Safety Performance Analysis of Alternative Intersection Implementations in Alabama

by

Henly Crosby

A thesis submitted to the Graduate Faculty of
Auburn University
in partial fulfillment of the
requirements for the Degree of
Master of Science

Auburn, Alabama
December 14, 2024

Keywords: Roundabout, Restricted Crossing U-Turn, Continuous Green T,
Safety Effectiveness, Crash Modification

Approved by

Rod E. Turochy, Chair, James M. Hunnicutt Professor in Traffic Engineering
Jeffrey J. LaMondia, Elton Z. and Lois G. Huff Professor (Transportation)
Huaguo Zhou, Elton Z. and Lois G. Huff Professor (Transportation)

Abstract

Much attention has been drawn to intersection safety in recent years. This research aims to develop quantifiable safety benefits, specific to Alabama, for alternative intersection designs such as roundabouts, RCUTs, and CGTs. Methodologies performed include, a simple before-after and a comparison group analysis. The simple before-after analysis results showed that roundabouts, RCUTs, and CGTs reduced total crashes per year by 17.1%, 23.9%, and 21.2%, and fatal and injury (FI) crashes per year by 48.2%, 60.5%, and 30.2%, respectively. The comparison group analysis resulted in total and FI CMFs of 0.38 and 0.20 for roundabouts, 0.60 and 0.26 for RCUTs, and 0.79 and 0.58 for CGTs. Additional safety performance assessments were made based on prior control type, area type, and changes in the manner of crash types before and after implementation. Knowledge of the safety performance of these design alternatives will aid future research and support further implementation.

Acknowledgments

I would like to thank and dedicate this thesis to my family, friends, classmates, professors, and mentors who have supported me throughout my academic journey. Gaining my undergraduate and graduate degrees at Auburn University has been the greatest blessing.

First, I would like to express my gratitude to my advisor Dr. Rod Turochy. I am grateful for the opportunity to have worked with Dr. Turochy throughout my time at Auburn. I am truly grateful for your dedication to always finding the time to provide me with guidance. I have grown academically and developed skills that I will carry with me throughout the rest of my career. I would also like to thank the other members of my committee, Dr. Huaguo Zhou and Dr. Jeffery LaMondia, for taking the time to review this thesis and providing their expertise when needed. Thank you, Dr. Zhou, for sharing your knowledge of traffic safety and providing me with such a unique learning opportunity through your traffic simulation course. Dr. LaMondia, thank you for always having such a positive attitude that fosters such a great learning environment. Your Introduction to Transportation course is what sparked my interest in pursuing a career in this field.

I would like to share my appreciation for all the Alabama Department of Transportation personnel and city and county engineers who contributed their valuable time and knowledge to this project. Thank you, Stuart Manson, from the Alabama Department of Transportation Traffic and Safety Operations Section and Jesse Norris from the Center for Advanced Public Safety, for your continued assistance and support throughout the completion of this research.

Lastly, I would like to thank my family. To my parents, Laurel and Stephen Crosby, my academic achievements would not have been possible without your constant love and support. I would also like to thank my brother and grandmother, Eli Crosby and Gayle Spraberry, who have always been there for me. I love you all.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

AADT	Annual Average Daily Traffic
ALDOT	Alabama Department of Transportation
AASHTO	American Association of State Highway Transportation Officials
AWSC	All-way Stop-controlled
CARE	Critical Analysis Reporting Environment
CF	Calibration Factor
CGT	Continuous Green T
CMF	Crash Modification Factor
EB	Empirical-Bayes
FHWA	Federal Highway Administration
FI	Fatal and Injury
GIS	Geographic Information Systems
HPMS	Highway Performance Monitoring System
HSM	*Highway Safety Manual*
MEV	Million Entering Vehicles
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
RCUT	Restricted Crossing U-Turn
RTM	Regression to the Mean
SE	Standard Error

SPF	Safety Performance Function
TWSC	Two-way Stop-controlled

Chapter One: Introduction

1.1. Motivation

Alternative intersection designs have become a popular treatment in traffic safety due to their ability to reduce the crash risk at intersections. In the United States, about 25-26% of all fatalities and 51% of traffic injuries occur at intersections (Steyn et al. 2015), (Wang & Cicchino 2022). Specifically, one-third of intersection fatalities occur at signalized intersections, and in 2009, stop-controlled intersections accounted for 60% of intersection fatalities and 25% of all reported fatalities (Guin et al. 2018). Signalized intersections typically experience a higher frequency of crashes, whereas stop-controlled intersections have a higher number of fatalities (Guin et al. 2018). Intersections are a necessary component of the overall roadway network, which is why improving the safety of intersections is a focus area of the Federal Highway Administration (FHWA) (FHWA Highway Safety Program, 2024).

The "Vision Zero approach" in traffic safety has become a widespread idea originating in Sweden in 1997, and it revolves around the idea that traffic deaths and injuries are avoidable (Ngo, 2023), (Rodegerdts et al., 2023). The FHWA supports the movement toward zero traffic fatalities and has stated that, "making intersections safer is a critical and essential step toward realizing that vision" (FHWA Highway Safety Program, 2024). Alternative intersection designs aim to reduce the occurrence of traffic collisions but focus on decreasing the severity of the crashes that do occur (FHWA Safety Program, 2024). According to the FHWA, the likelihood of a severe crash occurring at an intersection is based on conflict points, driver speeds, and the angle of a collision (FHWA Safety Program, 2024). Alternative intersection designs should reduce vehicular speeds and minimize conflict points, specifically crossing conflict points associated with left-turning vehicles since 12 of the conflict points at a conventional intersection are due to a vehicle turning left (FHWA Program, 2024).

1.2. Problem Statement

There is currently a lack of quantitative evidence on how these alternatives impact the number of total and severe crashes at intersections in Alabama. The alternative designs evaluated in this research include Roundabouts, Restricted Crossing U-turn (RCUT), and Continuous Green T (CGT) intersections. Roundabouts have become a common alternative design in the United States. The first roundabout in the United States was built in Las Vegas in the 1990s (Wang & Cicchino 2022). In 1997, the United States had a total of 50 roundabouts, growing to 3,200 in 2016 to now over 8,800 as of 2021 (Rodegerdts et al. 2023), (Savolainen et al. 2023). Due to the accelerated growth of roundabout construction, the impacts on safety have been evaluated thoroughly in other states and nationally but not in Alabama. RCUTs similarly have been discussed nationally and within certain states, but a comprehensive evaluation has not been conducted in Alabama. Throughout the United States, few studies have assessed the safety impacts of CGT implementation, and the results of the research that has been conducted have found opposing conclusions. Also, it is beneficial to have knowledge on how prior control type or area type may affect the safety performance of these alternative designs in order to guide future implementation decisions. For example, how alternative designs converted from a TWSC intersection are performing compared to those converted from a traffic signal.

1.3. Research Objectives

The objective of this research is to determine the change in a) the total number of crashes per year b) the number of fatal and injury (FI) crashes per year, and c) the manner of crash types after alternative intersection installation in Alabama, specifically roundabouts, RCUTs, and

CGTs. Thorough evaluations of alternative intersections have been done nationally and in other states, but there is a lack of understanding of the current safety performance of these alternative intersections in Alabama.

Specifically, this work will utilize historical crash data before and after the implementation of alternative designs to determine how the crashes at an intersection are affected. Safety was quantified in units of crashes per year, which acts as the dependent variable in this research. First, an assessment was made of the changes in the manner of crash distribution between the before and after periods, and a chi-square test of independence was performed to determine the statistical significance of the observed changes. The change in total and FI crashes due to the implementation of each alternative was determined using two separate methodologies outlined in the *Highway Safety Manual (HSM)*, a simple before-after analysis and comparison group analysis. The simple before-after analysis compared the mean crashes per year across all sites in the before period to the after period to estimate the percent reduction in crashes due to alternative intersection implementation. A paired means hypothesis test was also performed to confirm the statistical significance of these results. The comparison group analysis was performed to develop crash modification factors (CMFs) that consider variables that may influence the observed data, such as traffic volume, geometrics, and crash history. An overall estimate of the change in total and FI crashes per year due to the implementation of each alternative throughout the state was determined utilizing both methodologies. An additional analysis was performed utilizing both methodologies to determine how prior control type and area type affect the safety performance of each alternative. Lastly, the comparison group methodology was utilized to develop CMFs for target crash types which includes side impact, angle, and head-on collisions.

The safety benefits of alternative intersections determined from this research will be useful to the Alabama Department of Transportation (ALDOT) to guide future projects as the construction of these alternatives continues to increase. Having research specific to Alabama will be useful for gaining the support of those questioning the usefulness of alternative designs and motivating safer design decisions within the state. Prior research in other states can be beneficial to justify implementation, but it is best to examine data specific to Alabama due to differences in roadway conditions, crash reporting, driver behavior, etc. Gaining knowledge of the impact that prior control type and area type have on the safety effectiveness of these alternatives will aid in determining which locations are best suited for future construction. This research will especially contribute to the discussion on the safety impacts of CGTs since there is currently less available research related to this alternative. The analysis of the safety performance of alternative intersections in Alabama will assist future research related to design alternatives in Alabama as well as nationally.

1.4. Organization of Thesis

The following chapters of this thesis are organized as follows. First, Chapter Two will include a review of the current literature related to the safety effectiveness of roundabouts, RCUTs, and CGTs. An overview of methodologies included in the *Highway Safety Manual* (*HSM*) that are utilized to quantify the safety effectiveness of design alternatives will also be included. Within the literature review, safety effectiveness is evaluated in terms of total crashes, FI crashes, collision type, and multimodal impacts. Chapter Three contains the data collection procedure and methodologies that led to the results and conclusions. Data collection consisted of site details such as construction dates, location, geometric features as well as crash and volume data for each site. Chapter Three begins with a description of the approach utilized to evaluate the changes in the manner of crash distributions followed by the details of the simple before-after and comparison group methodologies. Chapter Four presents the results from each analysis, and Chapter Five discusses the conclusions drawn from the results and recommendations for future research projects and for practice.

Chapter Two: Literature Review

2.1. Introduction

This chapter contains a review of the literature related to the safety effectiveness of the implementation of Roundabouts, Restricted Crossing U-Turns, and Continuous Green T intersections. First, an overview will be provided of how safety effectiveness is quantified as described in the *Highway Safety Manual* (*HSM*). Second, an explanation of safety evaluation methodologies within the *HSM* used to assess a treatment or modification to the roadway environment is also included. Various safety studies utilizing these methodologies will then be reviewed to determine how each alternative is currently impacting intersection safety throughout the United States in terms of total crashes per year, FI crashes per year, and the occurrence of certain crash types. The literature was also used to identify any gaps within the existing research. Lastly, safety performance was further assessed based on the prior control type of the intersection and the effect each alternative has on various road users.

2.2. Safety Performance in the *Highway Safety Manual*

The *Highway Safety Manual* provides details on variables that influence the safety of a roadway facility, and the appropriate methodologies to conduct safety evaluations based on the available data. According to the *HSM*, the number of crashes, the severity of crashes, and the type of crashes that occur quantify safety performance (AASHTO 2010). The first edition of the HSM defines a crash as “a set of events that result in injury or property damage due to the collision of at least one motorized vehicle and may involve a collision with another motorized vehicle, a bicycle, a pedestrian, or an object” (AASHTO 2010). Crash severity is typically measured on the KABCO scale. Commonly discussed in this thesis is the occurrence of fatal and injury (FI) crashes, which include KABC-level crashes on the KABCO scale.

- K = fatal injury
- A = incapacitating injury
- B = non-incapacitating evident injury
- C = possible injury
- O = no injury or property damage only

The conflict points at an intersection often indicate how at-risk drivers are of being involved in a crash. The three types of intersection conflict points are crossing conflicts, diverging conflicts, and merging conflicts. Crossing conflict points are often associated with more severe crash types, such as left turn or angle crashes. Roadway user risk at an intersection is related to factors such as driver speeds and movement complexity, in addition to conflict points.

The *HSM* highlights that crashes are rare and random, so simply observing the number of crashes that occur does not necessarily reflect the safety performance because long-term crash trends and independent variables are not considered (AASHTO 2010), (Rodegerdts et al. 2023). Variables that influence crash data may include but are not limited to traffic volume, driver behavior, area type, or geometrics (AASHTO 2010). For intersections, important elements to consider are the traffic volume entering the intersection, the number of lanes, and the number of approaches (Ulak et al. 2020). The *HSM* outlines different crash evaluation methods to quantify how different treatment methods or alternatives affect safety (AASHTO 2010). Safety evaluation methodologies typically assess historical crash data while requiring a range of statistical expertise to incorporate variables that may influence the data.

