similar to the treated sites is used to account for the compounding factors. First, a safety performance function (SPF) that predicts the mean crash frequency of a site based on its traffic and physical characteristics is estimated using the crash experience and the characteristics of the reference sites. Second, the crash frequency of the treated sites during the before period and a hypothetical crash frequency after the period had a treatment not been implemented are predicted using the estimated SPF. Third, the crash frequency expected at the treated sites in the before period is calculated as the weighted average of observed before-period crash frequency and predicted one. The weight is determined when the SPF was estimated. In this way, the EB before-after study is able to account for the observed changes in crash frequencies before and after a treatment that may be due to regression-to-the-mean, traffic volumes, and time trends. Finally, the expected crash frequency of the treated sites in the after period is calculated by multiplying the expected crash frequency in the before period and a ratio of the predicted after-period crash frequency and predicted before-period crash frequency. Then the CMF is derived by comparing the expected crash frequency in the after period with the observed one.

The EB before-and-after study method has the advantage of accounting for compounding factors such as regression-to-mean, traffic volume, and time trends more accurately. However, this methodology is not without its challenges.

First, the comparability of the reference group might be an issue. While certain observed factors like traffic and physical characteristics can be controlled when selecting the reference sites, there are some other factors that are hard to observe or control. For example, changes in traffic volume caused by the countermeasure itself may affect comparability between the reference sites and the treated sites, leading to inaccurate CMF estimates. To address this issue, it is recommended to perform a comparability test (Hauer, 1997) to check for comparability between the two groups.

Second, obtaining a sufficient sample size can be a challenge in before-after studies as compared to cross-sectional studies. This is because before-after studies require monitoring the implementation of the treatment, while cross-sectional studies do not. A lack of a sufficient sample size can result in an estimated CMF that lacks statistical significance, as evidenced by many of the previous studies reviewed in section 2.2.

Third, it is important to note that spill-over effects may also be present in the before-after study. This occurs when the treatment being implemented affects the comparison group, rendering it no longer truly comparable. The impact of spill-over effects can vary depending on the type of treatment; for example, red-light cameras are more likely to have a higher impact compared to left-turn phasing treatments.

2.3.2 Cross-Sectional Study

Cross-sectional studies examine the crash experience of locations with and without the treatment and then attribute the difference in safety to that treatment. In practice, the cross-sectional analyses are based on multi-variable regression models.

Cross-sectional studies are useful where there are insufficient treatment sites or insufficient data for before-after studies. However, the major issue of the cross-sectional studies is that the comparison is between two distinct groups of sites. Therefore, the observed difference in crash experience can be due to known or unknown factors, other than the treatment of interest. Some known factors can be accounted for in the regression models. But those unknown or known but unmeasurable factors are difficult to account for. Therefore, as long as there are sufficient treatment sites, before-after studies are preferred.

2.3.3 Summary

This section provided an overview of the methods used to develop CMFs for left-turn phasing treatments. After a review of prior studies and guidance from the FHWA, the research team identified two methods as suitable options: the EB before-after study and cross-sectional study. The advantages and disadvantages of each method were briefly outlined. Given the available data and guidelines, the research team preferred to use the EB before-after study but would utilize the cross-sectional study as an alternative if necessary.

3. DATA AND STUDY SITES

3.1 Overview

This chapter covers the data sources, data collection process, and the identification and selection of study sites. The process of selecting the appropriate methodology based on data availability is also discussed. Last, a summary of the identified study sites and descriptive statistics is presented.

3.2 Data Collection

Five datasets are used in the study: 1) crash data; 2) traffic data, namely annual average daily traffic (AADT); 3) roadway characteristics; 4) demographic factors; and 5) information on left-turn phasing.

Detailed records of individual crashes from 2011 to 2019 are obtained from AASHTOWare Safety powered by UDOT's Numetric crash database system. While crash data from 2020 is available, after thorough consideration, they were excluded due to the impact of the COVID-19 pandemic. Since left-turn phasing treatments are targeting left-turn-related crashes, two parameters, namely "Left or U-Turn Involved" indicating the movements of the vehicles, and "Manner of Collision" are used to select the left-turn-related crashes. Rear-end crashes and sideswipe (same direction) crashes are excluded as they are unlikely to be targeted by left-turn phasing treatments. Crashes that occurred within the influence area of the intersection (250 feet from the center of the intersections) are map-matched with the signalized intersections by their geolocations. Then the total number of crashes as well as the number of left-turn-related per intersection per year are calculated.

AADT is used as the exposure measure. AADTs of both major roadways (major AADT) and minor roadways (minor) of the intersection are collected. The data were collected from an "AADT Google map" from UDOT. The map provides the AADT per roadway section and the locations of data-collecting detectors ("AADT stations"). The AADT stations were manually map-matched to the signalized intersections by the research team using geographic information system

(GIS) software. Only intersections with both major and minor AADT data available during the study period were kept.

Roadway characteristics of the intersections were collected manually from Google Street View by the research team. The team collected features of two intersecting roadways, including speed limit, the number of through lanes, the number of left-turn lanes, and the number of right-turn lanes. As Google Street View provides a series of historical images of the intersections, intersections whose geometries were changed significantly (i.e., changing from T-intersections to four-way intersections, adding/reducing lanes, and changing speed limits) were excluded to avoid the impact of the construction.

Demographic data, specifically housing density, was obtained from the 2020 US Census (*2020 Census*, n.d.) to provide some insights into human factors. The housing densities were collected at the block group level. When an intersection falls within a block group, its housing density was matched with that block group. In cases where an intersection is located at the boundary of multiple block groups, the average housing density of those block groups was used.

The final dataset in the study is the left-turn phasing information. As the study's primary objective is to develop CMFs for various left-turn phasing treatments, it is important to have knowledge of both the current and historical left-turn phasing at each intersection. The research team consulted regional signal engineers at UDOT to obtain a comprehensive list of signalized intersections that have undergone changes in left-turn phasing. The collected data was then manually verified by the research team using Google Street View.

3.3 Identifications of Study Sites and Methodology

The first-round selection of study sites is mainly based on the data availability. Figure 2 shows the process. It started with the matching of all signalized intersections in the state of Utah with the AADT stations to exclude those without either major AADT or minor AADT available. Then, the filtered intersections were map-matched with the housing density. Finally, the roadway characteristics of these intersections were manually collected and those with significant geometry changes (as mentioned in section 3.2) were excluded.

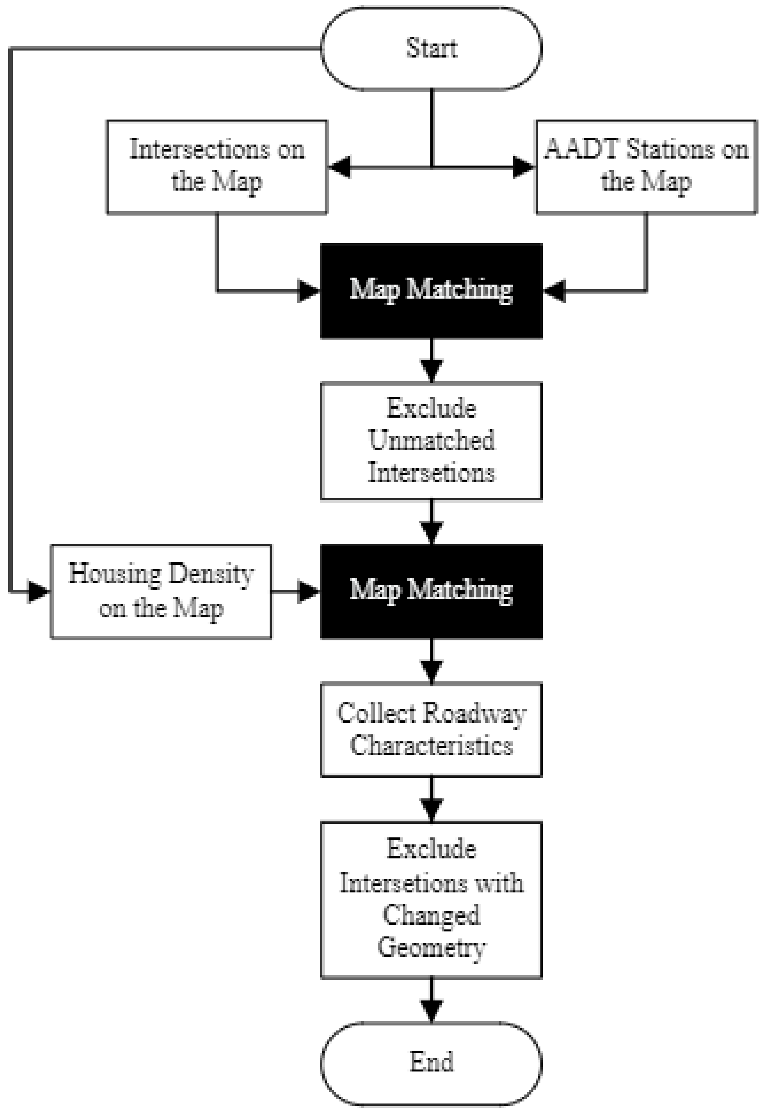


Figure 2 Process of First-Round Study Sites Identification

The second round of selection for study sites was based on the review of the current and historical left-turn phasing at the intersections. Our analysis revealed that conversions of left-turn phasing can occur at either a specific roadway or the entire intersection. For example, when converting the permissive left-turn phasing to the protected left-turn phasing, there are at least three distinct types [3] of conversions: converting both-roadway permissive to one-roadway permissive-protected (and one-roadway permissive), converting one-roadway permissive-

[3] Other conversion types, such as converting both-roadway permissive to one-approach permissive-protected, exist but are rare in the field and their sample sizes are insufficient for developing CMFs, so they were omitted.

protected (and one-roadway permissive) to both-roadway permissive-protected, and converting both-roadway permissive to both-roadway permissive-protected. After consulting with the TAC, we agreed that the safety impacts of these three conversions may vary and should not be consolidated as simply "converting permissive to permissive-protected." As a result, the research team carefully considered and decided to develop CMFs for the following conversions:

1. converting both-roadway permissive left-turn phasing to one-roadway permissive-protected (and one-roadway permissive) left-turn phasing;
2. converting one-roadway permissive-protected (and one-roadway permissive) left-turn phasing to both-roadway permissive-protected left-turn phasing;
3. converting both-roadway permissive-protected left-turn phasing to one-roadway protected (and one-roadway permissive-protected) left-turn phasing;
4. converting one-roadway protected (and one-roadway permissive-protected) left-turn phasing to both-roadway protected left-turn phasing;

It's important to note that while other types of left-turn phasing conversions exist, such as from both-roadway permissive to both-roadway permissive-protected or even from both-roadway permissive to one-roadway protected, we have limited our CMF development to the previously mentioned conversions. This reflects a gradual change toward a more protected left-turn phasing.