2.3. Predictive Method

The predictive method is the overarching method for conducting safety evaluations (AASHTO 2010). The first edition of the *HSM* describes the predictive method as “a structured methodology to estimate the expected average crash frequency (by total crashes, crash severity, or collision type) of a site, facility or roadway network for a given period, geometric design and traffic control features, and traffic volumes" (AASHTO 2010). The main components of the predictive method are safety performance functions (SPFs), crash modification factors (CMFs), and calibration factors (AASHTO 2010). SPFs are regression equations generated from the crash history of similar sites to predict the number of crashes at a location with a similar traffic volume, geometric features, and facility type (AASHTO 2010), (Guin et al. 2018). A CMF is a ratio that represents the expected change in crashes due to a certain roadway feature and is defined by Equation 2-1 obtained from the first edition of the HSM (AASHTO 2010).

$$CMF = \frac{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ b}{Expected\ Average\ Crash\ Frequency\ with\ Site\ Condition\ a}$$

Equation 2-1

The *HSM* includes SPFs developed for different intersection and segment types that must be calibrated to be applied to a local safety evaluation. Calibration factors (CFs) adjust existing SPFs to be more representative of local conditions. (AASHTO 2010). CFs should be used unless enough comparison data is available to generate an SPF specific to the project. (AASHTO 2010). The predictive method requires volume data and roadway characteristics to assign an appropriate SPF to a site, but no specific crash data is needed to estimate the crashes at a site if calibration is performed (AASHTO 2010). Before-after studies are commonly performed to evaluate safety and adopt the main components of the predictive method while also incorporating historical crash data in the analysis.

2.4. Before-After Studies

Before-after studies are the most common way to evaluate crash trends at a site and can involve simply comparing crashes before and after a certain treatment or be a statistical approach that incorporates independent variables influencing the observed data. Simple before-after studies base safety changes on the difference in crashes before and after a design alternative is implemented. This type of study only requires before and after-period crash data and does not consider factors that may affect the data, such as fluctuation in traffic volume or changes to the roadway geometry (AASHTO 2010). Simple before-after studies are susceptible to regression-to-the-mean (RTM) bias since long-term crash fluctuations of a site are not considered (AASHTO 2010). RTM occurs when crashes return to the long-term average values after a period of unusually high or low crashes (AASHTO 2010), (Gross et al. 2010). Bias occurs when a reduction in crashes would have been observed regardless, and this reduction is credited to a treatment method. RTM should be accounted for in safety studies, and the risk is reduced with a large sample size of sites and with more years of data included in the analysis (AASHTO 2010). Observational before-after studies should not be performed at a site where there were multiple changes to the roadway geometry or traffic control outside of those being evaluated because the observed change can no longer be credited to the study treatment or alternative (AASHTO 2010).

The Empirical-Bayes (EB) and comparison group methodologies are before-after approaches that consider more variables that may affect observed crash data within the analysis. The EB method determines the expected crashes of a location based on a weighted average between the predicted and observed crashes (AASHTO 2010). Using observed data as well as predicted improves the accuracy of safety studies and reduces the risk of regression-to-the-mean (RTM) bias (AASHTO 2010). Observed crash data can have limitations, making the SPFs used an important factor in the accuracy of safety estimations (AASHTO 2010). The EB method is often used to compute a CMF due to a treatment method. A comparison group analysis is another type of before-after study that uses a comparison group that acts as a control group to determine the effects a treatment has on safety (AASHTO 2010). The after-period annual average crash frequency of treated sites is compared to the comparison sites to determine differences in crashes (AASHTO 2010).

Lastly, a cross-sectional analysis is another methodology commonly performed when a before-after study cannot be done due to a lack of before-period data or date of construction information (AASHTO 2010), (Savolainen et al. 2023). Cross-sectional studies are like a comparison group analysis, but before-period data is not considered. Control sites that are similar in terms of traffic, geometry, etc., are compared to treatment sites to determine the effectiveness of the treatment. A cross-sectional study is subject to some bias because historical crash trends are not considered (AASHTO 2010). Also, the comparison sites are not guaranteed to be representative of the non-treatment condition since before-period data is not available (Herbel et al. 2010).

2.5. Roundabout Safety Impacts

2.5.1. Introduction

Roundabouts are a type of circular intersection that evolved from rotaries and traffic circles (Rodegerdts et al. 2023). Since rotaries have a larger diameter, drivers travel at higher speeds, whereas roundabouts are often used as a tool to slow drivers down (Rodegerdts et al. 2023). Roundabouts, in addition to reducing driver speeds, eliminate through and left turn movements since drivers all travel in one direction through the intersection. The number of conflict points are greatly reduced when converting from a conventional intersection to a single-lane roundabout. A conventional intersection has 32 conflict points while a single-lane roundabout only has 8 which is shown in Figure 2-1 (Savolainen et al. 2023), (Rodegerdts et al. 2023), (Coffrey et al. 2016), (Gross et al. 2013).

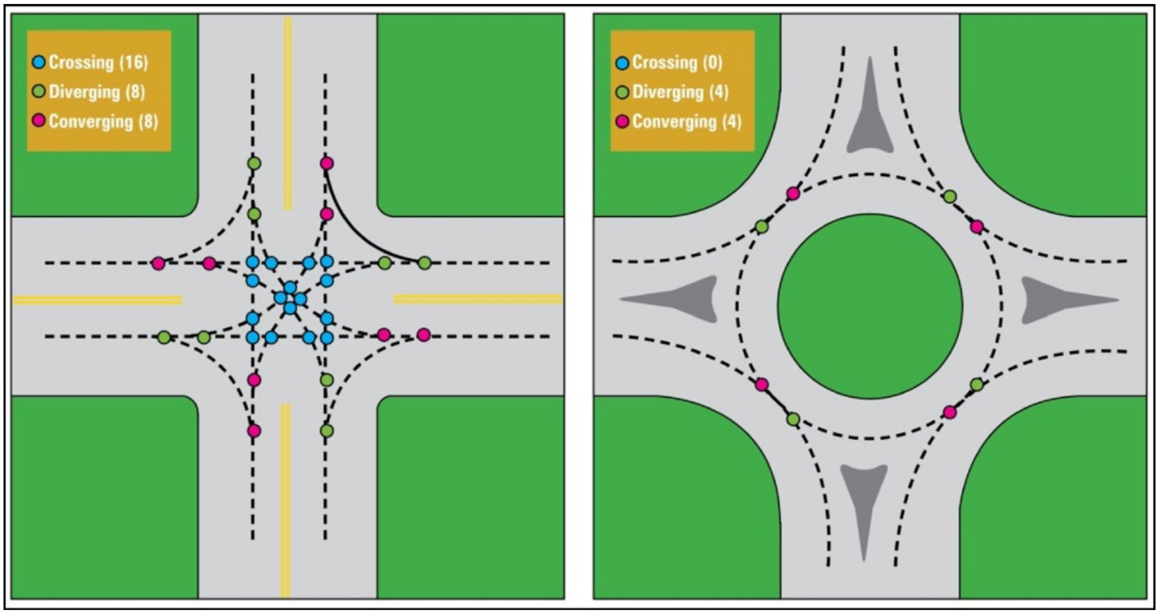

Figure 2-1: Single-lane Roundabout Conflict Points (Source: Gross et al. 2013)

There are zero crossing conflict points at a roundabout, which largely improves the safety of an intersection because crossing conflicts typically lead to more severe collision types such as head-on, left turn, and angle (Edara et al. 2015), (Rodegerdts et al. 2023). Diverging and merging conflicts are the most common conflict types that occur at roundabouts (Savolainen et al. 2023). A typical four-legged intersection has 16 crossing, 8 merging, and 8 diverging conflict points, whereas out of the 8 single-lane roundabout conflict points 4 are diverging and 4 are merging (Rodegerdts et al. 2023), (Gross et al. 2013). The overall reduction in total and crossing conflict points that occurs due to the implementation of a roundabout is a large contributing factor to the safety effectiveness of the alternative.

2.5.2. Overall Changes in Crash Frequency and Severity

Multiple research studies throughout the United States have been conducted to quantify how effective roundabouts are at reducing driver crash risk at intersections. Results typically show that the total number of crashes at an intersection can be expected to decrease after implementation, but some research has found opposing conclusions. Roundabouts have also been found to effectively reduce the number of FI crashes through the elimination of crossing conflicts and slowing of driver speeds.

Simple before-after observations of single-lane roundabout implementation conducted by the Minnesota Department of Transportation (MnDOT) and the Louisiana Transportation Research Center found that reductions in crash frequency and severity were observed after roundabout implementation. The results are shown in Table 2-1 below.

Table 2-1: Simple Before-After Analysis Results from the Literature

Reference	State	Number of Sites	Roundabout type	Methodology	Percent Change	
					Total	FI
Leuer, 2017	MN	104	Single lane	Simple Before-After	-27.0%	-60.0%
Sun & Ashifur 2019	LA	18	Single lane	Simple Before-After	-18.5%	-55.0%

The 2017 MnDOT study accounted for traffic volume changes, but both methodologies are approaches that did not consider variables that may influence the data. Out of the 104 sites included in the analysis by MnDOT, 81 were in urban areas and 23 were in rural.

Studies conducted throughout the United States that utilized methodologies to develop CMFs for roundabout conversion yielded similar results, which can be found in Table 2-2.

Table 2-2: Roundabout CMFs from the Literature

Reference	State	Number of Sites	Roundabout type	Methodology	CMF	
					Total	**FI**
Savolainen et al. 2023	MI	58	Single lane	Empirical-Bayes	1.03 *	0.6
		97	All	Empirical-Bayes	2.1	0.92 *
		89	Single/double	Empirical-Bayes	1.68	0.79
		108	Single/double	Cross-sectional Analysis	1.58	0.73
Wang & Cicchino 2022	IN	21	Single lane	Negative Binomial Model	0.49	0.5*
		64	All	Negative Binomial Model	0.79 *	0.53
Rodegerdts et al. 2007	Multiple	55	All	Empirical-Bayes	0.65	0.24

Note: * Not Statistically Significant

The Michigan study was conducted by the Michigan Department of Transportation (MDOT) in 2023 and included an EB analysis that utilized SPFs that accounted for traffic volume developed from reference sites. The results showed that single-lane roundabouts resulted in a slight increase in crashes, whereas all roundabouts had a much larger increase. MDOT also performed a cross-sectional analysis to include sites without pre-treatment data or a known construction year that also showed that single and double-lane roundabouts of all types led to an increase in crashes after conversion that corresponds to the EB method results for single and double-lane roundabouts (Savolainen et al. 2023). Despite yielding an increase in total crashes, the frequency of FI crashes decreased for all roundabout types (Savolainen et al. 2023). MDOT noted that fatal crashes made up 0.26% of crashes in the before period and only 0.06% of crashes in the after period (Savolainen et al. 2023). The percentage of injury crashes (A-level, B-level, and C-level) was reduced from 20.86% to 9.20%, and an increase in property damage only (PDO) crashes was also observed (Savolainen et al. 2023). A simple before-after safety analysis of 14 roundabouts in Pennsylvania did not find notable differences in crash frequency due to roundabout conversion but saw improvements in the severity of the crashes that occurred (Coffrey et al. 2016). Based on crash type distribution in the before and after periods, the study saw a reduction in fatal (1.2%) and major injury (3.6%) crashes (Coffrey et al. 2016). The study found an increase in PDO crashes and concluded that overall roundabouts effectively decrease severe crashes (Coffrey et al. 2016). Other studies did not find the same increase in crash frequency after roundabout conversion as MDOT. The 2022 Indiana study was a safety evaluation of 21 single-lane roundabouts in the "Roundabout City" Carmel, Indiana, and the results showed a significant reduction in total, FI, and PDO crashes (Wang & Cicchino 2022). This study developed negative binomial models using a comparison group but did not include traffic volume due to a lack of available data. Results were presented in the form of a percent change, and the approximate CMF associated with the percent change is presented in Table 2-2. Included in Table 2-2 is the National Cooperative Highway Research Program (NCHRP) Report 572, which noted reductions in crash frequency and severity based on an EB analysis of 55 roundabouts across several states (Rodegerdts et al. 2007).

Certain collision types, such as angle, right turn, head-on, and left turn, often result in a more severe outcome. Roundabouts eliminating crossing conflict points that lead to these collision types is a contributing factor to their safety effectiveness. Multiple roundabout safety evaluations conducted in Pennsylvania, Louisiana, and Minnesota have found notable reductions in angle, head-on, left turn, as well as rear-end collisions (Coffrey et al. 2016), (Leuer, 2017), (Savolainen et al. 2023), (Sun & Ashifur 2019). MnDOT also found that single-lane roundabouts decrease sideswipe crashes between vehicles traveling in opposing directions (Leuer, 2017). Despite the safety improvements stated above, Minnesota single-lane roundabouts did have an increase in head-on and pedestrian-involved collisions (Leuer, 2017).

An increase in single-vehicle and fixed-object crashes after roundabout implementation is a reoccurring trend among the existing research (Coffrey et al. 2016), (Savolainen et al. 2023). A study entitled "Accelerating Roundabout Implementation in the United States – Volume IV of VII" reviewed the contributing factors of FI crashes occurring at roundabouts by comparing them to nationwide intersection crash trends. The study first analyzed fatal crashes at roundabouts and identified 46 fatal crashes occurring across 19 states. Results showed that roundabouts had a higher portion of crashes involving night conditions, motorcycles, driving too quickly, impaired driving, and fixed objects than a typical intersection (Steyn et al. 2015). Out of the 46 fatal crashes, 83% were single-vehicle crashes (Steyn et al. 2015). Thirty-nine (85%) of the fatal crashes were collisions with a fixed object and 35 involved a vehicle hitting a curb, making up 76% of the fatal crashes at roundabouts (Steyn et al. 2015). A separate injury crash analysis was conducted for roundabouts located in Washington and Wisconsin, excluding fatal and PDO. In both states, rear-end collisions accounted for most of the total injury crashes but collisions with a fixed object, typically a curb, made up a larger portion of severe injury (A and B-level crashes) crashes (Steyn et al. 2015). Single-vehicle crashes in this study often occurred due to drivers traveling too quickly when entering the roundabout or impaired driving (Steyn et al. 2015). The Louisiana Transportation Research Center found that the most common cause of an increase in single-vehicle crashes after roundabout conversion was lack of driver visibility during nighttime conditions (Sun & Ashifur 2019). Despite the increase in fixed object crashes at roundabouts, those that do occur are likely less severe due to lower driver speeds (Coffrey et al. 2016). Included in NCHRP Research Report 1043 is a review of roundabout crash types adapted from NCHRP Research Report 888. The data showed opposing trends, with a higher proportion of severe collisions at roundabouts involving multiple vehicles instead of a single vehicle

(Rodegerdts et al. 2023). Like other previous research, the most common single-vehicle crash type was a collision with a fixed object, typically a curb (Rodegerdts et al. 2023). This research was a review of roundabout crash types and did not assess the changes in crash type due to roundabout implementation.

The current research shows roundabouts typically reduce the number of total crashes and FI crashes experienced at an intersection while single-lane roundabouts offer the greatest improvements over those with multiple lanes, but there have been some opposing conclusions on whether roundabouts decrease the average number of crashes per year. Roundabouts effectively reduce the occurrence of severe crashes due to the movement of vehicles in the same direction, eliminating crossing conflicts and reducing driver speeds. Additionally, roundabouts have typically been found to decrease the occurrence of angle, left-turn, and right-turn collisions that are often more severe than other collision types, such as rear-end or sideswipes. Multiple studies also reported a reduction in head-on collisions. Sideswipes from opposing directions were reduced while some research reported an increase in sideswipe crashes in the same direction. Lastly, studies frequently reported concerns associated with an increase in severe single-vehicle crashes, specifically collisions with a fixed object associated with roundabouts.

2.5.3. Signalized Intersection to Roundabout Conversion

Roundabouts are a common solution to reduce the frequency and severity of crashes at conventional signalized intersections. A study performed by the MnDOT included an assessment of the crash rates at roundabouts throughout Minnesota compared to other intersection configurations. The study found that signalized intersections on low-volume and low-speed roads had a crash rate of 0.52 per million entering vehicles (MEV), signalized intersections on high-volume, low-speed roads had a crash rate of 0.70 MEV, and signalized intersections on high-volume, high-speed roads had a crash rate of 0.45 MEV (Leuer, 2017). A single-lane roundabout had the lowest crash rate of 0.32 MEV (Leuer, 2017). Single-lane roundabouts also had lower serious injury crash rates than all signalized intersection scenarios, having a crash rate of 0.31 MEV (Leuer, 2017). Signalized intersections on low-volume/low-speed roads, high-volume/low-speed roads, and high-volume/high-speed roads had serious injury crash rates of 0.45 MEV, 0.76 MEV, and 0.48 MEV (Leuer, 2017). Table 2-3 displays CMFs associated with converting a signalized intersection to a roundabout adapted from three safety studies that performed an EB analysis. The results show reductions in terms of severity, and two out of three studies also reported reductions in the total number of crashes.

Table 2-3: CMFs for Signalized Intersection to Roundabout Conversion

Reference	State	Number of Sites	Roundabout type	Methodology	CMF	
					Total	FI
Savolainen et al. 2023	MDOT	43	Single/double	Empirical-Bayes	1.92	0.81
Rodegerdts et al. 2007	Multiple	9	All	Empirical-Bayes	0.52	0.22
Gross et al. 2013	Multiple	28	All	Empirical-Bayes	0.792	0.342

Note: * Not Statistically Significant

A study included in Table 2-3 entitled, “Safety effectiveness of converting signalized intersections to roundabouts,” collected crash data from roundabouts throughout the United States that were previously signalized and performed an EB analysis as well as a cross-sectional analysis to confirm the EB analysis results (Gross et al. 2013). The results showed improvements in safety in terms of crash frequency as well as severity with not much difference between single and multilane roundabouts (Gross et al. 2013). The study noted that as the annual average daily traffic (AADT) of the intersection increased, the less notable improvements in crash frequency from roundabout implementation, but the crash severity changes were unaffected (Gross et al.

2013). NCHRP Report 572 (Rodegerts et al. 2007) included in Table 2-3, performed an EB analysis of 9 previously signalized intersections in urban and suburban settings converted to a roundabout and found similar results showing a reduction in crash frequency and an even larger reduction in terms of severity. The study performed for MDOT conducted additional EB analyses based on the prior control type of the roundabout. Forty-three of the sites included in the analysis were previously signalized intersections, and the results when these sites were grouped showed similar results to the analysis that included all prior control types (Savolainen et al. 2023). The results once again showed an increase in overall crash frequency, but the increase was larger when converting from a signalized intersection (Savolainen et al. 2023). Despite an increase in total crash frequency, FI crashes were reduced (Savolainen et al. 2023). When converting a signalized intersection to a roundabout, there will likely be a reduction in total crash frequency. If the number of crashes per year does increase, a reduction in FI crashes is still expected.

2.5.4. Stop-controlled Intersection to Roundabout Conversion

Safety evaluations on roundabouts that were previously stop-controlled intersections have found similar results in terms of reductions in total and FI crashes per year after roundabout implementation. There is currently more available research on two-way stop-controlled (TWSC) to roundabout conversion than all-way stop-controlled (AWSC). A simple before-after analysis of 11 single-lane roundabouts in Arizona, most of which were converted from a TWSC intersection, saw an 18% decrease in total crash rate per year and a 63% reduction in FI crash rate per year (Mamlouk & Souliman 2019). PDO crashes increased slightly by about 2% per year (Mamlouk & Souliman 2019). When incorporating changes in traffic volume in the analysis, the study found reductions in total (19%), FI (58%), and PDO crash rate per million vehicles (4%)

(Mamlouk & Souliman 2019). Multiple research reports have developed CMFs from the EB methodology to quantify the safety effectiveness of converting a stop-controlled intersection to a roundabout, and a summary of the results can be found in Table 2-4.

Table 2-4: CMFs for Stop-controlled Intersection to Roundabout Conversion

Reference	State	Number of Sites	Prior Control Type	Roundabout type	Methodology	CMF	
						Total	FI
Savolainen et al. 2023	MI	46	Stop-controlled	Single/double	Empirical-Bayes	1.29	0.76
Rodegerdts et al. 2007	N/A	10	AWSC	All	Empirical-Bayes	1.03	1.28
		36	TWSC	All	Empirical-Bayes	0.56	0.18
		9	TWSC	Single lane (R)	Empirical-Bayes	0.29	0.13
		12	TWSC	Single lane (U)	Empirical-Bayes	0.61	0.22
		4	TWSC	Single lane (S)	Empirical-Bayes	0.22	0.22
Sun & Ashifur 2019	LA	11	TWSC	Single lane	Empirical-Bayes	0.51	-
		5	TWSC	Single lane	Empirical-Bayes	0.28	-
Guin et al. 2018	GA	16	Stop-controlled	Single lane	Empirical-Bayes	0.63	0.49
		27	Stop-controlled	All	Empirical-Bayes	0.44	0.31

R = Rural, U = Urban, S = Suburban

As seen in Table 2-4, more research is available for assessing the potential safety effectiveness of converting a TWSC intersection to a roundabout versus AWSC conversion. Most studies have observed a reduction in crash frequency in addition to severity when converting a TWSC intersection to a roundabout. NCHRP Report 572, included in Table 2-4, included CMFs developed from an EB analysis for 10 AWSC and 36 TWSC intersections to roundabout conversions and assessed TWSC conversion further based on area type (Rodegerts et al. 2007). The resultant CMFs for total and FI crashes for each group can be found in Table 2-4. Based on NCHRP Report 572 results, TWSC to roundabout conversion leads to greater safety improvements compared to AWSC conversion, which resulted in an increase in total crashes and FI crashes. This result was based on a smaller sample size of AWSC intersections and based on the given standard errors for total and FI crashes (0.146 and 0.406) it could not be concluded at a 95% confidence level whether AWSC to roundabout conversion resulted in an increase, decrease, or no change in crashes. The results based on area type showed roundabouts in rural and suburban settings having slightly better safety performance. The study performed by the Louisiana Transportation Research Center found that 11 roundabouts converted from a TWSC intersection had an overall reduction in crashes. Five out of 11 sites included in the analysis did not change the number of approaches after conversion, and when grouped greater safety improvements were reported. Both results are displayed in Table 2-4. This study also included a simple before-after for AWSC intersection to roundabout conversion that showed approximately a 24% increase in total crashes, a 25% decrease in injury crashes, and a 28% decrease in angle crashes (Sun & Ashifur 2019). A study entitled, "Safety Evaluation of Roundabouts in Georgia" adopted an approach based on the EB method due to a lack of data availability (Guin et al. 2018). The study generated CMFs for 23 roundabouts converted from a stop-controlled intersection, not including triple-lane roundabouts or those with five approaches. Sixteen out of the 23 sites were single-lane roundabouts with four approaches. The results were a CMF of 0.63 and 0.49 for total and FI crashes at the 16 single-lane, 4-approach roundabouts and a CMF of 0.44 and 0.31 for total and FI crashes at all 23 roundabouts included in the study (Guin et al. 2018). The safety analysis in Georgia performed by the Georgia Department of Transportation (GDOT) conducted two separate EB analyses. The first results listed under reference Guin et al. 2018 in Table 2-4 included four-leg stop-controlled intersections converted to four-leg single-lane roundabouts only. The second results considered all roundabout types with a varying number of approaches, and 25 out of 27 sites included were single-lane roundabouts. When assessing the safety effects of converting a stop-controlled intersection to a roundabout, most research has found greater safety improvements when converting from a TWSC intersection versus an AWSC. The evaluation conducted by MnDOT comparing the crash rate at roundabouts to other traffic control types found opposing results due to single-lane roundabouts having a crash rate of 0.32 MEV, which is higher than urban TWSC intersections (0.18 MEV) and rural TWSC intersections (0.25 MEV), but lower than AWSC intersections (0.35 MEV) (Leuer, 2017). Despite this, single-lane roundabouts showed lower crash rates for serious injury crashes, having a crash rate of 0.31 MEV, while urban TWSC had a serious injury crash rate of 0.33 MEV, rural TWSC had a serious crash rate of 1.05 MEV, and AWSCs had a serious crash rate of 0.57 MEV (Leuer, 2017). These results correspond with the other research results that some roundabout sites may experience an increase in total crashes, but crash severity is expected to reduce.

2.5.5. Multimodal Impacts

Pedestrians and bicyclists comprise a small percentage of crashes at an intersection but are still an important factor in the safety of an intersection since crashes involving these groups can often be severe.

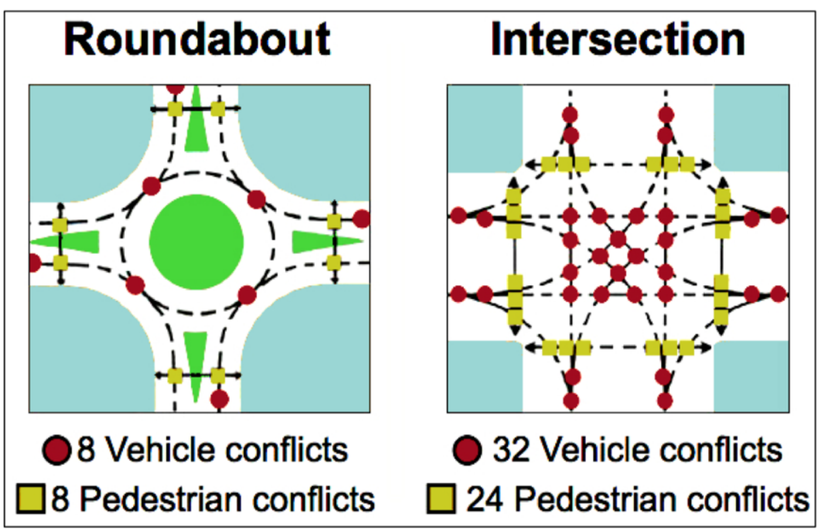

Figure 2-2: Single-lane Pedestrian Roundabout Conflict Points (Source: Savolainen et al. 2023)

Single-lane roundabouts reduce the number of pedestrian conflict points from 24 at a conventional intersection to 8, which can be seen in Figure 2-2 (Savolainen et al. 2023). Also, slower driving speeds at roundabouts improve the safety of pedestrians and bicyclists at the intersection in addition to other vehicles. Roundabouts are often designed with splitter islands that are utilized for pedestrian crossing. Splitter islands provide pedestrian refuge mid-crossing while also controlling vehicle speeds and separating conflicting traffic flows (Robinson et al. 2000). Bicyclists may utilize the same crossings as pedestrians through a multi-use path or travel alongside vehicles. There is currently not much research comparing safety effects for bicyclists at roundabouts compared to other intersections (Rodegerdts et al. 2023). The Louisiana Transportation Research Center study reported no pedestrian-involved crashes between 18 roundabouts after conversion, whereas one occurred at the same sites prior to conversion (Sun & Ashifur 2019). The safety evaluation conducted by MnDOT found an increase in pedestrian and bicyclist crashes after single lane roundabout implementation (Leuer, 2017). A study entitled, "Accelerating Roundabout Implementation in the United States – Volume IV of VII" found positive results for pedestrian and bicyclist involved crashes showing that roundabouts nationwide had fewer fatal crashes involving pedestrians and bicyclists (Steyn et al. 2015). The study also found that roundabouts had a higher percentage of crashes involving a motorcyclist, which are typically more severe, compared to other intersections (Steyn et al. 2015). The only two fatal crashes that occurred between the 18 roundabouts in the Louisiana Transportation Research Study were a motorcyclist running off the road (Sun & Ashifur 2019) Motorcycle crashes typically occur in the circle due to losing control (Rodegerdts et al. 2023), (Steyn et al. 2015). The evaluation also found an increase in heavy vehicle related crashes (Sun & Ashifur 2019). A survey conducted by Kansas State University and researchers from the American

Transportation Research Institute found that roundabouts are difficult for heavy vehicles to navigate, with commercial truck drivers reporting issues with roundabouts being too small, running onto curbs, difficulty merging, and trailers encroaching or drifting (Park & Pierce 2013). A large portion of respondents (73%) reported that roundabouts are more difficult to navigate than other intersections (Park & Pierce 2013). The reduction of conflict points and driver speeds, as well as design features such as splitter islands, likely reduce pedestrian and bicyclist crash risk at roundabouts, but some research has shown an increase in crashes involving these vulnerable road users. Another concern among the existing research is the ability of motorcyclists to navigate roundabouts.