In addition, the CMF for converting from "doghouse" to FYA permissive-protected left-turn phasing was already estimated in a previous study (Medina et al., 2018) for Utah intersections, thus, this type of treatment is omitted in this study. Furthermore, three-way intersections were not considered in this study due to the difficulty in defining "one-roadway" and "both-roadway" for these types of intersections.

Table 7 illustrates the number of intersections that underwent the four types of left-turn phasing treatments and have available data. The major challenge is the availability of traffic data. Despite there being more intersections that underwent the treatments during the study period, the minor AADT data is missing for the majority of these intersections. And even for the intersections with minor AADT data available, the data are available only since 2017. As a result, the sample size of treatment sites is insufficient to conduct a before-after study. Although the before-after study is preferred according to the literature review, due to the limited data availability, the cross-sectional study is used.

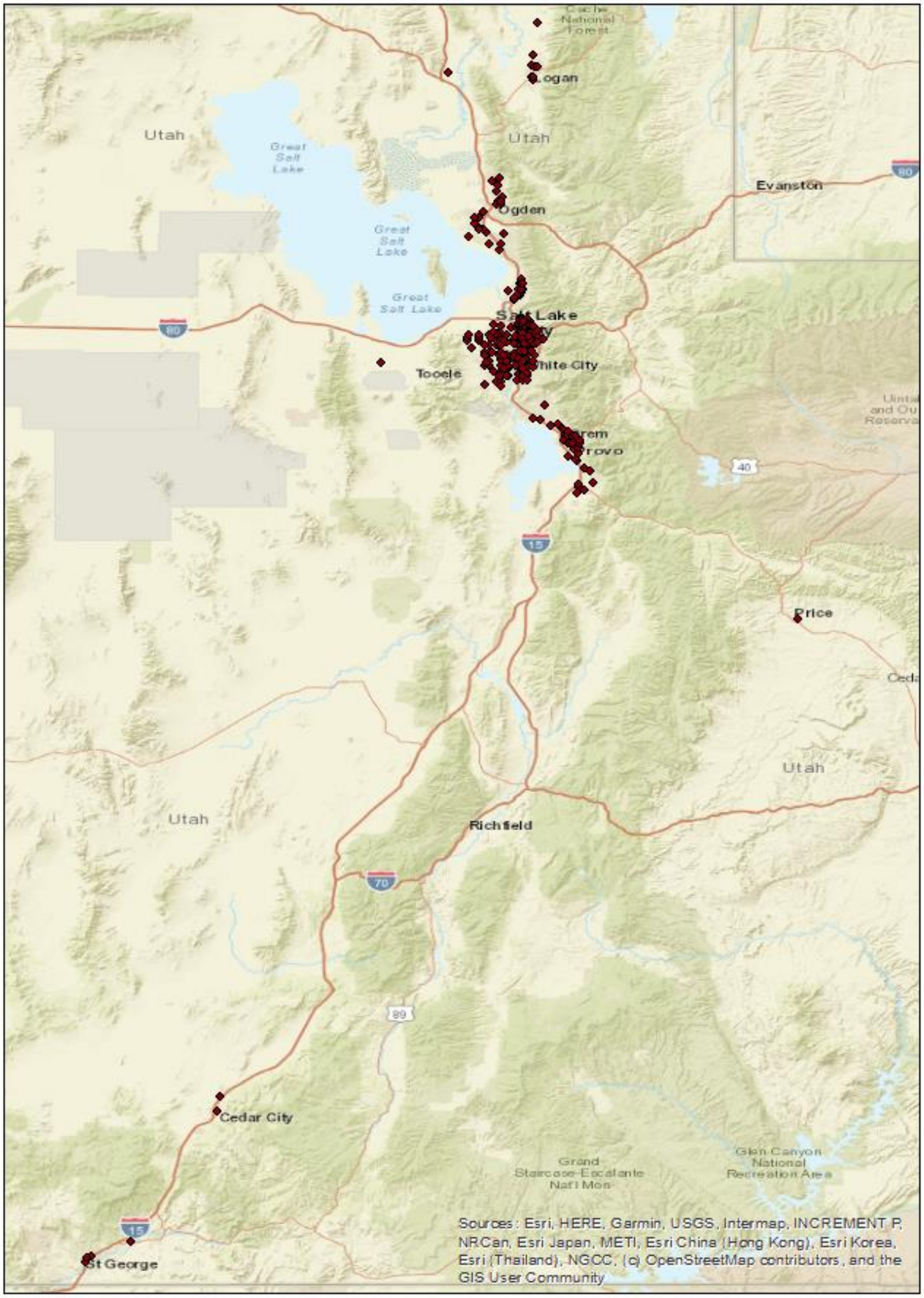
Table 7 Number of Intersections Underwent Treatments with Data Available

Treatment	Number
Both-Roadway Permissive to One-Roadway Permissive-Protected	2
One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected	2
Both-Roadway Permissive-Protected to One-Roadway Protected	0
One-Roadway Protected to Both-Roadway Protected	0

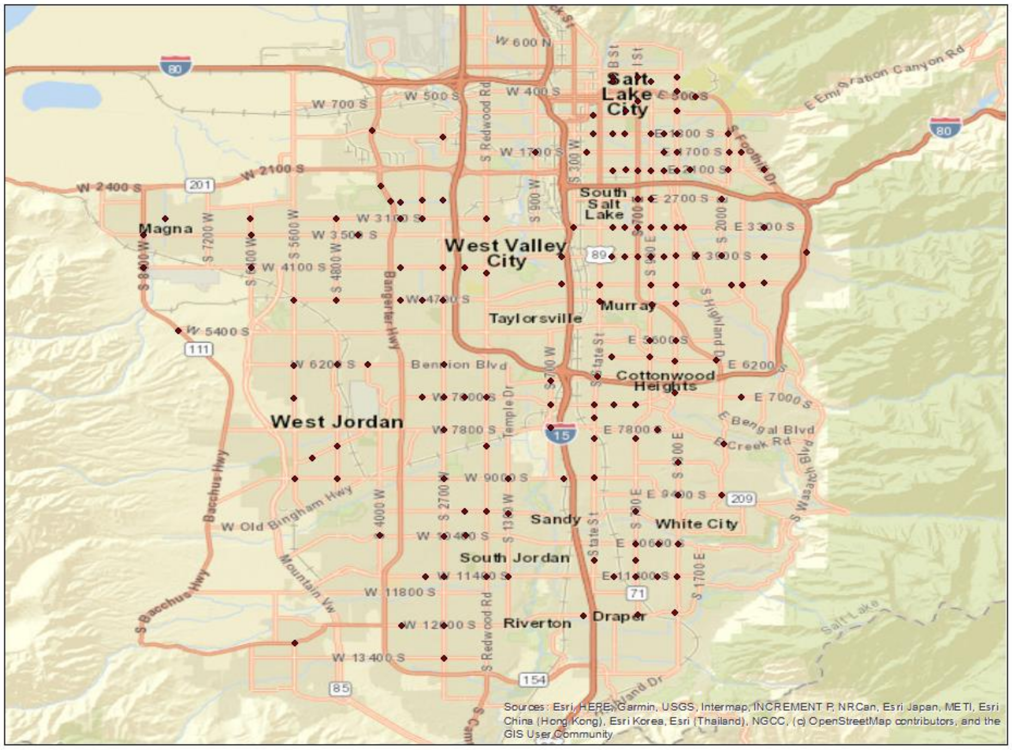
Table 8 shows the final number of sites selected as study sites in Utah for the cross-sectional study. The total number of intersections selected is 256. The study was limited to the years from 2017 to 2019 due to the limited availability of minor AADT data. The locations of these 256 intersections are shown in Figure 3.

Table 8 Number of Study Sites

Left-Turn Phasing	Number
Both-Roadway Permissive	89
One-Roadway Permissive-Protected	33
Both-Roadway Permissive-Protected	90
One-Roadway Protected	23
Both-Roadway Protected	21
Total	256



(a) Whole State



(b) Salt Lake County

(c) Utah County

(d) Davis County and Weber County

Figure 3 Study Sites

3.4 Summary

In this chapter, the data collection process, study site selection, and methodology identification were discussed. The data collected included crash data, AADT, roadway characteristics (speed limits and number of lanes), housing density, and left-turn phasing information. Table 8 summarizes the variables that will be utilized in the development of the CMFs.

Table 9 Variable Description

Name	Description
Total Crash	Average total number of crashes occurred annually during the study period (dependent)
Left Crash	Average number of left-turn-related-crashes occurred annually during the study period (dependent)
Major AADT	AADT of the major roadway
Major Through Lanes	Number of through lanes of the major roadway
Major Left Lanes	Number of left-turn lanes of the major roadway
Major Right Lanes	Number of right-turn lanes of the major roadway
Major Speed Limit	Posted speed limit of the major roadway
Minor AADT	AADT of the minor roadway
Minor Through Lanes	Number of through lanes of the minor roadway
Minor Left Lanes	Number of left-turn lanes of the minor roadway
Minor Right Lanes	Number of right-turn lanes of the minor roadway
Minor Speed Limit	Posted speed limit of the minor roadway
Housing Density	Housing units per square miles
Treatment	Treatment indicator. The value is assigned to 1 for treatment sites and 0 for comparison sites.