2.5.6. Conclusion

Existing research on roundabout safety, specifically single-lane roundabouts, has found that the alternative is a practical solution to decrease the frequency and severity of crashes at an intersection. Roundabouts improve safety by reducing driver speeds and conflict points, specifically crossing conflicts. The change in conflict points due to roundabout implantation include:

- Total conflict points reduced from 32 to 8
- Crossing conflicts reduced from 16 to 0
- Diverging conflicts reduced from 8 to 4
- Merging conflicts reduced from 8 to 4 (Rodegerdts et al. 2023), (Gross et al. 2013).

Most existing research on roundabouts throughout the United States has reported a reduction in total crashes per year, but some cases have found that roundabouts have a negative impact or no impact at all on crash frequency. The most important safety difference between roundabouts and conventional intersections is the elimination of crossing conflict points. In terms of crash severity, research agrees that roundabouts effectively reduce the number of FI crashes per year that occur at an intersection. Studies have found opposing results on whether PDO crashes are expected to increase or decrease, but PDO crashes are not severe. Research on signalized intersection to roundabout conversion has found that FI crash rates are expected to decrease, but impacts on overall crash frequency are not as clear. Further research has been done on TWSC to roundabout conversion versus AWSC, and the results show reductions in total and FI crashes. AWSC intersection to roundabout conversion has been found to potentially increase the total and FI crashes at a site. Roundabout safety concerns frequently reported include fixed object crashes and motorcycle involved crashes. Roundabouts accommodate pedestrians and bicyclists well and reduce vehicle-pedestrian conflict points from 24 to 8 (Savolainen et al. 2023). There is less risk at a roundabout of a severe crash involving a vulnerable road user due to slower driver speeds and design features such as splitter islands.

2.6 RCUT Safety Impacts

2.6.1. Introduction

Restricted Crossing U-turn Intersections (RCUTs) prevent minor road drivers from turning left or crossing through an intersection, forcing them to turn right and make a U-turn downstream. These movements are a low priority and high risk at a typical intersection due to drivers having to navigate multiple lanes of high-speed and high-volume traffic. In the United States, the RCUT was first discussed by Richard Kramer as a method to reduce congestion on suburban arterials (Hummer et al. 2014). Despite being initially designed for operational purposes, RCUTs eliminate complex turning movements that can be dangerous along a high-speed, high-volume roadway. RCUTs can be signalized, stop-controlled, or yield-controlled.

Figure 2-3 displays the typical location of signals at an RCUT which are often at the main intersection and crossover locations.

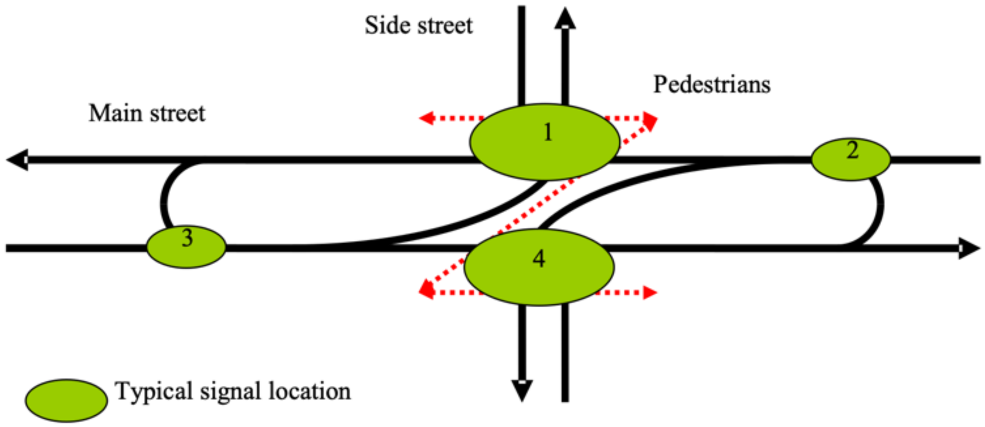

Figure 2-3: RCUT Signal Locations (Source: Hughes et al. 2010)

RCUTs improve safety by reducing the number of conflict points like roundabouts, and signalized RCUTs may provide additional benefits by managing driver speeds and protecting the left turn movement from the major road (Hummer & Rao 2017). As shown in Figures 2-4 and 2-5, RCUTs reduce the number of conflict points from 32 at a conventional four-legged intersection to 14, lowering crossing conflict points from 16 to 2 (Al-Omari et al. 2020), (Hummer & Rao 2017), (Hummer et al. 2014), (Mishra & Pulugurtha 2021). Left turn movements from the major road are typically permitted but may be restricted to further decrease the number of crossing conflicts at an RCUT.

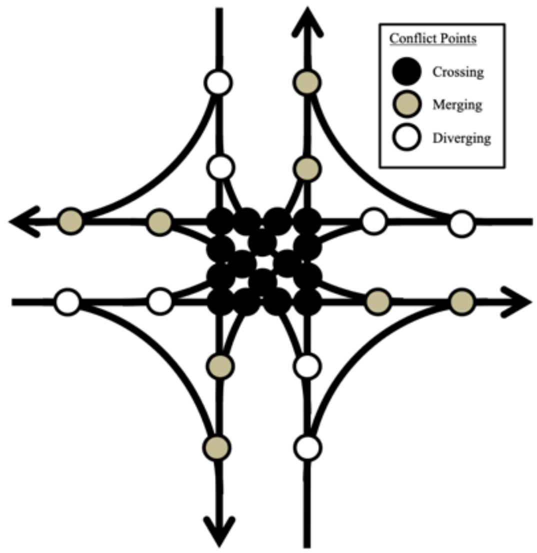

Figure 2-4: Typical Four-Legged Intersection Conflict Points (Source: Hummer & Rao 2017)

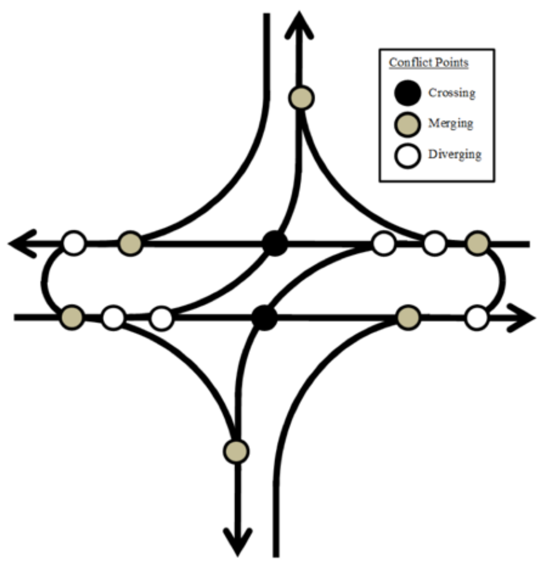

Figure 2-5: Conflict Points at an RCUT Intersection (Source: Hummer & Rao 2017)

RCUT implementation is common on a four-lane divided highway and reduces the number of conflict points from 42 to 24 while significantly reducing crossing conflicts from 24 to 4 (Edara et al. 2015), (WDOT). Figures 2-6 and 2-7 show the comparison of conflict points by lane between a four-lane divided highway and an RCUT.

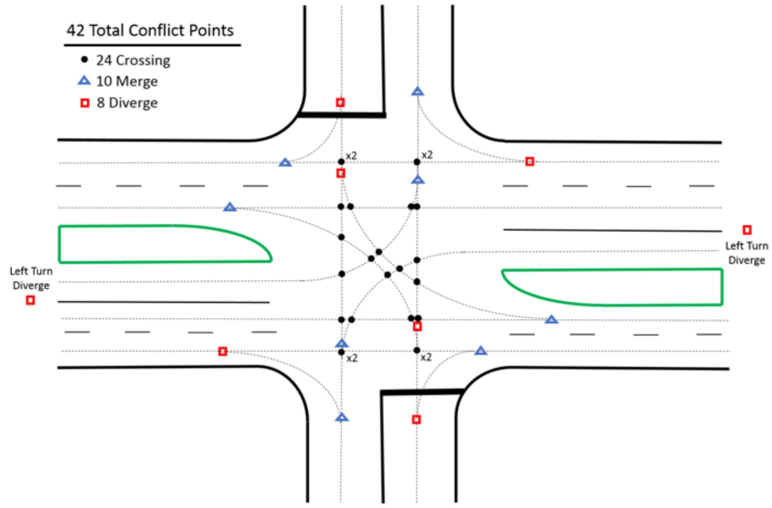

Figure 2-6: Four-lane Divided Highway Conflict Points (Source: WDOT)

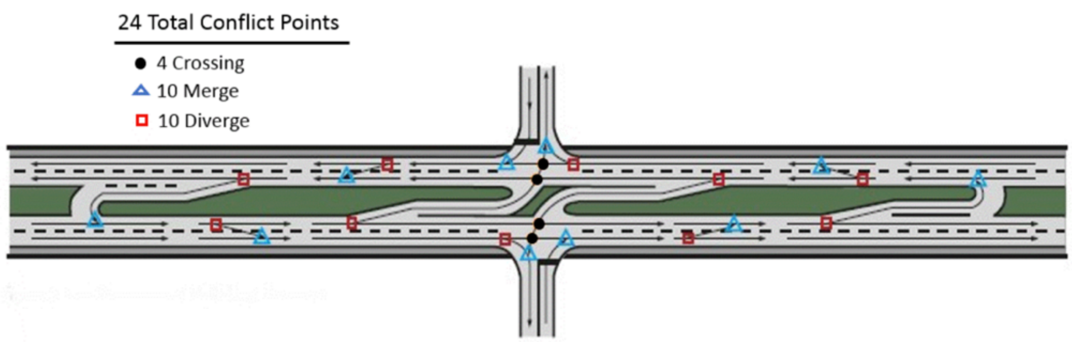

Figure 2-7: RCUT Conflict Point Diagram on a Four-Lane Divided Highway (Source: WDOT)

RCUTs may be four legs, three legs, or offset depending on minor road locations (Hughes et al. 2010). Also, RCUTs perform best at locations with a lower minor street traffic volume since these drivers must perform additional turning movements (Mishra & Pulugurtha 2021).

2.6.2. Overall Changes in Crash Frequency and Severity

Research projects conducted throughout the United States have concluded that RCUT implementation leads to a reduction in the number of total and FI crashes per year at an intersection. A summary of the CMFs adapted from the literature is shown in Table 2-5.

Table 2-5: RCUT CMFs from the Literature

Reference	State	Number of Sites	Methodology	CMF	
				Total	FI
Sun & Ashifur, 2019	LA	6	Improved prediction model	0.87	-
		6	Improved prediction model **	0.69	-
		6	Empirical-Bayes **	0.8	-
Hummer et al. 2010	NC	13	Empirical-Bayes	0.728	0.49
		13	Comparison group	0.538	0.373
Al-Omari et al. 2020	MI, NC, OH	12	Comparison group	0.76	0.567

Note: * Not statistically significant, ** Only considered the main RCUT intersection, not the entire section

In 2019, the Louisiana Transportation Research Center performed an EB analysis and an improved prediction methodology to determine the safety effectiveness of 10 signalized and stop-controlled RCUTs within the state. Six out of the 10 RCUTs included in the study were "complete RCUTs" with a main intersection and two U-turn crossovers (Sun & Ashifur 2019). Three sites were located on an urban 4-lane divided highway, two on an urban 6-lane divided highway, and one on a rural 4-lane divided highway (Sun & Ashifur 2019). Two separate improved prediction models were generated, one considering the entire RCUT section and one considering the main intersection only (Sun & Ashifur 2019). The EB analysis in this study only included the main intersection. The RCUT section crashes included those occurring at and in between U-turn crossovers whereas intersection only crashes were those within 150 ft from the main intersection (Sun & Ashifur 2019). Both improved prediction models and the EB analysis for the six "complete RCUTs" showed a reduction in crashes presented in Table 2-5 (Sun &

Ashifur 2019). The highest reduction in crashes was observed using the improved prediction model only considering the main intersection. The 2010 North Carolina study was performed by the North Carolina Department of Transportation (NCDOT) and evaluated TWSC RCUTs in rural locations. The evaluation of signalized sites within the report was not conclusive (Hummer et al. 2010). The study performed a comparison group analysis and an EB analysis that involved calibrating the 14-step method outlined in Chapter 9 of the *HSM* (Hummer et al. 2010). Both methods showed that unsignalized RCUTs effectively reduce total and FI crashes at intersections along divided highways. Lastly, included in Table 2-5 is a research article entitled *Safety Evaluation of Median U-Turn Crossover-Based Intersections* (Al-Omari et al. 2020). The study conducted a safety evaluation of 12 signalized RCUTs using a before-after methodology with a comparison group containing 20 comparison sites (Al-Omari et al. 2020). Three different RCUT crash influence area scenarios were assessed, and it was determined that a 250 ft circular buffer around the main intersection and another 50 ft buffer around each crossover yielded the most accurate results for collecting crash data related to the RCUT (Al-Omari et al. 2020). The study found similar results to other safety evaluations, showing that RCUT implementation can offer significant reductions in crashes. The safety evaluation of RCUTs conducted by the Louisiana Transportation Research Center did not perform an EB analysis or improved prediction methodologies when assessing crash changes based on severity and crash type, but the simple before-after analysis shows notable safety improvements. When considering the 6 complete RCUTs, fatal crashes were reduced by 100% for both the RCUT section and intersection only (Sun & Ashifur 2019). Injury crashes for the RCUT section and intersection only were also reduced by approximately 12.8% and 45.1% (Sun & Ashifur 2019).

RCUT construction has been found to significantly reduce the number of FI crashes due to eliminating through and left turn movements from the minor road at intersections with high-speed divided or undivided highways. Removing these challenging maneuvers for drivers reduces the likelihood of severe collision types from occurring. Intersections along divided highways have a higher portion of right-angle crashes due to the difficulty navigating the intersection from the minor road, and this is one of the main crash types RCUTs are implemented to prevent (Inman et al. 2012), (Sun & Ashifur 2019). Multiple safety evaluations have proven that RCUTs are effective at reducing angle, head-on, and left-turn collisions (Al-Omari et al. 2020), (Hummer et al. 2010), (Sun & Ashifur 2019). Studies have opposing results on how RCUTs impact the occurrence of sideswipe crashes, but this risk can be reduced through acceleration lanes, deceleration lanes, and adequate weaving segment lengths (Sun et al. 2019). In some cases, an increase in single-vehicle crashes has occurred, whereas other times, no significant changes were observed (Al-Omari et al. 2020), (Sun et al. 2019). Research also commonly reported reductions in rear-end crashes after RCUT implementation (Al-Omari et al. 2020), (Sun & Ashifur 2019). Using the comparison group methodology, NCDOT observed a decrease in rear-end crashes, whereas the EB method resulted in an increase in rear-end crashes (Hummer et al. 2010). Overall, RCUT implementation can be expected to result in a reduction of targeted severe collision types in addition to total, FI, and PDO crashes.

2.6.3. Signalized Intersection to RCUT Conversion

The North Carolina Department of Transportation conducted a safety evaluation of RCUTs based on prior intersection control type entitled “Safety Evaluation of Unsignalized and Signalized Restricted Crossing U-Turn (RCUT) Intersections in Rural and Suburban Areas Based on Prior Control Type.” Out of the 42 sites included in the study, two were signalized

RCUTs converted from a signalized intersection. One site was in a rural area, and one was in a suburban area. The CMFs developed from an EB analysis for each site can be found in Table 2-6, showing that each site experienced a reduction in total crashes and an even greater reduction in FI crashes. The suburban site had a greater reduction in total crashes than the rural, but for FI crashes, the rural site had greater improvements (Mishra & Pulugurtha 2021). The Federal Highway Administration (FHWA) conducted an evaluation of RCUTs titled, *Safety Evaluation of Signalized Restricted Crossing U-Turn Intersections*. This study developed CMFs for signalized RCUTs located in Alabama, North Carolina, Ohio, and Texas. The study only included sites that already were previously signalized, resulting in 11 study sites. All sites were in a suburban area and on four or six-lane arterial roadways, and the analysis incorporated crash data from the entire RCUT section (Hummer & Rao 2017). A comparison group analysis was performed, and the results show that signalized RCUTs converted from a conventional signalized intersection resulted in a reduction in total and FI crashes. The CMFs resulting from the comparison group analysis can be found in Table 2-6.

Table 2-6: CMFs for Signalized Intersection to RCUT Conversion

Reference	State	Number of Sites	RCUT Control Type	Methodology	CMF	
					Total	FI
Mishra & Pulugurtha 2021	NC	1 (R)	Signal	Empirical-Bayes **	0.9 *	0.16 *
		1 (S)	Signal	Empirical-Bayes **	0.69 *	0.59 *
Hummer & Rao 2017	AL, NC, OH, TX	11 (S)	Signal	Comparison group	0.85 *	0.78 *

Note: * Not statistically significant, ** Only considered the main RCUT intersection not the entire section

R = Rural, S = Suburban

The FHWA evaluation of RCUTs also included a before-after analysis adjusted for traffic volume. One of the 11 sites was removed from the traffic volume analysis due to a lack of official volume data (Hummer & Rao 2017). The traffic volume analysis resulted in all sites having a resultant CMF of 1.00 for total crashes and 1.07 for injury crashes (Hummer & Rao 2017). The comparison site analysis was preferred over the traffic volume analysis and the study recommended the CMFs presented in Table 2-6 for converting a signalized intersection to a signalized RCUT (Hummer & Rao 2017). The Alabama sites included in the study, US-231 at Plum Rd and US-231 at Retail Rd in Dothan, resulted in CMFs of 0.51 and 0.17 for overall crashes and 0.45 and 0.23 for injury crashes in the comparison site analysis (Hummer & Rao 2017). The study mentioned that the odds ratio methodology for selecting comparison sites was more precise for overall crashes versus injury crashes, based on how close the odds ratio value is to 1.00, due to injury crashes having a smaller sample size (Hummer & Rao 2017). Lastly, the study found a decrease in angle crashes but an increase in sideswipe and rear-end crashes at signalized RCUTs (Hummer & Rao 2017). An increase in sideswipe crashes agrees with some of the previously mentioned research, but most studies have found a reduction in rear-end collisions.

2.6.4. Stop-controlled Intersection to RCUT Conversion

The same study conducted by the NCDOT entitled "Safety Evaluation of Unsignalized and Signalized Restricted Crossing U-Turn (RCUT) Intersections in Rural and Suburban Areas Based on Prior Control Type" included 19 rural and 18 suburban site locations converted from a typical TWSC intersection to an unsignalized RCUT. Out of the 19 rural sites, 9 had crossovers located at a median opening and 10 had U-turns locations at the next intersection. CMFs determined from the EB analysis that indicate a reduction in total and FI injury crashes are shown in Table 2-7. As previously mentioned, the results of this study only included data from the main RCUT intersection not the entire system. Unsignalized RCUTs greatly reduced the severity of crashes, and it was concluded that unsignalized RCUTs are a more practical choice over signalized (Mishra & Pulugurtha 2021). Table 2-7 also includes CMFs developed from two safety evaluations conducted in Missouri and Maryland of unsignalized RCUTs.

Table 2-7: CMFs for Stop-controlled Intersection to RCUT Conversion

Reference	State	Number of Sites	RCUT Control Type	Methodology	CMF	
					Total	FI
Mishra & Pulugurtha 2021	NC	19 (R)	TWSC	Empirical-Bayes **	0.29	0.24
		18 (S)	TWSC	Empirical-Bayes **	0.35	0.27
Edara et al. 2015	MO	5	TWSC	Empirical-Bayes	0.69	0.36
Inman et al. 2012	MD	9 (R)	TWSC	Comparison Group	0.72 *	-
		9 (R)	TWSC	Empirical-Bayes	0.56 *	-

Note: * Unknown statistical significance, ** Only considered the main RCUT intersection not the entire section

R = Rural, S = Suburban

The study conducted in Missouri entitled "Empirical Evaluation of J-Turn Intersection Performance: Analysis of Conflict Measures and Crashes," had positive results when assessing the safety effects of converting a TWSC intersection to an unsignalized RCUT. Crash data from the entire RCUT section was incorporated into the analysis and yielded a reduction in total and FI crash frequency (Edara et al. 2015). The report included that RCUTs reduced annual serious injury crashes by 91.6%, minor injury crashes by 67.9%, and PDO crashes (Edara et al. 2015). Also, RCUT implementation reduced right-angle crashes and eliminated left-turn crashes, which often have a more severe outcome compared to other crash types (Edara et al. 2015). In Maryland, an RCUT and a conventional stop-controlled intersection on a rural four-lane divided highway were both recorded on two weekdays to perform a field analysis to compare the observed performance of each. Observations showed fewer traffic conflicts at the RCUT, reduced crossing conflicts, and little effects on weaving conflicts (Inman et al. 2012). The field evaluation report also included a safety analysis of 9 rural RCUTs located on two different four-lane divided highways within the state. The results of the comparison group analysis and EB analysis presented in Table 2-7 showed reductions in average total crashes per year. The study also noted a 70% reduction in fatal crashes and a 42% reduction in injury crashes due to RCUT implementation based on simple before-after data (Inman et al. 2012).

2.6.5. Multimodal Impacts

RCUTs typically positively impact pedestrian safety since they reduce the number of crossing points between pedestrians and vehicles. RCUTs compared to a conventional intersection, reduce the number of pedestrian-vehicle conflict points from 12 to 5 at a three-approach intersection and from 24 to 8 at a four-approach intersection (Hummer et al. 2014), (Hummer & Rao 2017). RCUTs further improve safety for pedestrians by not only reducing the number of conflict points but also minimizing encounters between pedestrians and left-turning vehicles (Hummer et al. 2014). This is beneficial because pedestrians are not always easily visible to vehicles turning left at an intersection (Hummer et al. 2014). The FHWA report entitled "Restricted Crossing U-turn Informational Guide" discusses the "Z" crossing layout shown in Figure 2-9 (Hummer et al. 2014). Minor streets are crossed similarly to a conventional intersection whereas on the major road pedestrians cross diagonally (Hummer et al. 2014). This crossing movement improves safety for pedestrians since the median breaks up the crossing distance while also providing refuge, allowing pedestrians to cross one direction of travel at a time.

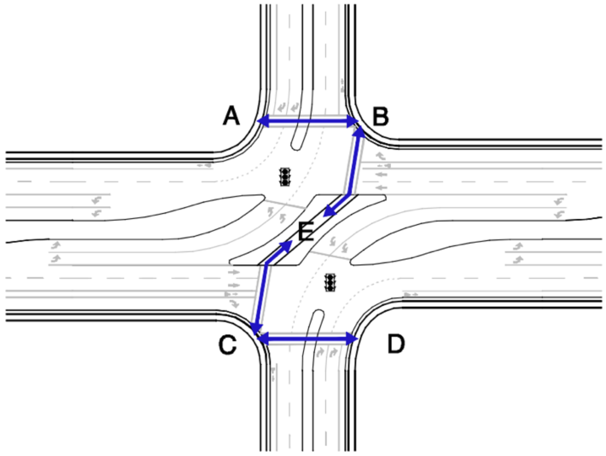

Figure 2-8: RCUT "Z" Crossing Movement (Source: Hummer et al. 2014)

Bicyclists can navigate an RCUT in three ways…

- Follow the same route as pedestrians through a shared use path
- Follow the same route as vehicles
- Through additional bicycle facilities (Hummer et al. 2014).

For example, bicyclists following the same route as vehicles may have difficulty navigating U-turn crossovers and one solution is providing a separate bicyclist U-turn location (Hummer et al. 2014).

Lastly, RCUT locations with a large volume of heavy vehicles may be designed with a larger median width, loons, or dual U-turn lanes to accommodate a larger turn radius depicted in Figure 2-8 (Hughes et al. 2010), (Hummer et al. 2014).

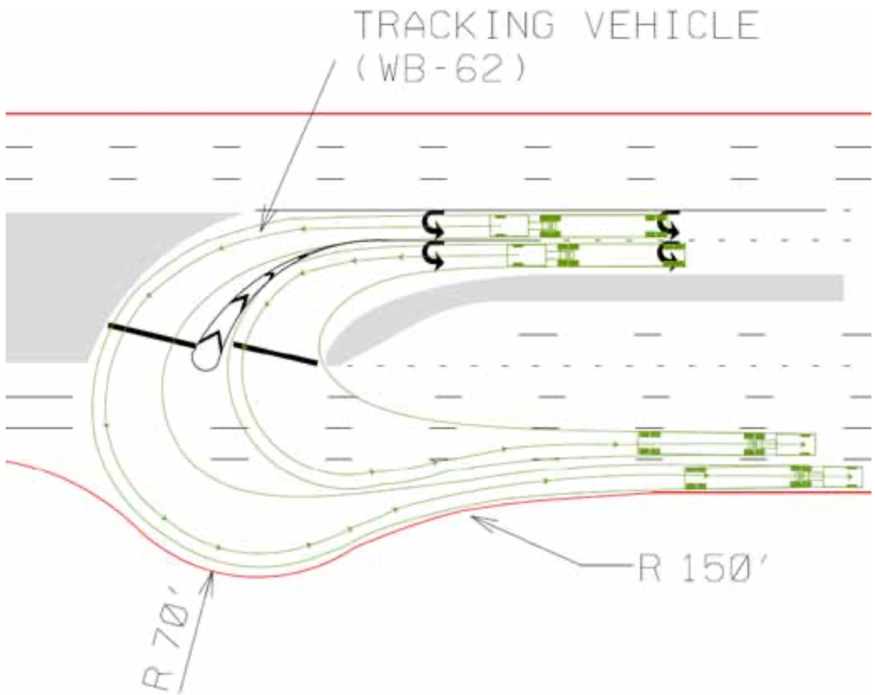

Figure 2-9: Loon and Dual U-Turn Lanes at an RCUT (Source: Hughes et al. 2010)

2.6.6. Conclusion

Current research on Restricted Crossing U-turn Intersections shows that the alternative effectively reduces the total and FI crashes. Navigating an intersection on a high-volume and/or high-speed roadway from a minor road can be difficult for drivers. RCUTs are frequently implemented on four-lane divided highways for this reason. Eliminating these movements decreases the total number of conflict points as well as high-risk crossing conflict points from…

- 32 to 14 vehicle-vehicle total conflict points at a 4-leg intersection
- 16 to 2 vehicle-vehicle crossing conflict points at a 4-leg intersection
- 42 to 24 vehicle-vehicle total conflict points at a four-lane divided highway
- 24 to 4 vehicle-vehicle crossing conflict points at a four-lane divided highway
- 12 to 5 vehicle-pedestrian conflict points at a 3-leg intersection

- 24 to 8 vehicle-pedestrian conflict points at a 4-leg intersection (Edara et al. 2015), (Hummer et al. 2014), (Hummer & Rao 2017), (Mishra & Pulugurtha 2021), (WDOT).