Due to the constraints of data availability, a cross-sectional study approach was adopted, using 256 signalized intersections in Utah as the study sites. Table 10 presents the descriptive statistics of the variables, including crash data, AADT, roadway characteristics, housing density, and left-turn phasing, that will be used in the calculation of the CMFs.

Table 10 Descriptive Statistics

Name	Left-Turn	Statistics			
		Mean	S.D.	Min	Max
Total Crash	Both Permissive	5.89	4.63	0.33	21.00
	One Permissive-Protected	8.11	5.77	1.67	26.33
	Both Permissive-Protected	14.30	7.94	2.33	38.00

Name	Left-Turn	Statistics			
		Mean	S.D.	Min	Max
	One Protected	20.86	12.47	7.00	52.00
	Both Protected	22.97	13.00	8.67	61.33
Left Crash	Both Permissive	1.40	1.33	0.00	6.00
	One Permissive-Protected	2.56	1.82	0.00	8.67
	Both Permissive-Protected	4.68	3.57	0.00	17.00
	One Protected	5.70	4.50	1.00	16.67
	Both Protected	2.95	2.49	0.67	12.33
Major AADT	Both Permissive	17533.33	10267.36	3700.00	51333.33
	One Permissive-Protected	20896.97	9568.57	6266.67	41333.33
	Both Permissive-Protected	25364.81	9760.09	8633.33	53000.00
	One Protected	36097.10	12189.48	7900.00	58000.00
	Both Protected	34809.52	8787.98	17666.67	48333.33
Major Through Lanes	Both Permissive	1.54	0.60	1.00	3.00
	One Permissive-Protected	1.82	0.68	1.00	3.00
	Both Permissive-Protected	1.84	0.60	1.00	3.00
	One Protected	2.61	0.78	1.00	4.00
	Both Protected	2.52	0.60	1.00	3.00
Major Left Lanes	Both Permissive	0.98	0.15	0.00	1.00
	One Permissive-Protected	1.00	0.00	1.00	1.00
	Both Permissive-Protected	1.00	0.00	1.00	1.00
	One Protected	1.26	0.45	1.00	2.00
	Both Protected	1.81	0.40	1.00	2.00
Major Right Lanes	Both Permissive	0.52	0.50	0.00	1.00
	One Permissive-Protected	0.70	0.47	0.00	1.00
	Both Permissive-Protected	0.82	0.41	0.00	2.00
	One Protected	0.65	0.49	0.00	1.00
	Both Protected	0.81	0.40	0.00	1.00
Major Speed Limit	Both Permissive	36.57	7.93	25.00	60.00
	One Permissive-Protected	39.39	6.93	30.00	60.00
	Both Permissive-Protected	38.17	5.27	25.00	55.00
	One Protected	39.57	5.82	25.00	50.00
	Both Protected	43.10	5.12	35.00	55.00
Minor AADT	Both Permissive	5225.36	3930.58	120.00	16333.33
	One Permissive-Protected	5257.47	3826.41	430.00	13666.67
	Both Permissive-Protected	11143.48	5294.10	500.00	25333.33
	One Protected	15575.36	8716.43	1033.33	40000.00
	Both Protected	17041.27	10147.66	1033.33	36333.33
Minor Through Lanes	Both Permissive	1.10	0.34	1.00	3.00
	One Permissive-Protected	1.12	0.33	1.00	2.00
	Both Permissive-Protected	1.20	0.40	1.00	2.00
	One Protected	1.52	0.51	1.00	2.00
	Both Protected	2.00	0.63	1.00	3.00
Minor Left Lanes	Both Permissive	0.94	0.23	0.00	1.00
	One Permissive-Protected	1.00	0.00	1.00	1.00
	Both Permissive-Protected	1.00	0.00	1.00	1.00

Name	Left-Turn	Statistics			
		Mean	S.D.	Min	Max
	One Protected	1.43	0.51	1.00	2.00
	Both Protected	1.86	0.36	1.00	2.00
Minor Right Lanes	Both Permissive	0.49	0.50	0.00	1.00
	One Permissive-Protected	0.58	0.50	0.00	1.00
	Both Permissive-Protected	0.82	0.38	0.00	1.00
	One Protected	0.87	0.46	0.00	2.00
	Both Protected	0.86	0.36	0.00	1.00
Minor Speed Limit	Both Permissive	30.62	6.52	20.00	55.00
	One Permissive-Protected	31.52	5.37	25.00	40.00
	Both Permissive-Protected	33.56	4.99	25.00	45.00
	One Protected	34.13	5.36	25.00	45.00
	Both Protected	38.57	5.51	30.00	55.00
Housing Density	Both Permissive	2.23	2.00	0.00	9.90
	One Permissive-Protected	1.73	1.07	0.03	6.07
	Both Permissive-Protected	1.91	1.20	0.08	7.18
	One Protected	1.87	0.88	0.35	3.64
	Both Protected	1.33	1.14	0.08	3.71

4. CMF DEVELOPMENT

4.1 Overview

This chapter first introduces the methodology for the development of CMFs. The SPF estimates and CMFs for four distinct left-turn phasing treatments are then presented. Subsequently, the potential issues and possible solutions are discussed based on the results of the CMF development. Last, a comprehensive summary of the CMFs is given.

4.2 Methodology

This study adopted the cross-sectional design to develop CMFs. The cross-sectional design compares the crash experience of locations with and without a certain treatment and then attributes any differences in safety to that treatment. In this study, for example, when estimating the CMF of converting both-roadway permissive left-turn phasing to one-roadway permissive-protected left-turn phasing, the intersections whose left-turn phasing is one-roadway permissive-protected are utilized as the treatment sites and the dummy variable "treatment" is assigned to be 1; the intersections whose left-turn phasing are both-roadway permissive are utilized as the comparison sites, and the dummy variable "treatment" is assigned to be 0. Intersections with other types of left-turning phasing will not be used in the modeling.

As the cross-sectional analyses are based on multi-variable regression models, in other words, SPFs, this study adopts the widely used Negative Binomial (NB) model to estimate SPFs. An NB modal can be specified as follows:

$$\lambda_i = \exp(\boldsymbol{\beta X_i} + \varepsilon_i) \tag{1}$$

$$P(y_i) = \frac{\Gamma\left(y_i + \frac{1}{\alpha}\right)}{\Gamma(y_i + 1)\Gamma\left(\frac{1}{\alpha}\right)} \left(\frac{\frac{1}{\alpha}}{\frac{1}{\alpha} + \lambda_i}\right)^{\frac{1}{\alpha}} \left(\frac{\lambda_i}{\frac{1}{\alpha} + \lambda_i}\right)^{y_i} \tag{2}$$

where $P(y_i)$ is the probability of intersection i having y_i crashes in a given year and $\Gamma(\cdot)$ is the gamma function; λ_i is the Poisson parameter which is the expected number of crashes in the given time period; $\boldsymbol{X_i}$ is a set of explanatory variables; $\boldsymbol{\beta}$ is the corresponding coefficient set; ε_i is the error term and $\exp(\varepsilon_i)$ is gamma-distributed with mean 1 and variance α. Akaike Information Criterion (AIC) is used as the goodness-of-fit measures.

CMFs are then estimated by:

$$CMF_t = \exp(\beta_t) \tag{3}$$

where CMF_t is the CMF of the treatment; and β_t is the coefficient of the dummy treatment variable.

4.3 Converting Both-Roadway Permissive Left-Turn Phasing to One-Roadway Permissive-Protected Left-Turn Phasing

Table 11 presents the results of the SPF estimation for total crash frequency. Only variables that are statistically significant at a 0.05 level are included in the model, excluding the treatment indicator. The results reveal that the treatment indicator is not statistically significant, indicating that the conversion from both-roadway permissive to one-roadway permissive-protected left-turn phasing has no statistically significant impact on safety. To avoid confusion, the point estimates for the CMF of this conversion are not presented.

Table 11 Estimates of SPF for Total Crash Frequency of Converting Both-Roadway Permissive to One-Roadway Permissive-Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-4.6984	0.7961	-5.902	<0.0001
Ln (Major AADT)**	0.5294	0.0823	6.434	<0.0001
Ln (Minor AADT)*	-0.0783	0.0316	-2.474	0.0134
Major Through Lanes**	0.3988	0.0777	5.131	<0.0001
Major Right-Turn Lanes*	0.1560	0.0793	1.966	0.0493
Major Speed Limit**	-0.0172	0.0059	-2.914	0.0035
Minor Right-Turn Lanes*	-0.1694	0.0766	-2.211	0.0270
Minor Speed Limit**	0.0618	0.0066	9.356	<0.0001
Treatment	0.1280	0.0787	1.626	0.1040
Sample Size	366 (122×3)			
AIC	1940.7			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Although there are no previous studies estimating roadway-based CMFs, the CMFs of converting permissive left-turn phasing to permissive-protected can serve as references. Most of the studies reviewed (Chen et al., 2015; Davis & Aul, 2007; Simpson & Troy, 2015; Srinivasan et al., 2008) also found that the conversion is statistically insignificant for total crash frequencies.

Table 12 shows the estimates of SPF for the left-turn-related crash frequency. The treatment indicator is statistically significant and has a positive sign, which indicates that the treatment increased the total crash frequency. The point estimate of the CMF of left-turn-related crashes for converting both-roadway permissive to one-roadway permissive-protected is 1.4161, indicating the left-turn-related crash frequency increased by 41.61%.