Estimated from the literature, a 13-46% reduction in overall crashes and a 43-63% reduction in FI crashes can be expected due to RCUT implementation. PDO crashes have also been found to decrease. The research currently uses different methodologies when assessing crashes occurring at RCUTs. Some studies only incorporated crashes occurring at the main intersection, while others considered the entire RCUT section or used a buffer around the main intersection and crossovers. Typically, studies that only assessed the main intersection found a greater reduction in total and FI crashes. RCUTs are effective at reducing more severe crash types such as left turn, angle, and head-on collisions. Studies have also noted reductions in rear-end and multiple-vehicle crashes, but there have been opposing results for sideswipe and single-vehicle crashes. Evaluations based on prior control type had similar results for signalized intersection to signalized RCUT conversion resulting in a reduction of total and FI crashes. Similar results were found for converting a TWSC to an unsignalized RCUT. Conversion from a TWSC intersection has also been found to reduce PDO, left turn, and right-angle crashes. More research has been conducted regarding TWSC conversion, likely due to a larger study site availability.

2.7. Continuous Green T Safety Impacts

2.7.1. Introduction

A Continuous Green T Intersection (CGT) permits vehicles on the major approach furthest from the minor road to flow freely through the intersection. The continuous through movement is typically depicted by a green arrow while left-turning vehicles from the minor road must merge in the continuous direction utilizing an acceleration lane (VDOT, 2023). CGTs and conventional T-intersections have the same number and type of conflict points. At CGTs, left-turning drivers are further protected before merging through delineators, curbed islands, pavement markings, etc. (Donnell et al. 2016). The acceleration lane also provides drivers more time to make decisions before merging and reduces the angle of potential collisions. The location of the conflict points at a CGT and conventional T-intersection, each with one travel lane in each direction, are shown below in Figures 2-10 and 2-11.

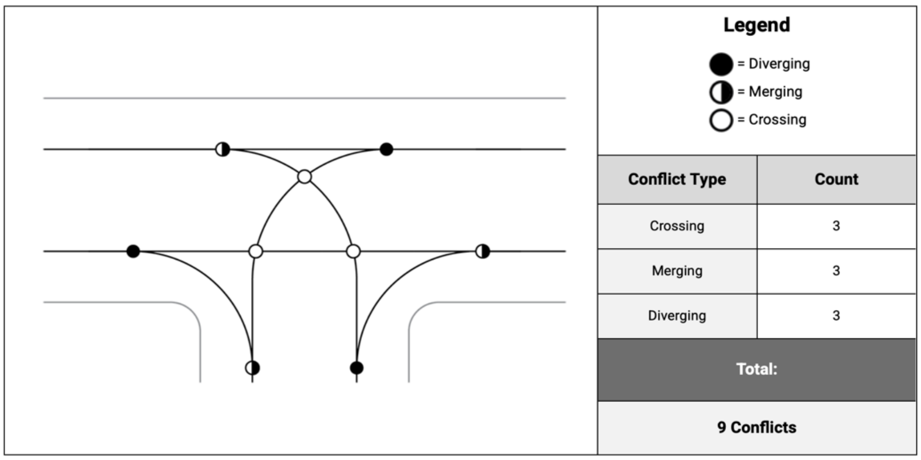

Figure 2-10: Conventional T-intersection Conflict Points (Source: VDOT, 2023)

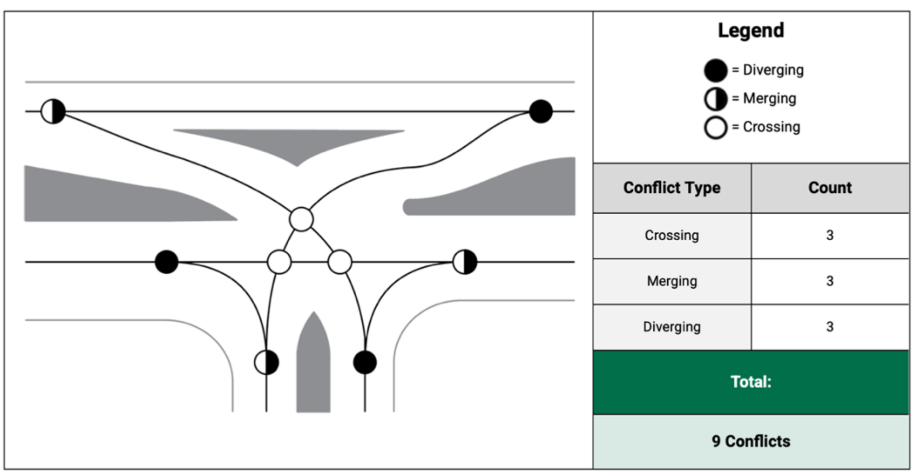

Figure 2-11: Continuous Green T-intersection Conflict Points (Source: VDOT, 2023)

CGTs increase the throughput of an intersection in the major direction. Similar to RCUTs, CGTs perform best at a location with a large through movement volume on the major road and fewer vehicles turning left from the minor road since they must find gaps in the continuously flowing roadway (Ngo, 2023), (VDOT, 2023).

2.7.2. Overall Changes in Crash Frequency and Severity

Less information is currently known on the safety effectiveness of CGTs compared to the other alternative intersections within this research. Before-after studies of CGTs have found inconclusive results with some reporting a decrease in total and FI crashes due to implementation and others reporting the opposite. In Florida, some CGTs have been converted back into conventional intersection designs due to safety concerns, difficulties accommodating pedestrians, geometric changes, and a lack of following Manual on Uniform Traffic Control Devices (MUTCD) guidelines (Lee et al. 2020). These concerns agree with those reported by other DOTs and transportation personnel in a survey conducted by the Minnesota Department of Transportation (MnDOT). The survey found that most CGTs improved safety overall, but the main safety concerns were truck acceleration, pedestrian crossing, driver confusion, traffic control devices, and driveways (Van Sluijs et al. 2018). The survey also found that DOTs report CGTs are safer when designed with a long acceleration lane and physical separation between the continuous direction and merging vehicles (Van Sluijs et al. 2018).

A research project sponsored by the Florida Department of Transportation (FDOT) conducted EB and cross-sectional analyses to determine the safety effects of converting CGTs back to conventional intersections. The cross-sectional analysis was performed to confirm the results of EB analysis using a larger sample size from multiple states (Lee et al. 2020). The EB analysis included six treated sites that were previously CGTs, and the comparison group contained thirteen CGTs (Lee et al. 2020). The results from this evaluation in terms of crash frequency and severity are shown in Table 2-8. Overall, the results indicate that CGTs have a higher rate of total, FI, and PDO crashes (Lee et al. 2020). This study also noted that physical separation between the acceleration lane and the major road can improve the safety of a CGT. None of the treated sites included in the EB analysis had any physical separation in the before-period which may contribute to the large safety improvement observed from removing the CGTs (Lee et al. 2020). A study published by FHWA assessing CGTs in Florida and South Carolina found that CGT implementation reduced total and FI crashes, the results are presented in Table 2-8 (Donnell et al. 2016). For Florida, 30 treatment sites were matched to 38 comparison sites, and in South Carolina, 16 treatment sites were matched to 21 comparison sites. The results were not statistically significant, potentially due to a small sample size, but indicate that a reduction in crashes can be expected due to CGT implementation.

Table 2-8: CGT CMFs from the Literature

Reference	State	Number of Sites	Prior Control Type	Methodology	CMF	
					Total	**FI**
Lee et al. 2020	FL	6	CGT	Empirical-Bayes	0.66	0.51
Donnell et al. 2016	FL, SC	46	Signal	Propensity scores framework	0.958 *	0.846 *

Note: * Not statistically significant

The study conducted by FDOT also saw a reduction in rear-end, single-vehicle, and CGT-related crashes when converting CGTs back into conventional intersections (Lee et al. 2020). The study defines a CGT-related crash as, “any collision (e.g., angled, left-turn, or sideswipe) between a through vehicle on the flat side (top) of the T-intersection and a left-turning vehicle from the minor road” (Lee et al. 2020). Angle crashes are a severe crash type that commonly occurs at signalized T-intersection, and a case study of two CGT conversions in Colorado found that angle crashes decreased after conversion (Rice & Znamenacek 2010). Both CGTs combined saw a 96.8% reduction in angle crashes, a 70% reduction in injury crashes, and a 60% reduction in total crashes (Rice & Znamenacek 2010). These intersections before conversion were rural signalized intersections with a high rate of angle and injury crashes (Rice & Znamenacek 2010). The results of this study were based only on 2 years of before and after data and did not account for variables potentially affecting the data, such as RTM bias.

2.7.3. Multimodal Impacts

Based on the current research, CGT intersections do not easily accommodate pedestrians and bicyclists. Issues related to pedestrian safety were commonly reported by DOTs in the MnDOT survey and were also part of the reason some Florida CGTs have been converted back to a signalized T intersection (Lee et al. 2020), (Van Sluijs et al. 2018). Pedestrians and bicyclists can cross the minor road at a CGT like a typical intersection, but crosswalks are not provided to cross the major road, and since vehicles are flowing continuously, it can be difficult for pedestrians to find gaps (VDOT, 2023). The study conducted by FDOT observed the safety improvements of CGTs conversion into conventional intersections and found no increase in crashes involving non-motorized users at CGTs compared to the conventional, but this was not statistically significant. CGTs are likely better suited at an intersection with a low volume of pedestrians and bicyclists.

2.7.4. Conclusion

CGTs improve the operational performance of a T-intersection due to the continuous flow of vehicles, but the safety impacts are not as clear. CGTs and conventional T-intersections have the same number and type of conflict points…

- 3 crossing conflict points
- 3 merging conflict points
- 3 diverging conflict points (VDOT, 2023)

In Florida, CGTs have been converted back into conventional T-intersections due to concerns that correspond to those reported by different DOTs that participated in the survey conducted by the MnDOT. Despite reporting some safety concerns, DOTs in the MnDOT survey concluded that CGTs overall improve safety, and other research has indicated this as well. The FHWA safety evaluation of CGTs and the case study of two CGTs conducted in Colorado both reported reductions in total, FI, and angle crashes. CGTs effectively reduce angle crash risk because drivers turning left from the minor road merge onto the major road utilizing an acceleration lane separated from the continuous flow lanes. The FHWA report also noted a decline in rear-end and sideswipe crashes due to CGT implementation. Despite this, CGTs in Florida were found to negatively impact total, FI, PDO, and rear-end crashes at T-intersections. Current research on the safety effectiveness of CGTs is limited, and the literature has found opposing results on whether CGT implementation will lead to a reduction in the total and FI crashes at an intersection.

2.8. Summary

The goal of this literature review was to a) identify the various methods utilized to quantify the safety effectiveness of design alternatives, b) determine how each alternative is currently performing in terms of safety throughout the United States, and c) find any gaps within the existing research. Before-after studies are the most common technique to assess the safety effects of a design feature or countermeasure. Before-after studies utilize historical, observed crash data and range in complexity. The accuracy of results improves when more years of data are included in the analysis and variables that may influence the observed data are considered, such as traffic volume, geometrics, and area type.

Intersections are a high-risk location for drivers, and existing research points towards that design alternatives can reduce this risk, but it is unknown how roundabouts, RCUTs, and CGTs are currently performing in Alabama. The *HSM* defines safety in terms of the occurrence of total crashes, severe crashes, and certain crash types (AASHTO 2010). Overall, research on the safety of roundabouts and RCUTs indicates positive results, showing reductions in the number of total and FI crashes per year. Each alternative reduces the total number of conflict points at an intersection while minimizing crossing conflicts and movement complexity. Roundabouts also effectively reduce driver speeds. There have been some opposing results on whether roundabouts result in a reduction in total crashes, but research agrees that the severity of crashes decreases after construction. Some concerns with roundabout safety are fixed object collisions and motorcyclists. Both alternatives have also been found to effectively reduce the frequency of more severe crash types such as angle, left turn, and head-on collisions. They also both reduce the number of vehicle-pedestrian conflict points and have facilities that provide pedestrian refuge and the ability to cross opposing traffic flows separately. Assessments based on prior control type for roundabouts and RCUTs have found similar results in terms of the number of total crashes, FI crashes, and severe crash types. The study of TWSC intersection conversion to alternative designs has been thorough, but there is a lack of attention toward AWSC conversion. Also, few studies have conducted safety evaluations of CGT implementation based on prior control type. Overall, there is less research on the safety effects of CGT conversion compared to roundabouts and RCUTs. A conventional T-intersection and a CGT have the same conflict points, and the existing research has found opposing results on how CGT implementation impacts the total and FI crashes at an intersection. The current research also indicates that CGT implementation may reduce angle crashes since drivers from the minor road utilize an acceleration lane to merge on the major. Lastly, research has reported concerns with pedestrians and bicyclists crossing the continuous flow direction. This thesis aims to expand upon the current knowledge of the safety performance of roundabouts, RCUTs, and CGTs and evaluate the changes in total and FI crashes per year after the implementation of these alternative designs throughout Alabama.