Table 12 Estimates of SPF for Left-Turn-Related Crash Frequency of Converting Both-Roadway Permissive to One-Roadway Permissive-Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-8.3764	1.2100	-6.923	<0.0001
Ln (Major AADT)**	0.6670	0.1263	5.283	<0.0001
Major Through Lanes**	0.3933	0.1069	3.681	0.0002
Major Speed Limit*	-0.0218	0.0087	-2.493	0.0127
Minor Left-Turn Lanes*	0.9011	0.3664	2.459	0.0139
Minor Right-Turn Lanes **	-0.2917	0.1106	-2.637	0.0084
Minor Speed Limit **	0.0623	0.0094	6.604	<0.0001
Housing Density**	-0.1516	0.0434	-3.497	0.0005
Treatment**	0.3479	0.1075	3.236	0.0012
Sample Size	366 (122×3)			
AIC	1179.7			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Although this higher CMF is not typically reported in earlier studies, a study conducted in Utah (Medina et al., 2018) also found that the CMF of left-turn-related crashes is higher than 1, although statistically insignificant. There could be several reasons for the increased crash frequency. The first reason is that UDOT operations in Utah may be different from other states, leading to different CMFs. Second, the lack of available data on left-turning volumes, which should serve as the exposure measure of left-turn-related crashes, may lead to a confounding effect in the treatment indicator, which may implicitly account for the higher left-turning volumes at intersections with one-roadway permissive-protected phasing. A more detailed discussion will be provided in section 4.7. Third, the limitations inherent in cross-sectional studies may also have contributed to the findings.

4.4 Converting One-Roadway Permissive-Protected Left-Turn Phasing to Both-Roadway Permissive-Protected Left-Turn Phasing

Table 13 shows the estimates of SPF for the total crash frequency. The treatment indicator, which represents the conversion from one-roadway permissive to both-roadway permissive-protected, is statistically significant and has a positive coefficient, indicating that the treatment led to an increase in the total crash frequency. The point estimate of the CMF for total crashes is 1.3296, meaning that the frequency of total crashes rose by 32.96% after the treatment.

Table 13 Estimates of SPF for Total Crash Frequency of Converting One-Roadway to Both-Roadway Permissive-Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-5.1571	0.8000	-6.446	<0.0001
Ln (Major AADT)**	0.3703	0.0848	4.367	<0.0001
Ln (Minor AADT)**	0.1496	0.0354	4.228	<0.0001
Major Through Lanes**	0.1887	0.0561	3.363	0.0008
Major Speed Limit**	0.0199	0.0052	3.800	0.0001
Minor Speed Limit**	0.0374	0.0058	6.405	<0.0001
Treatment**	0.2849	0.0729	3.910	<0.0001
Sample Size	369 (123×3)			
AIC	2323.5			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

The results of the SPF estimation for the left-turn-related crash frequency, presented in Table 14, indicate that converting one-roadway permissive to both-roadway permissive-protected has led to a statistically significant increase in left-turn-related crashes. The point estimate of the CMF is 1.2880, meaning that the frequency of such crashes has risen by 28.80%.

Table 14 Estimates of SPF for Left-Turn-Related Crash Frequency of Converting One-Roadway to Both-Roadway Permissive-Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-7.9647	1.1579	-6.878	<0.0001
Ln (Major AADT)**	0.4666	0.1238	3.770	0.0002
Ln (Minor AADT)**	0.1721	0.0527	3.262	0.0011
Major Through Lanes**	0.3251	0.0793	4.100	<0.0001
Major Speed Limit**	0.0237	0.0077	3.102	0.0019
Minor Through Lanes*	0.9011	0.3664	2.459	0.0139
Minor Speed Limit**	0.0363	0.0085	4.293	<0.0001
Housing Density**	-0.1023	0.0361	-2.832	0.0046
Treatment*	0.2532	0.1029	2.460	0.0139
Sample Size	369 (123×3)			
AIC	1669.8			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Again, there are no previous studies estimating roadway-based CMFs. But it is not appropriate to use the CMFs of converting permissive left-turn phasing to permissive-protected as references, as the comparison sites in this study (one-roadway permissive-protected) are fundamentally different from those in previous studies (both-roadway permissive). The higher CMFs for both total and left-turn-related crashes may be attributed to unique operations by UDOT, failure to account for left-turning volumes, and the limitations of the cross-sectional design.

4.5 Converting Both-Roadway Permissive-Protected Left-Turn Phasing to One-Roadway Protected Left-Turn Phasing

Table 15 shows the SPF estimates for the total crash frequency. The treatment indicator was found to be statistically insignificant, suggesting that the treatment did not have a statistically significant impact on safety. As a result, the CMF for the conversion of both-roadway permissive-protected to one-roadway protected is also considered statistically insignificant, and therefore, the specific point estimate is not presented to avoid any confusion.

Table 15 Estimates of SPF for Total Crash Frequency of Converting Both-Roadway Permissive-Protected to One-Roadway Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-6.1962	0.7682	-8.066	<0.0001
Ln (Major AADT)**	0.5622	0.0716	7.851	<0.0001
Ln (Minor AADT)**	0.1177	0.0435	2.705	0.0068
Major Speed Limit**	0.0215	0.0054	3.962	<0.0001
Minor Through Lanes**	0.2202	0.0691	3.188	0.0014
Minor Speed Limit**	0.0324	0.0062	5.187	<0.0001
Housing Density**	-0.0660	0.0254	-2.596	0.0094
Treatment	0.0315	0.0712	0.442	0.6587
Sample Size	339 (113×3)			
AIC	2260.5			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table 16 presents the estimates of SPF for frequency of the left-turn-related crash. The treatment indicator is statistically significant and has a negative sign, implying that the treatment resulted in a reduction of crash frequency. The CMF of converting both-roadway permissive-protected to one-roadway permissive-protected was estimated to be 0.7329, meaning that the frequency of left-turn-related crashes decreased by 26.71%.

Table 16 Estimates of SPF for Left-Turn-Related Crash Frequency of Converting Both-Roadway Permissive-Protected to One-Roadway Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-11.3974	1.1857	-9.612	<0.0001
Ln (Major AADT)**	0.8381	0.1079	7.771	<0.0001
Ln (Minor AADT)*	0.1521	0.0651	2.338	0.0194
Major Speed Limit**	0.0357	0.0078	4.549	<0.0001
Minor Through Lanes**	0.3368	0.0934	3.606	0.0003
Minor Speed Limit **	0.0443	0.0088	5.037	<0.0001
Housing Density**	-0.1552	0.0371	-4.178	<0.0001
Treatment**	-0.3107	0.1013	-3.066	0.0022
Sample Size	339 (113×3)			
AIC	1631.4			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

The CMFs from previous studies of converting permissive-protected left-turn phasing to protected can provide references. Most of the studies reviewed (Davis & Aul, 2007; Srinivasan et al., 2008) also found that the conversion is statistically insignificant for total crash frequencies, and the CMF of left-turn-related crashes are less than 1 (Asaduzzaman et al., 2021; Davis & Aul, 2007; Srinivasan et al., 2008), which are similar to what we found in this study.

4.6 Converting One-Roadway Protected to Both-Roadway Left-Turn Phasing to Protected Left-Turn Phasing

Table 17 shows the SPF estimates for total crash frequency. The treatment indicator is not statistically significant, suggesting that the conversion has no significant effect on safety. As a result, the CMF of converting one-roadway protected to both-roadway protected is considered statistically insignificant, and the point estimate is omitted to avoid confusion.

Table 17 Estimates of SPF for Total Crash Frequency of Converting One-Roadway Protected to Both-Roadway Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-4.3408	1.3798	-3.146	0.0017
Ln (Major AADT)**	0.5076	0.1413	3.592	0.0003
Ln (Minor AADT)**	0.2531	0.0588	4.304	<0.0001
Minor Left-Turn Lanes*	-0.2354	0.1054	-2.232	0.0256
Treatment	0.1614	0.0989	1.631	0.1028
Sample Size	132 (44×3)			
AIC	986.03			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table 18 presents the results of the SPF estimation for left-turn-related crash frequency. The treatment indicator is statistically significant and has a negative sign, indicating that the treatment can lead to a reduction in crash frequency. The point estimate of the CMF for converting both-roadway permissive to one-roadway permissive-protected is 0.5051, meaning the left-turn-related crash frequency decreased by 49.49%.

Table 18 Estimates of SPF for Left-Turn-Related Crash Frequency of Converting One-Roadway Protected to Both-Roadway Protected

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-7.4160	2.2387	-3.313	0.0009
Ln (Major AADT)*	0.5358	0.2275	2.355	0.0185
Ln (Minor AADT)**	0.3714	0.1000	3.715	0.0002
Treatment**	-0.6830	0.1417	-4.822	<0.0001
Sample Size	132 (44×3)			
AIC	639.23			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

The estimated CMFs exhibit a similar trend to those found in the conversion from both-roadway permissive to one-roadway permissive-protected. Additionally, converting one-roadway to both-roadway protected has the potential to further reduce the frequency of left-turn-related crashes.

4.7 Discussion

4.7.1 Unavailable Left-Turn Volume

The lack of left-turn volume data during the study period (2017-2019) is a limitation. Left-turn volume is a crucial factor in determining crash exposure for left-turn phasing treatments, especially for left-turn-related crashes. In practice, the high cross-product of left-turn volume and conflicting through volume is often used as a warrant for implementing more protected left-turn phasing. Even if the AADT is similar between two intersections, the intersection with a more protected left-turn phasing (e.g., permissive-protected) is likely to have higher left-turn volume than the intersection with a less protected phasing (e.g., permissive). Therefore, if the left-turn volume is not explicitly modeled in the SPF, the treatment indicator (representing a more protected left-turn phasing) could overestimate the safety impact due to the implicit inclusion of the higher left-turn volume (exposure). This could result in an overestimation of the CMFs.

In an effort to address the issue of overestimation, the research team included a current-year (2022) left-turn ratio in the SPF estimations as a proxy for treatment-year left-turn volumes.

The left-turn ratio is calculated as the ratio of left-turning volume to total volume and can be defined as:

$$\alpha_{LT} = \frac{q_{LT}}{q_{LT} + q_T + q_{RT}} \tag{4}$$

where α_{LT} is the left-turn ratio of the roadway; q_{LT}, q_T, and q_{RT} are the volumes of left-turn, through, and right-turn, respectively.

The current-year left-turn ratios were estimated from the turning movement counts obtained through the Automated Traffic Signal Performance Metrics. They were estimated based on the left-turning volume and total volume of four typical Wednesdays across the four seasons. However, the turning movement counts were not available for all study sites, as seen in Table 19 which shows the reduction in sample size caused by the inclusion of the left-turn ratios.

Table 19 Reduction in Sample Size Due to the Inclusion of Left-Turn Ratios

Left-Turn Treatment	Original	With Left-Turn Ratio	Reduction
Both-Roadway Permissive	89	21	-76%
One-Roadway Permissive-Protected	33	17	-48%
Both-Roadway Permissive-Protected	90	56	-38%
One-Roadway Protected	23	21	-9%
Both-Roadway Protected	21	14	-33%
Total	256	185	-28%

Table 20 summarizes the statistical significance of including the current-year left-turn ratios in the calculation of eight SPFs. The estimated SPFs can be found in the appendix (Tables A1-A3). Only three out of eight SPFs showed statistical significance for the left-turn ratios. The inclusion of the ratios resulted in a reduction of sample size and caused two CMFs for left-turn crashes to change from being statistically significant to insignificant. The limited availability of current-year left-turn ratios and the potential for inaccurate estimates of previous year's volumes make them unsuitable for use in estimating SPFs. Therefore, they should not be employed in the estimations of the SPFs.

Table 20 Statistical Significance of Left-Turn Ratios

Conversion	Crash Type	Significance of Factors	Significance of Conversion
Both-Roadway Permissive to One-Roadway Permissive-Protected	Total Crash	Insignificant	N/A
	Left-Turn Crash	Significant	Insignificant
One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected	Total Crash	Insignificant	N/A
	Left-Turn Crash	Insignificant	N/A
Both-Roadway Permissive-Protected to One-Roadway Protected	Total Crash	Insignificant	N/A
	Left-Turn Crash	Insignificant	N/A
One-Roadway Protected to Both-Roadway Protected	Total Crash	Significant	Significant
	Left-Turn Crash	Significant	Insignificant

4.7.2 Inclusion of Housing Density

One TAC member asked to check the benefits of including demographic factors, i.e., housing density, due to the additional data collection efforts. The results in Table 21 show that demographic factors are statistically significant for only four SPFs out of eight. If demographic information is not available, the estimated CMFs are still considered acceptable, although they may be slightly overestimated without these factors.

Table 21 Differences in CMFs Caused by the Inclusion of Housing Density

Treatment	Crash Type	CMF	
		With HD	W/o HD
Both-Roadway Permissive to One-Roadway Permissive-Protected	Left-Turn Crash	1.4161	1.4695
One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected	Left-Turn Crash	1.2880	1.2901
Both-Roadway Permissive-Protected to One-Roadway Protected	Total Crash	Insignificant	Insignificant
	Left-Turn Crash	0.7329	0.7772

4.7.3 Other Limitations and Further Direction

Due to the data availability, the study adopted the cross-sectional design. However, since the study sites have not undergone the treatments, the observed difference in crash frequency can be due to factors other than the treatments. There may be unknown or unmeasured factors that were not taken into account. This could lead to inaccurate estimations of the CMFs.

As mentioned earlier, the discrepancy in CMFs estimated for Utah intersections compared to other localities may be attributed to the varying operations of traffic agencies. To verify this, the next step is to conduct a survey of practices among other states to determine if UDOT operations result in these differences in CMFs

4.8 Summary

In this chapter, the CMFs for four different left-turn phasing treatments were determined. Table 22 summarizes the findings. In general, the conversion from permissive to permissive-protected left-turn signals showed no improvement in safety. However, converting permissive-protected signals to protected signals did result in a reduction of left-turn-related crashes. The most effective way to improve safety in terms of reducing the frequency of left-turn-related crashes was found to be the implementation of protected left-turn phasing for both intersecting roadways.

Table 22 CMFs of Different Left-Turning Treatments

Treatment	Crash Type	CMF
Both-Roadway Permissive to One-Roadway Permissive-Protected	Total Crash	Insignificant
	Left-Turn Crash	1.4161
One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected	Total Crash	1.3296
	Left-Turn Crash	1.2880
Both-Roadway Permissive-Protected to One-Roadway Protected	Total Crash	Insignificant
	Left-Turn Crash	0.7329
One-Roadway Protected to Both-Roadway Protected	Total Crash	Insignificant
	Left-Turn Crash	0.5051

5. CMF COMPARISION

5.1 Introduction

In Chapter 4, the team found differences in the CMFs for permissive-protected left-turn phasing at Utah intersections compared to similar treatments in other localities. To better understand the impact of the operating permissive-protected left-turn phasing on safety performance, the research team collaborated with UDOT to conduct a survey of state transportation agencies. This chapter provides details on the design, procedure, and results of the survey, followed by a comparison of the CMFs and operating approaches.

5.2 Survey

5.2.1 Design and Procedure

The survey aims at understanding the current practice of state transportation agencies in the operations of permissive-protected left-turn signal phasing. Three aspects are of the research team's interest, the use of left-turn-related detectors, the green time of left-turn phasing, and the time-of-day (TOD) timings. Six questions were asked:

1. For protected-permissive left-turn phasing, where are the left-turn detectors placed? Stop line, advance, or both? (*Detector*)
2. If advance detectors are used, how far back are they placed from the stop bar? (*Detector*)
3. Typically, how are the minimum green times of the protected portion of the phase determined? Is there a typical or average minimum green time? (*Left-Turn Green Time*)
4. Typically, what extension time is used to extend the protected portions of the phase if the minimum green time is not sufficient to clear the queue? (*Left-Turn Green Time*)
5. What is a typical or average maximum green time for the protected portion of the phase? (*Left-Turn Green Time*)

6. Are there any protected-permissive signals running in a Time-of-Day (TOD) manner (namely, running during specific periods of the day and turned off during other times)? If yes, can you give a brief description of how they are operating? (*TOD*)

The survey was created using Google Forms and was distributed by UDOT through the Research Advisory Committee of the American Association of State Highway and Transportation Officials. The survey period ran from December 2022 to January 2023, during which 26 state transportation agencies, including UDOT, responded. The agencies that participated in the survey are:

- Alaska Department of Transportation and Public Facilities
- Arkansas Department of Transportation
- Colorado Department of Transportation
- Georgia Department of Transportation
- Idaho Transportation Department
- Illinois Department of Transportation
- Indiana Department of Transportation
- Kentucky Transportation Cabinet
- Louisiana Department of Transportation and Development
- Massachusetts Department of Transportation
- Minnesota Department of Transportation
- Mississippi Department of Transportation
- Nebraska Department of Transportation
- New Hampshire Department of Transportation
- North Carolina Department of Transportation
- Oklahoma Department of Transportation
- Pennsylvania Department of Transportation
- Rhode Island Department of Transportation
- South Carolina Department of Transportation
- South Dakota Department of Transportation
- Texas Department of Transportation

- Ohio Department of Transportation
- Utah Department of Transportation
- Vermont Agency of Transportation
- Virginia Department of Transportation
- Washington State Department of Transportation.

5.2.2 Results

All transportation agencies use stop-line detectors for left-turn signals, however, only some of them use advanced detectors. Figure 1 illustrates the usage of advanced detectors among state transportation agencies, with "optional" indicating that they are used in only some intersections. Full responses to the survey can be found in the Appendix.

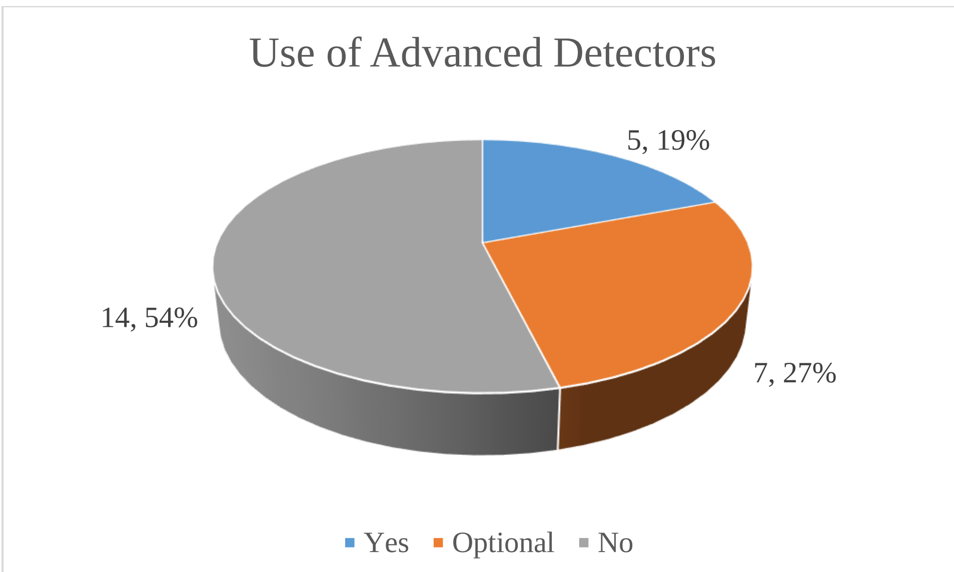


Figure 4 The Usage of Advanced Detectors

Among the state transportation agencies that use advanced detectors, most have them placed 50 feet from the stop line. However, the distance can vary, with some placing them as close as 20 feet (Minnesota) and others as far as 104 feet (Idaho).

Most state transportation agencies determine the green times using signal timing manuals and state-specific guidelines/manuals. For the minimum green time of the protected portion of the permissive-protected phase, the average across the states that provided a numerical value is six seconds. Figure 2 provides a distribution across the states.