Chapter Three: Methodology

3.1. Introduction

This chapter outlines the data collection procedure and analysis methods used to evaluate the safety impacts of alternative intersection implementation in Alabama. The data collection involved compiling a list of sample treatment sites and collecting the necessary crash and volume data at each site. Google Maps and Google Earth were used to gather the necessary location and geometric details. Crash data was collected using the Critical Analysis Reporting Environment (CARE) managed by the Center for Advanced Public Safety at the University of Alabama, and the crash data collection and screening procedure is described in this chapter. Volume data was collected using the Alabama Traffic Data Portal (TDM Public), and the total entering volume on the major and minor approaches was determined. Before-after studies are the most common technique to assess the safety effectiveness of a treatment or design alternative. As previously mentioned, before-after studies utilize historical crash data and can range in complexity. To accurately quantify the safety effectiveness of alternative intersection implementations in Alabama, in-depth methodologies that incorporate variables that influence crash data were considered. The Empirical-Bayes method was explored but deemed inapplicable due to multiple reasons. First, there is currently a lack of Alabama specific SPFs or calibration factors to utilize in the EB approach. Second, the *HSM* provides guidance on when the EB method is applicable, stating that it should not be performed at, "Intersections at which the basic number of intersection legs or type of traffic control is changed as part of a project" (AASHTO, 2010). Due to this being the case for all sites, other methodologies were explored. Two analysis methods were selected, a simple before-after analysis and before-after analysis using a comparison group. A paired means hypothesis test was also performed to determine the statistical significance of the simple before-after results. The comparison group analysis was informed by a FHWA report entitled, “A Guide to Developing Quality Crash Modification Factors” (Gross et al. 2010). The comparison group methodology incorporates variables that may influence crash data such as traffic volume, number of approaches, and area type, into the development of CMFs. Additional analyses on the influence of prior control type and area type on safety performance were also conducted utilizing each methodology. Lastly, an assessment was made of the changes in the distribution of crash types across all sites after the implementation of each alternative intersection design.

3.2. Data Collection

3.2.1. Study Site Selection

To draw conclusions on the safety implications of each alternative intersection examined, a comprehensive list of sample sites that would be representative of the population was developed. All known sites throughout the state were included in the initial site list which consisted of 56 roundabouts, 19 RCUTs, and 13 CGTs. Site characteristics and geometric features such as major and minor road names, county, city, number of legs, number of lanes, latitude and longitude, and area type were determined for each site using available satellite imagery from Google Earth and Google Maps.

To conduct a before-after analysis, the start and end dates of construction for each site needed to be determined to select appropriate analysis periods. If the construction date for a site was unable to be provided by the associated ALDOT region or locality, historical imagery from Google Maps and Google Earth was used to estimate a start and end date. Most sites with a construction start date before 2016, and all sites with a construction completion date after August 2023 were removed from the study due to a lack of available crash and volume data. Also, any sites where the intersection was non-existent in the before-period were removed. The final list of sites can be found in Appendix A and includes 22 roundabouts, 15 RCUTs, and 6 CGTs.

An additional objective of this research was to assess the safety performance of each alternative based on independent variables such as prior control type, area type, and number of approaches. As previously mentioned, these characteristics were determined using the historical satellite imagery at each site and the descriptive statistics can be found in Tables 3-1 to 3-3.

Table 3-1: Site Location Based on Prior Control Type

Prior Control Type	Number of Roundabouts	Number of RCUTs	Number of CGTs
Signalized	5	1	0
TWSC	10	14	6
AWSC	7	0	0
Total	22	15	6

Table 3-2: Site Location Based on Number of Approaches

Number of Approaches	Number of Roundabouts	Number of RCUTs	Number of CGTs
3	6	1	6
4	14	14	-
5	2	-	-
Total	22	15	6

Table 3-3: Site Location Based on Area Type

Area Type	Number of Roundabouts	Number of RCUTs	Number of CGTs
Urban	8	7	1
Rural	14	8	5
Total	22	15	6

Approximately 63% of the sites within this research are in a rural location, 67% have 4 approaches, and 70% were previously TWSC. Only single-lane roundabouts were incorporated into the study due to having an inadequate sample size of double-lane roundabouts. All RCUTs evaluated were unsignalized intersections prior to implementation except for one location. The U-turn crossovers at each RCUT were either at a designated median opening (8 sites) or at the next signalized on unsignalized intersection (7 sites). Cases where crossovers were located at the next intersection are commonly part of a corridor-wide project where multiple RCUTs were installed along the same highway, often sharing crossovers. All RCUTs were located on either a 4-lane (11 sites) or 6-lane divided highway (4 sites) whereas all CGTs were located on a 4-lane divided highway except one site (County Rd 8 & County Rd 4) was implemented on a 2-lane highway. A map generated using ArcGIS Pro displaying site locations can be found in Figure 3-1. Figures 3-2 and 3-3 display the locations of sites based on prior control type as well as area type.