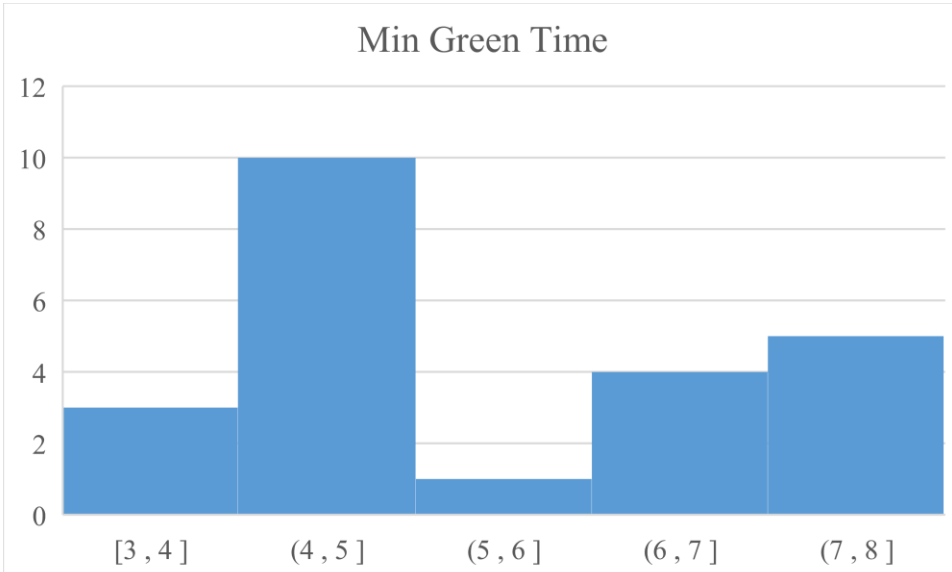


Figure 5 Minimum Green Time of the Protected Portion

The majority of state transportation agencies that provided a numerical value for green extension use an average of two to three seconds. However, they also mentioned that the length can vary by local areas. One interesting remark made by Ohio Department of Transportation states that the length also varies by the detector type: "For Wavetronix radar, we tend to keep the extension very short 0.5-1 second because the product holds the call in the controller. For loops, we keep it around 3-4 seconds."

The maximum green time for the protected portion of the permissive-protected phase varies greatly among the states and highly depends on the local traffic conditions. The research team was unable to derive a meaningful numerical value (e.g., mean) for the maximum green time. For more information, readers are encouraged to refer to the raw responses in the appendix.

As for the TOD operations, the research team would like to clarify that the term TOD in this survey refers to the operation of a protected-permissive signal during specific periods of the day. It does not indicate whether a state transportation agency uses time-of-day signal timing plans. For instance, a signal operating as protected during some times and permissive-protected during others would be considered as operating in a time-of-day manner.

As shown in Figure 3, the majority of state transportation agencies surveyed operate the permissive-protected left-turn signal phasing in a time-of-day (TOD) manner to some extent. While some states operate the signals as protected and permissive-protected (e.g., Colorado, Mississippi, Pennsylvania, and Virginia), others operate as permissive and permissive-protected (e.g., Nebraska and South Dakota), and some operate as permissive, permissive-protected, and protected. However, some states noted that driver expectancy is a critical factor when considering TOD operations.

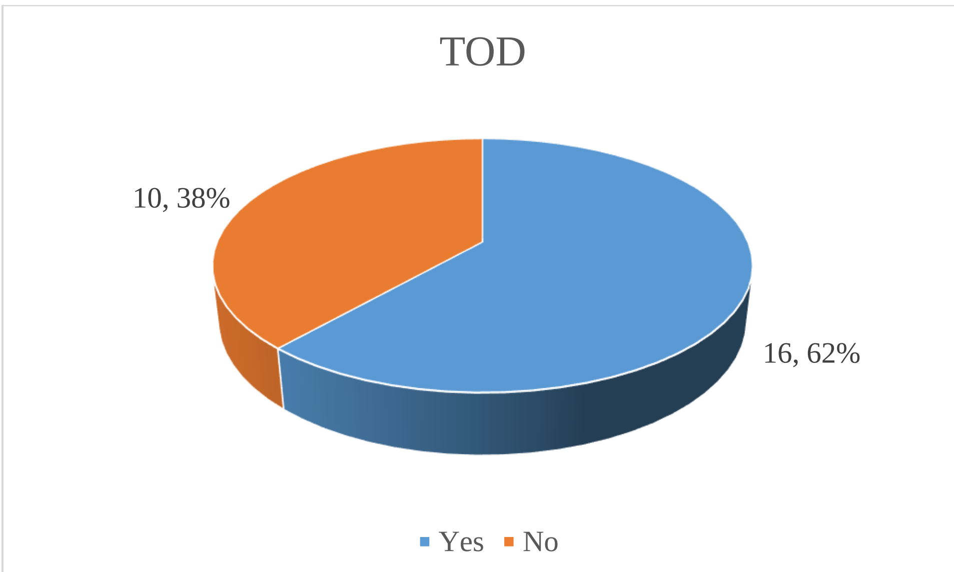


Figure 6 Whether a State Transportation Agency Operates the Permissive-Protected Left-Turn Phasing in TOD Manner

5.3 Comparison

The CMFs are not available for all states surveyed. According to section 2.2, the CMFs of converting permissive left-turn phasing to permissive-protected left-turn phasing are available only for two states, namely Minnesota and North Carolina. Table 23 summarizes the operation approaches of the aforementioned two states and the state of Utah as well as the reference CMFs.

For Minnesota, although the advanced detectors are used, they are placed as far as 35 feet from the stop line, which is closer than those used in Utah. As advanced detectors are typically used to detect the queue and extend the green time of the protected portion of the permissive-protected left-turn phase, closer advanced detectors are able to extend the green time when there is a shorter queue, which can lead to a longer protected portion. Nevertheless, the typical green extension used by the Minnesota Department of Transportation (MnDOT) is longer than that used by UDOT. Therefore, on average, the protected portion of the permissive-protected left-turn phase in Minnesota is likely to be longer than that in Utah.

Table 23 CMFs of Different Left-Turning Treatments

State	Advanced Detector		Green Time		TOD	CMF#
	Existence	Location	Min	Extension		
MN	Yes	20' and 35'	5 sec	2-8 sec	Yes, all types	0.527
NC	Yes, but rare	50'	7 sec	2 sec (6x40 loops); 1 sec (6x60 loops, rare)	Yes, protected only	0.598
UT	Yes	45'-50'	5 sec	1.8 seconds (advanced); 0.6 seconds (stop line)	Yes, all types	1.416

CMFs used for Minnesota and North Carolina are the most recent ones in order to reflect the "current" operation as much as possible. The reference CMF for Utah is the CMF of converting both-approach permissive to one-approach permissive-protected.

In North Carolina, advanced detectors are not typically used now due to the increased maintenance required (refer to Table A8 in the Appendix). In other words, the protected portion of the permissive-protected phase is typically called and extended by stop-line detectors. Therefore, there exist probabilities for extending the green time even when the end of the queue approaches the stop line, resulting in a longer average protected portion. Moreover, the typical minimum green time used by the North Carolina Department of Transportation (NCDOT) is longer than that used by UDOT. Hence, on average, the protected portion of the permissive-protected left-turn phase in Minnesota is likely to be longer than that in Utah.

In conclusion, the approach of operating the permissive-protected left-turn phases by MnDOT and NCDOT are likely to result in a longer protected portion, on average, compared to UDOT. Since the protected left-turn phasing is safer, this extended protected portion can increase overall safety performance and lead to a lower crash modification factor (CMF), especially for left-turn-related crashes.

6. CONCLUSION

6.1 Summary

In this project, the research team developed CMFs of various left-turn phasing treatments for both total crashes and left-turn-related crashes for Utah intersections. The treatments studied are:

1. Converting from both-roadway permissive left-turn phasing to one-roadway permissive-protected left-turn phasing;
2. Converting from one-roadway permissive-protected left-turn phasing to both-roadway permissive-protected left-turn phasing;
3. Converting from both-roadway permissive-protected left-turn phasing to one-roadway protected left-turn phasing;
4. Converting from one-roadway protected left-turn phasing to both-roadway protected left-turn phasing.

Five datasets were used in the study: 1) crash data collected from Numetric; 2) AADT provided by UDOT; 3) roadway characteristics collected from Google Street View; 4) demographic factors collected from US Census; and 5) information on left-turn phasing collected from Google Street View and verified with the information provided by UDOT. A cross-sectional study was used to develop the CMFs. The SPFs used to estimate the CMFs are developed using Negative-Binomial (NB) models. Additionally, the team conducted a survey of other states' practices to understand how UDOT's approach to left-turn phasing may result in different CMFs compared to other localities.

6.2 Findings

For converting both-roadway permissive to one-roadway permissive-protected left-turn phasing, the CMF of all types of crashes is statistically insignificant and the CMF of left-turn crashes is 1.4161 (See Table 24). For converting one-roadway to both-roadway permissive-protected left-turn phasing, the CMF of all types of crashes is 1.3296 and the CMF of left-turn crashes is 1.2880. For converting both-roadway permissive-protected to one-roadway protected left-turn phasing, the CMF of all types of crashes is statistically insignificant and the CMF of left-turn crashes is 0.7329. For converting one-roadway to both-roadway protected left-turn phasing, the CMF of all types of crashes is statistically insignificant and the CMF of left-turn crashes is 0.5051. In general, the conversion from permissive to permissive-protected left-turn signals showed no improvement in safety.

Table 24 Summary of CMFs

Treatment	Crash Type	CMF
Both-Roadway Permissive to One-Roadway Permissive-Protected	Total Crash	Insignificant
	Left-Turn Crash	1.4161
One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected	Total Crash	1.3296
	Left-Turn Crash	1.2880
Both-Roadway Permissive-Protected to One-Roadway Protected	Total Crash	Insignificant
	Left-Turn Crash	0.7329
One-Roadway Protected to Both-Roadway Protected	Total Crash	Insignificant
	Left-Turn Crash	0.5051

However, converting permissive-protected signals to protected signals did result in a reduction of left-turn-related crashes. The most effective way to improve safety in terms of reducing the frequency of left-turn-related crashes was found to be the implementation of protected left-turn phasing for both intersecting roadways. The results of the CMF estimates for converting to protected left-turn phasing align with findings from other states, but the CMF estimates for converting to permissive-protected phasing are higher. A possible reason indicated by the survey is that the operations of UDOT may lead to a shorter protected portion of the permissive-protected phasing compared to the states with lower CMFs.

6.3 Limitations and Challenges

The major limitation in the CMF development is the lack of available data on left-turning volumes, which should serve as the exposure measure of left-turn-related crashes, and may lead to a confounding effect in the treatment indicator, which may implicitly account for the higher left-turning volumes at intersections with one-roadway permissive-protected phasing. This could result in an overestimation of the CMFs. Future studies should consider collecting and utilizing left-turning volumes, as well as conflicting through volumes, for the development of more accurate CMFs. Additionally, if data availability permits, a before-after study could be conducted to account for factors that were not considered in this study. Furthermore, it is important to note that this study did not differentiate between left-turn phasing treatments for major and minor roadways. For example, a more detailed analysis could be conducted that differentiates between intersections with major-roadway-permissive-protected-minor-roadway-permissive-left-turn phasings and those with minor-roadway-permissive-protected-major-roadway-permissive-left-turn phasings.

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APPENDIX

Table A1 Estimates of SPF for Left-Turn Crash Frequency of Converting Both-Roadway Permissive to One-Roadway Permissive-Protected with Left-Turn Ratio

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-10.0706	2.2975	-4.383	<0.0001
Ln (Major AADT)**	0.7599	0.2435	3.121	0.0018
Major Left-Turn Ratio**	3.1705	0.8987	3.528	0.0004
Major Through Lanes**	0.5168	0.1569	3.293	0.0010
Minor Right-Turn Lanes*	-0.3619	0.1678	-2.157	0.0310
Minor Speed Limit**	0.0592	0.0171	3.461	0.0005
Treatment	0.1479	0.1988	0.744	0.4569
Sample Size	120 (40×3)			
AIC	403.51			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A2 Estimates of SPF for Total Crash Frequency of Converting One-Roadway Protected to Both-Roadway Protected with Left-Turn Ratio

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)	-0.1187	0.8980	-0.132	0.8948
Ln (Minor AADT)**	0.3675	0.0854	4.303	<0.0001
Minor Left-Turn Ratio**	1.0820	0.3957	2.734	0.0063
Minor Left-Turn Lanes**	-0.6081	0.1268	-4.797	<0.0001
Treatment**	0.4483	0.1175	3.816	0.0001
Sample Size	105 (35×3)			
AIC	784.42			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A3 Estimates of SPF for Left-Turn Crash Frequency of Converting One-Roadway Protected to Both-Roadway Protected with Left-Turn Ratio

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-2.6513	1.4347	-1.848	0.0646
Ln (Minor AADT)**	0.5209	0.1358	3.835	0.0001
Major Left-Turn Ratio*	-1.5410	0.7339	-2.100	0.0358
Minor Left-Turn Ratio*	1.5751	0.6206	2.538	0.0111
Minor Left-Turn Lanes**	-0.7331	0.1909	-3.841	0.0001
Treatment	-0.1460	0.1836	-0.795	0.4265
Sample Size	105 (35×3)			
AIC	518.84			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A4 Estimates of SPF for Left-Turn Crash Frequency of Converting from Both-Roadway Permissive to One-Roadway Permissive-Protected without Housing Density

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-8.4205	1.2219	-6.891	<0.0001
Ln (Major AADT)**	0.5701	0.1251	4.558	<0.0001
Major Through Lanes**	0.3219	0.1031	3.121	0.0018
Major Left-Turn Lanes**	0.9037	0.3691	2.448	0.0144
Major Right-Turn Lanes**	-0.2272	0.1102	-2.061	0.0393
Minor Speed Limit**	0.0606	0.0082	7.387	<0.0001
Treatment**	0.3846	0.1092	3.522	0.0004
Sample Size	366 (122×3)			
AIC	1190			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A5 Estimates of SPF for Left-Turn Crash Frequency of Converting One-Roadway Permissive-Protected to Both-Roadway Permissive-Protected without Housing Density

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-7.8090	1.1645	-6.706	<0.0001
Ln (Major AADT)**	0.4020	0.1220	3.295	0.0010
Ln (Minor AADT)**	0.1688	0.0531	3.181	0.0015
Major Through Lanes**	0.3234	0.0802	4.035	<0.0001
Major Speed Limit **	0.0305	0.0074	4.126	<0.0001
Minor Through Lanes*	0.2135	0.0964	2.215	0.0268
Minor Speed Limit**	0.0405	0.0084	4.824	<0.0001
Treatment*	0.2547	0.1040	2.448	0.0143
Sample Size	369 (123×3)			
AIC	1675.2			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A6 Estimates of SPF for Total Crash Frequency of Converting Both-Roadway Permissive-Protected to One-Roadway Protected without Housing Density

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-6.2010	0.7754	-7.998	<0.0001
Ln (Major AADT)**	0.5408	0.0709	7.624	<0.0001
Ln (Minor AADT)*	0.1123	0.0439	2.557	0.0105
Major Speed Limit **	0.0237	0.0054	4.386	<0.0001
Minor Through Lanes*	0.1958	0.0685	2.859	0.0043
Minor Speed Limit**	0.0350	0.0062	5.607	<0.0001
Treatment	0.0558	0.0717	0.779	0.4359
Sample Size	339 (113×3)			
AIC	2260.5			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A7 Estimates of SPF for Left-Turn Crash Frequency of Converting Both-Roadway Permissive-Protected to One-Roadway Protected without Housing Density

Variable	Estimates	Std. Error	Z Value	P Value
(Intercept)**	-11.2334	1.2074	-9.304	<0.0001
Ln (Major AADT)**	0.7676	0.1075	7.141	<0.0001
Ln (Minor AADT)*	0.1460	0.0661	2.209	0.0272
Major Speed Limit **	0.0422	0.0080	5.295	<0.0001
Minor Through Lanes**	0.2769	0.0948	2.921	0.0035
Minor Speed Limit**	0.0483	0.0090	5.365	<0.0001
Treatment*	-0.2520	0.1038	-2.426	0.0153
Sample Size	339 (113×3)			
AIC	1646.5			

***** Statistically significant at 0.05 level.
** Statistically significant at 0.01 level.

Table A8 Responses to the Survey

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
SCDOT	Both, but usually just at stop line	50'	SCDOT Traffic Signal Design Guidelines recommends min green time of 8 seconds	3 seconds per Traffic Signal Design Guidelines	15 seconds	Yes. This operation seems to meet driver expectation
Vermont Agency of Transportation	Both	50'-75'	5 second typical min green	2.0 - 3.0 seconds	15 seconds I would estimate	We have tried to operate Protected only based on time of day and received a lot of complaints that the FYA wasn't working properly which caused confusion and we therefore reverted back to FYA at all times. That was in 2016, when we didn't have wide spread use of FYA's, we will be trying the protected only based on time of day on a recently completed project. We plan to only operating protected only during the AM and PM peak periods when volumes warrant protected

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
						only based on speeds.
Minnesota Department of Transportation	6'x6' detector at 5', 20', 35', optional 50' http://www.dot.state.mn.us/trafficeng/publ/signaldesign/signal-design-manual.pdf page 4.13.	See above	7 seconds for protected, 5 seconds for protected/permissive http://www.dot.state.mn.us/trafficeng/publ/signaloperations/signal-timing-manual.pdf page 4-17	Back detector distance divided by speed, usually 2 to 8 seconds. http://www.dot.state.mn.us/trafficeng/publ/signaloperations/signal-timing-manual.pdf page 4-19	Calculated based on volumes. Typical 10 to 45 seconds. http://www.dot.state.mn.us/trafficeng/publ/signaloperations/signal-timing-manual.pdf page 4-21	Yes. http://www.dot.state.mn.us/trafficeng/publ/signaloperations/signal-timing-manual.pdf pages 4-27 through 4-29.
Mississippi Department of Transportation	STOPBAR	No Advance Detection for Left turns	6 to 10 seconds based on geometry, heavy vehicle frequency, or volume	3.0 Seconds on average	20 seconds on average	Yes, we run protected only during peak hours based on sight distance and heavy opposing thru volume then switch to protected/permitted during off-peak. The operation seems to be working satisfactorily.
South Dakota Dept. of Transportation	Typically stop line, but have used advance loops on high speed facilities.	The set-back distance depends on the 85th percentile approach speed and the turn bay geometry.	Our Road Design Manual has a chart that is based on functional classification.	Three or four seconds (varies on local area preference). We do use volume-density on some high speed approaches.	Mainline thru = 40-sec, Mainline left = 15-sec, Minor road thru = 20-sec, Minor road left = 10	Yes; we do that during peak times if the left turn volume is low. From our perspective it does what it is intended to do, i.e. shift unused clearance interval time to critical

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
						phases. From a user left turner perspective, the practice is an unholy abomination originating in the bowels of hell, i.e. they aren't happy not getting a green arrow at certain TODs.
Idaho Transportation Department	Both	104'	Would be based on recommendations from Signal Timing Manual	Would be based on recommendations from Signal Timing Manual	Would be based on recommendations from Signal Timing Manual	Yes, at a signal near a school where students would use the signal to get to school in the morning and to leave school in the afternoon. During time of day when students are coming to and leaving the school, the permissive left turn phase would be turned off.
AKDOT&PF Central Region	stop line	n/a	servers queue, min green 7 sec.	60' detection zone with 2 sec ext, zone goes from -10 (i.e. into intersection) to +50 before stop bar	40 sec - depends on volumes	Yes, we use volume cross product warrants (e.g. >100000 for crossing 2+lane road) They run in protected mode only.

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
NCDOT	Most of our detection for left turns is at the stop line. Some older installations have loops cut 50' from the stop bar for protected left turn detection with another (optional) loop cut at the stop line for permissive left turn detection. This operation is not typically used now due to increased maintenance needs.	50'	Minimum Green is determined by a standard published in our Signal Design Manual. 7 seconds is used for all left turn and side street through phases.	When 6x40 loops are installed for the left turn, we use an extension time of 2.0 seconds. At older installations where 6x60 loops are installed for the left turn, we use an extension time of 1.0 seconds.	Plans will typically show a max green of 15-30 seconds for protected left turn phases. However, field personnel are given the freedom to adjust Max Green times for site specific conditions.	Yes. Plans are designed to show two phasing diagrams (Default Phasing - Protected/Permitted and Alternate Phasing - Fully Protected). A note is added to the plans stating that field personnel determine the hours of operation of each phasing plan. When the signal is operated in the fully protected mode, the loops for the left turn are modified to have shorter delay times.
Arkansas Department of Transportation	Both	Typical 85ft	6-12 seconds	2.0-4.0	35 dependent upon demand and storage	No
NDOT (Nebraska Department of Transportation)	At the stop bar	No advance detectors are used for left turn movements to my knowledge on NDOT's network	Minimum green times of the protected portion of the phase are typically determined by HCM based analysis software (Synchro) or a typical value is used, and adjusted in the	Typical extension time for the protected portions of the turning phase is 3 seconds	Typical maximum green times for the protected portion of the phase would be 15 seconds, but there is a lot of variance to this based on traffic utilizing this movement.	Yes, at certain intersections NDOT will sometimes not activate the protected phase of a left turn during the off-peak times to operate the intersection more efficiently, and then

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
			field by observation from the Traffic Engineer. The typical value for minimum green times of the protected portion of the left turn is usually 5-7 seconds.			activate the protected turn during busier periods of the day.
Indiana Department of Transportation	Stop line		5 seconds is the typical minimum green time	It varies from 2 to 3.5 seconds, typically	15 to 25 seconds	This varies by district. Some districts permit changes in phase operation by TOD while others don't. Some traffic signals switch between protected and protected/permissive and some switch between protected/permissive and permissive operation. INDOT has an operations memorandum that gives guidance on the type of left turn operation to use at a traffic signal.
Colorado DOT	Stop line		5 seconds is typical, 3 seconds sometimes used for locations with low volume	1.5-2.5 seconds.	This varies significantly based on demand patterns. 7 seconds is typically the	We operate protected-only by TOD (protected-permissive at other times) but not

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
					minimum force off time used regardless of split calculations recommending lower values.	protected-permissive by TOD (and permissive-only at other times).
Illinois DOT	Stop line	N/A	Typically 6 to 8 seconds based on engineering judgment.	Typically 1.0 to 2.5 seconds based on engineering judgment.	Can vary greatly. May range from 12 to 30 sec depending on left-turn volume.	We typically do not change between protected-permissive and protected only by TOD. The phasing scheme is either one or the other 24-7.
Texas Department of Transportation (TxDOT)	Stop-line detection is used for left-turns	N/A	TxDOT guidelines give a range of 5 to 8 seconds for minimum green. The more typical value is 5 seconds; however, some intersections have values as high as 10 seconds. Factors for selecting higher than 5 sec minimum green include left-turn volume, rail crossings, schools, and heavy large truck volumes.	Typical values range between 1 to 2 seconds.	20 to 30 seconds depending on traffic volume and timing plan.	The TxDOT traffic signals manual allows for a variable left-turn mode. Variable left means that the signal can change between protected-only or protected-permissive and/or permissive-only mode according to time of day or possibly by rail or emergency preemption. There could be a few districts that are using variable left-turn mode on a limited scale. For the most part, driver expectancy is of

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
						great concern when considering using this mode. If this mode is being used, then it is probably protected-only in heavy peak times, protected/permissive during off-peak, and permissive-only at nighttime operations.
The Ohio Department of Transportation	Majority are stop line detectors. We do have some locations that use second car detection as well. we do not use advanced detection in pm-pt left turn lanes.	N/A	Typically, 7-10 seconds	It depends on the detection solution. For Wavetronix radar, we tend to keep the extension very short 0.5-1 second because the product holds the call in the controller. For loops, we keep it around 3-4 seconds.	20-25 seconds	We currently do not have any. We attempted to run one signal like this using flashing yellow arrow and found the crashes went up and turned off the permissive operation
ridot	just stop line	na	synchro. 5 to 6 seconds	ITE values	varies	no
NHDOT	Stop Line	Typically, Not Used	Typical Min time is set 5 sec for min	3 - 5 seconds	15	No
Massachusetts DOT	Stop line	n/a	Typical 8 seconds	Typical 2-second gap out	It can vary significantly by location	No

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
Oklahoma Department of Transportation	Stop line	NA	Depends on the relative "importance" of the movement	Typically 2-3 seconds	Depends on traffic volumes	Not that we are aware
Georgia Department of Transportation	Stop line	Dependent upon approach speed	Typically, 2-5 seconds, targeted to satisfy driver expectancy. Largely driven by engineering judgment.	Function of detector zone length and approach speed	15-30 seconds but depends on context and engineering judgement.	Yes. Flashing Yellow Arrow displays, most driven by pattern where traffic conditions suggest insufficient gaps for left turns, or other operational considerations like upstream metering. Can be driven by time of day or through a traffic responsive system. Have tested using dynamic systems driven by previous cycle gaps measured through upstream setback detection.
Kentucky Transportation Cabinet	Typical placement would be a 6' x 30' loop at the stop bar. As we go utilize radar detection more and more, that provides flexibility.	Typical setback would be 50'.	Each district office determines specific timing for each location, so it would depend on the location, volumes, etc.	A 3-second gap out is typically used.	15-20 seconds is probably average, but again that could vary depending on the location.	Yes, we utilized TOD at select locations. Some places will use protected-only/prot-perm and others will use prot-perm/permitted. In either case, when used, we typically

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
						run the more restrictive phasing either throughout the daytime (e.g. 6 am - 6 pm) or just during the AM and PM peaks, and then run the less restrictive phasing all other times and overnight.
Louisiana Department of Transportation and Development	We typically just install stop line. We do have a few that have advanced but they are used for clearing.	This is based on the length of the queue and turn lane length.	Typically, we start with a min of 5s and adjust based on field observations.	Typically, we start with a min of 6s and adjust based on field observations.	The max green is first based on analysis and then adjusted based on field observations.	We do have TOD for some signals. We do not have any that are protected for only certain times of days.
Virginia Department of Transportation (VDOT)	Stop line	We do not typically use advance detectors for left turns.	Minimum green times for left turns are usually determined based on volumes, heavy vehicle percentage, grade, and major vs minor direction of movement. It is not formula driven. Major movement minimum green is generally in the range of 5 to 10 seconds with an average of 7 seconds. Minimum green for minor direction left turns	Extension times for left turns are generally in the range of 2 to 3 seconds.	Minimum green for left-turns is generally in the range of 5 to 10 seconds with an average of 7 seconds. Minimum green for minor direction left turns can be as low as 3 seconds.	VDOT does operate some protected-permitted signals in TOD mode. VDOT uses flashing yellow arrows (FYAs) to operate protected-permitted left-turn signals. Where FYAs are operating in TOD mode it is generally to exclude permissive movements during AM and PM peak travel hours when volumes are highest

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
			can be as low as 3 seconds.			and available gaps are very limited.
Pennsylvania Department of Transportation	Stop line	N/A	Typically 3 seconds, can be extended if start-up lost time needs are higher (high truck volume, etc.)	Normally 3 seconds	Normally determined from Synchro analysis	We have set some FYA signals to run protected-permissive vs. protected-prohibited by TOD using either conflict analysis or crash analysis
WSDOT	Most locations are stop line only. Some locations also include advanced, but we are working on a more formal and consistent practice for them.	One region uses 60-77 feet in advance of the stop line, and another uses 85th percentile speed (ft/s units) x 2 seconds or at the start of the full turn lane width, whichever is closer to the stop line.	Varies by location, but usually determined by site conditions and observation. Typical minimum is 5 seconds.	Anywhere from 0.5 to 3 seconds, depending on detection available.	Ranges from 20-50 seconds, depending on site conditions (speeds and volumes).	Yes. Some locations alternate between protected only and protected/permissive by TOD, others alternate between protected only, protected/permissive, and permissive only by TOD. Protected only portions may be leading or lagging depending on the location.
UDOT	We typically have a detection zone at the stop line that calls the permissive phase, and an advance detector (we call it a "queue" detector) that is 45-	The trailing edge of the queue detector is typically 45-50' upstream of the stop line.	We typically program 5s for the minimum green time for all protected left turn movements. There are some exceptions with larger min green times, for example	We use a formula adapted from the Signal Timing Manual to determine the vehicle extension/passage/unit extension time. For a typical protected/permissive	The maximum green time will vary considerably depending on the situation, but I would say that when running free in overnight hours, we generally use about	Yes, we have a variety of these. We may omit the protected green phase in small cycles when traffic demand is low. If the P/P display is a Flashing Yellow

Q0 (Agency)	Q1 (Detector Used)	Q2 (Location of the Advance Detectors)	Q3 (Min Left-Turn Green)	Q4 (Left-Turn Green Extensions)	Q5 (Max Left-Turn Green Time)	Q6 (TOD Operations)
	50' upstream of the stop line.		where we have a very heavy movement, where there are a lot of heavy trucks, or where the left turn movement is the predominant movement from the approach. Other than during preemption events we do not use min green times below 4s.	left turn, the extension is done from the queue detector only which has a length of about 15ft. We usually assume a moving speed of 20mph for left turns, and this results in a vehicle extension time of 1.8s for most of our left turns (this corresponds to a maximum allowable headway of 3.0s). If the stop line detector is used instead of the queue detector, the extension is typically only 0.6s because those detectors are longer.	20s as a maximum green time for left turns. It would be rare that the turn would need that much time and it is expected that gap out will occur.	Arrow, we may omit the permissive (flashing yellow) phase during times when there are insufficient safe gaps for drivers to turn; when we have lead/lag operation that might result in a "perceived yellow trap" (where drivers turning left see the adjacent thru signals change from green to yellow, and mistakenly assume that the oncoming thru signals have also changed, even though the FYA is still displayed); or in a few cases during service of a conflicting pedestrian movement.