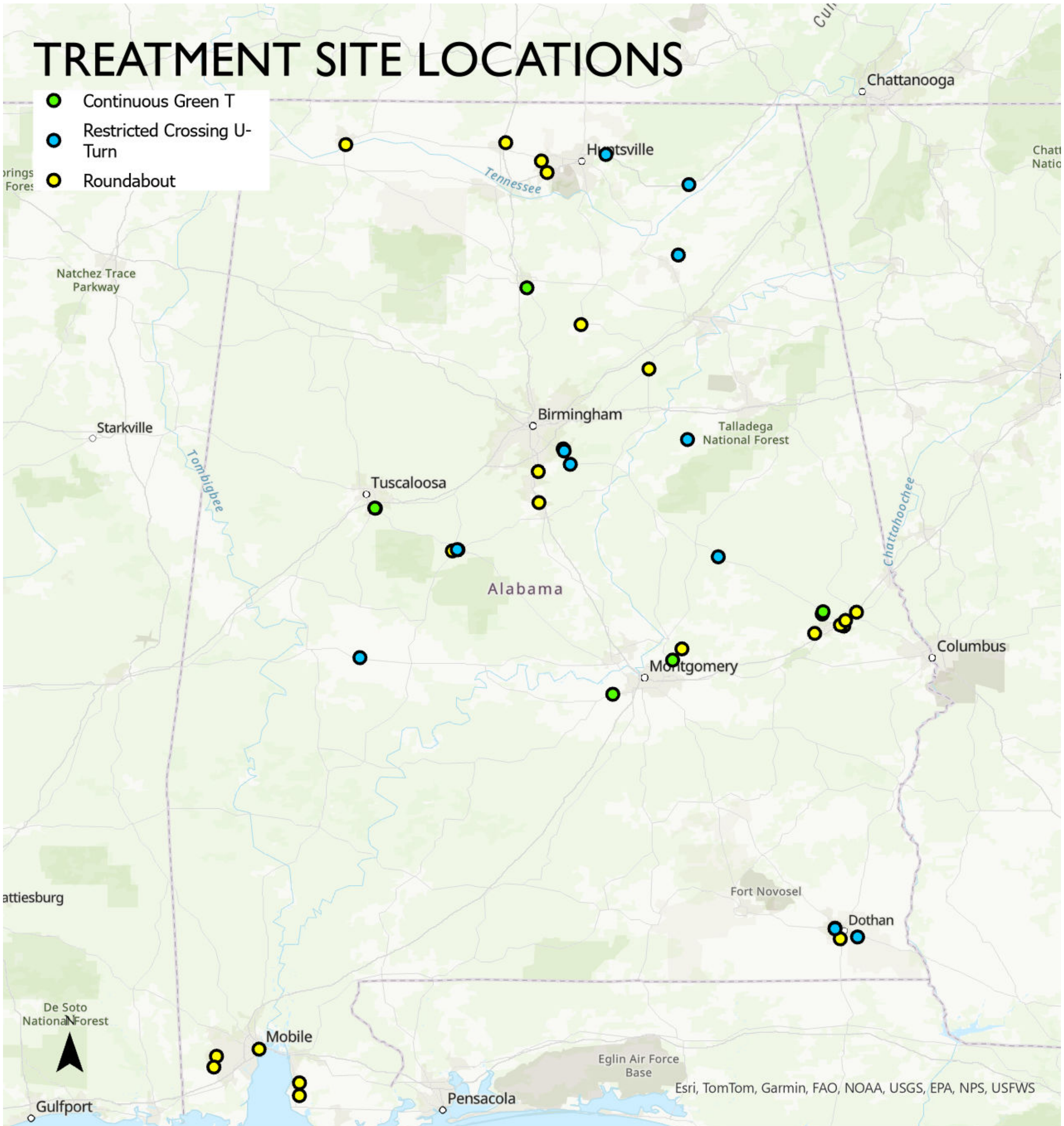

Figure 3-1: Site Location Map

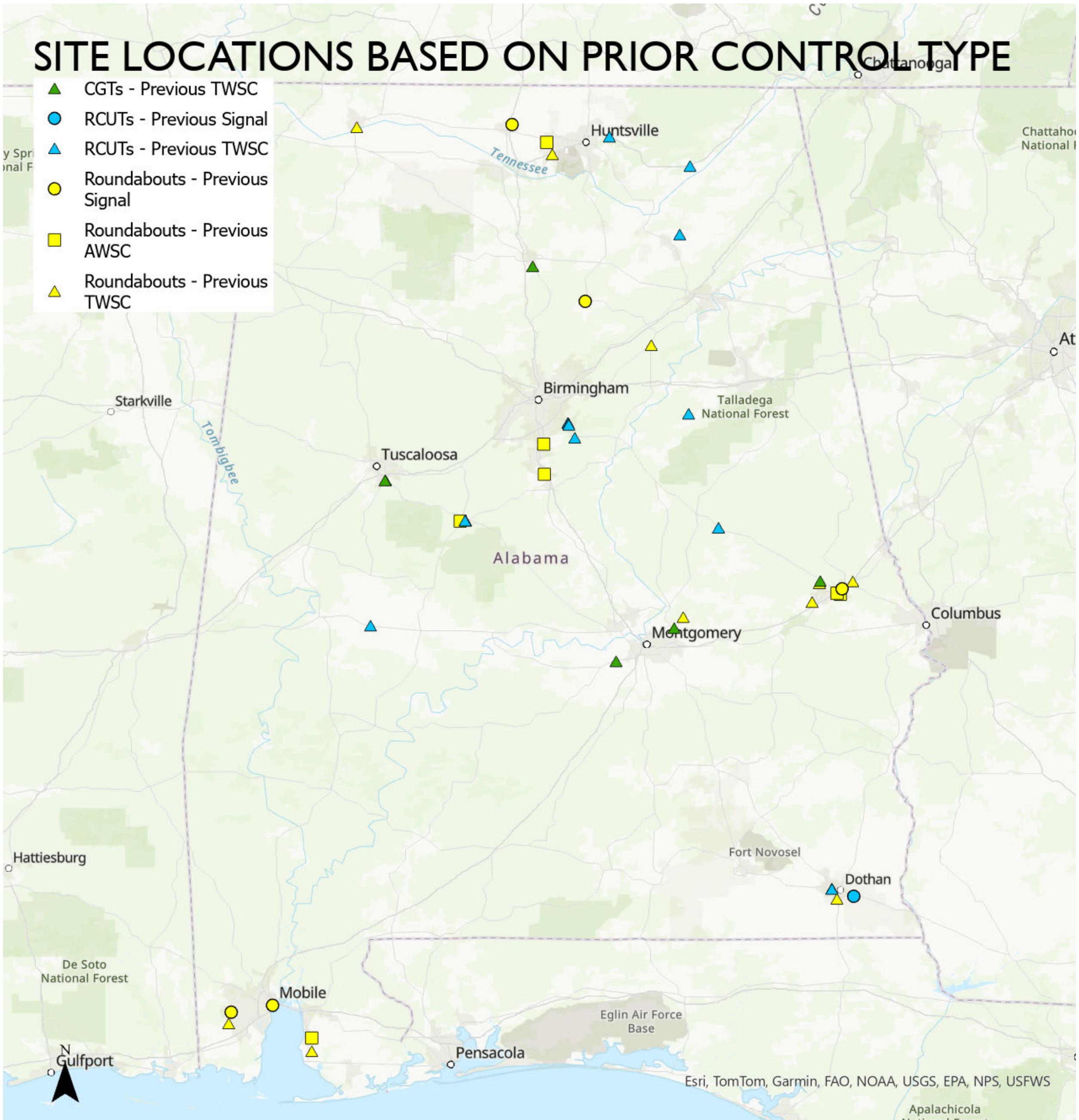

Figure 3-2: Site Location Map by Prior Control Type

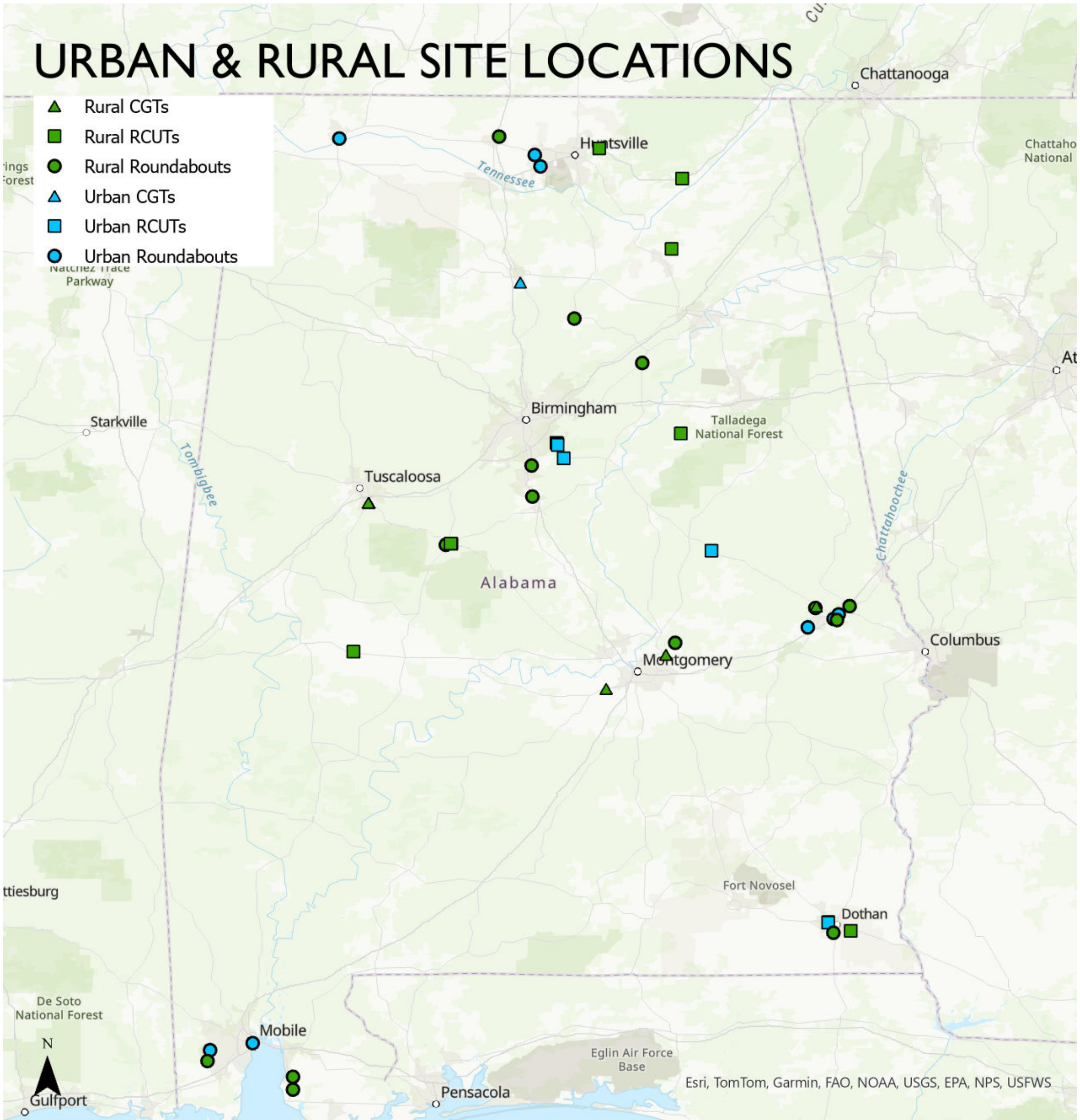

Figure 3-3: Site Location by Area Type

3.2.2. Crash Data

Crash data was collected using the Critical Analysis Reporting Environment (CARE) managed by the Center for Advanced Public Safety at the University of Alabama. CARE, at the time of this research, allowed permitted users to access details for all crashes reported in

Alabama dating back to 2016. The crash reports associated with each crash are also accessible through CARE. Based on the date of construction of each site, before and after periods of analysis were selected. The before and after periods excluded the time the intersection was under construction, and ideally included 3 to 5 years of data. All sites with at least one year of available crash data during the before and after period were included in the analysis, but a period of 3 to 5 years was used when possible. Due to only having access to crash data dating back to 2016 for most sites, a large portion of the remaining sites were installed in recent years resulting in less after period data. Table 3-4 below shows the number of sites that have data within this ideal range and those with less years of data available. Tables 3-5 through 3-7 show the breakdown of data availability specific to roundabouts, RCUTs, CGTs.

Table 3-4: Number of Years of Crash Data Available at All Sites

	3 to 5 years of after-period data	**1 to 3 years of after-period data**
3 to 5 years of before-period data	8	25
1 to 3 years of before-period data	6	4

Table 3-5: Number of Years of Crash Data Available at Roundabouts

	3 to 5 years of after-period data	**1 to 3 years of after-period data**
3 to 5 years of before-period data	5	11
1 to 3 years of before-period data	4	2

Table 3-6: Number of Years of Crash Data Available at RCUTs

	3 to 5 years of after-period data	**1 to 3 years of after-period data**
3 to 5 years of before-period data	3	11
1 to 3 years of before-period data	0	1

Table 3-7: Number of Years of Crash Data Available at CGTs

	3 to 5 years of after-period data	1 to 3 years of after-period data
3 to 5 years of before-period data	0	3
1 to 3 years of before-period data	2	1

Crash data was collected by year in terms of crash severity and manner of crash. The CARE portal provides a map of crash locations based on geographic coordinates which was used to collect site-specific crash data. All crashes located at the study site that were labeled as "At Intersection" by the reporting officer were included in the analysis. All other crashes occurring in proximity of the intersection were analyzed individually to determine if they were associated with the intersection, based on crash report narratives. It was important to also assess crashes located along the approaches of the intersection due to some crashes being reported upstream of the intersection. All crashes associated with turning movements and drivers navigating the intersection were included in the analysis, as well as those along approaches due to congestion and queuing at the intersection. Crashes that were not related to the intersection operation, such as a collision with debris from a previous crash, a collision with an animal, or a collision due to temporary traffic control were not included. Including all crashes within a specific distance from the main intersection was not done to avoid including unrelated collisions at nearby intersections or driveways. Assessing crashes based on the crash report narratives also ensured that crashes occurring at the study intersection that may have been reported outside of a potential selected buffer were included.

The current literature reflects various methods for collecting crash data at RCUTs. Areas where crashes associated with an RCUT may occur include the main intersection, crossover locations, or in between the two. Some studies only evaluated crashes at the main intersection of the RCUT while others used a buffer around the main intersection and crossovers. For this research, the goal was to incorporate crashes at the main intersection, U-turn crossovers, and the segments in between that were related to the presence of the RCUT. If crossovers were located at a median opening where the only movement permitted was a U-turn, all associated crashes were included. For sites where crossovers were located at the next intersection, the crash report narrative of each crash was examined and those that were the result of a vehicle making a U-turn were included. Crash report narratives of crashes were also assessed individually for crashes occurring between the main intersection and crossovers to determine if any were associated with the RCUT, such as a collision due to a vehicle attempting to maneuver toward turn lanes. During the before period, only crashes occurring at the main intersection were included.

3.2.3. Volume Data

Traffic volume contributes to the number of crashes at an intersection because as volume increases, exposure also increases. Based on the current research, traffic volume was the largest contributing factor to crash rate, making it a priority to incorporate volume into this safety evaluation through the comparison group analysis. Yearly AADT data was used to match treatment and comparison sites with a similar traffic volume. The 2017-2023 AADT data was recorded from the online Alabama Traffic Data Portal (TDM Public) using portable or permanent count stations located on the approaches of each site. Some local roads did not have count stations available on the portal. In this case, ALDOT or the corresponding city or county engineer was contacted to obtain traffic volume data if available.

Once the available data was obtained for each site, the two-way AADT on each approach could then be used to determine the total entering traffic volume from the major and minor approaches. If counters were available on all approaches, the average between the two on the major road and the two on the minor was found assuming a 50/50 directional split. At least one AADT value on both the major and minor roads was needed to estimate a total entering AADT. If a counter on one approach was unavailable, then it was assumed that the two-way AADT count was the total entering volume across both approaches.

3.3. Analysis Methods

3.3.1. Manner of Crash Evaluation

Lastly, the manner of crash changes after the implementation of roundabouts, RCUTs, and CGTs were assessed. This was based on the differences in the proportion of crash types across all sites between the before and after periods. The question being answered is what percentage of total crashes in the before period were angle collisions compared to the after period. A chi-square test of independence was performed to determine if the distribution of the manner of crash changes between analysis periods was statistically significant at a 0.05 significance level. The null hypothesis was that the proportions of crash types were independent of the period of analysis, meaning the implementation of a design alternative did not have an influence on the manner of crash changes in terms of statistical significance. The alternative hypothesis was that the proportions of crash types were dependent on the analysis period or that there was a statistically significant difference between the two, meaning the presence of an alternative intersection influenced the manner of crash changes. This analysis was conducted separately for each alternative intersection type and considered all 22 roundabouts, 15 RCUTs, and 6 CGTs**.**

3.3.2. Simple Before-After Analysis

A simple before-after analysis solely uses crash data before and after the implementation of an alternative to determine the impact that alternative has on crash rates. As previously mentioned, variables that may introduce bias in the crash data, such as AADT, are not incorporated into the analysis. The percent reduction of crashes per year at each site due to alternative intersection implementation was calculated and the mean percent reduction across all sites was determined. This resulted in an overall percent reduction in crashes attributed to the implementation of each alternative.

A paired means hypothesis test was performed to determine the significance of these crash changes. The objective was to test the hypothesis shown in Equation 3-1 that the mean crashes per year occurring at a site after alternative intersection implementation is significantly less than the mean crashes per year prior to implementation, disproving the null hypothesis, Equation 3-2. The dependent variables are total and FI crashes per year and the independent variable is the presence of an alternative intersection design. This method incorporated 22 roundabouts, 15 RCUTs, and 6 CGTs into the analysis.

$$H_1: \mu_{Before-Period} > \mu_{After-Period}$$

Equation 3-1

$$H_0: \mu_{Before-Period} \leq \mu_{After-Period}$$

Equation 3-2

Also, it was mentioned that ideally each analysis period should consider 3 to 5 years of data. This was not possible for every site due to data limitations. A supplemental unrelated means hypothesis test was performed to determine if there was a statistically significant difference in the observed reduction in total and FI crashes per year at each site due to differences in the number of years considered in the analysis.

3.3.3. Before-After Analysis with a Comparison Group

According to the *HSM*, "The purpose of a comparison group is to estimate the change in crash frequency that would have occurred if a treatment had not been put in place" (AASHTO, 2010). One of the benefits of a comparison group analysis is that it accounts for various factors that may affect the crash data. For example, it is typical for AADT to be related to the occurrence of crashes, but it can be difficult to quantify the impact of other variables (AASHTO, 2010). In this method, the change in crashes between the before and after period that occurs at control sites is used to predict the change in crashes that would have occurred at the treatment sites if conversion had not taken place.

An ideal comparison site was in the same jurisdiction and area type while also having similar geometric characteristics, traffic volume, and crash history as the treatment site it is matched to. The main geometric characteristics considered to identify suitable comparison sites were the number of lanes, number of approaches, and the intersection angle, skewed or 90 degrees. These conditions were followed unless, due to an inadequate sample size, other sites needed to be explored. It was also necessary that comparison sites had the same traffic control type as the treatment site before conversion. Historical satellite imagery was used to determine the traffic control type and ensure that no major geometric changes occurred at any comparison sites during either period of analysis. Volume data is necessary to form a representative comparison group and the more factors that are considered the stronger the prediction. SPFs may also be used in a comparison group analysis to determine calibration factors that adjust for nonlinear changes in traffic volume (AASHTO, 2010). According to the *HSM*, “If no SPFs are available, then the effects of traffic volume are assumed to be linear, decreasing the accuracy of the results,” which is the case for this analysis (AASHTO, 2010). In addition to the Alabama Traffic Data Portal, the Highway Performance Monitoring System (HPMS) was used to form an initial list of comparison sites based on traffic volume. AADT was collected during 2017-2023 for each comparison site. Treatment and comparison sites were matched based on a range of total entering

AADT on the major approaches and a separate total entering AADT range for the minor approaches occurring from 2017-2023. Some treatment sites did not have traffic volume available on the local minor roads. In this case, sites were matched based on the major approaches AADT and having a similar amount of land development on the minor approaches.

Once comparison sites were selected, the crash data was collected for the same before and after periods as the treatment site. Treatment and comparison sites must have similar crash trends in the before period for the comparison sites to be representative of the treatment sites in the after period. To confirm that treatment and comparison groups had a similar number of crashes in the before period, an odds ratio needed to be calculated. In this research, the odds ratio was found by computing the ratio of total crashes in the before period between the treatment and comparison group shown in Equation 3-3. Ideally, an odds ratio should consider yearly crash fluctuations, but due to not having multiple sites with the same analysis periods, there was not a large enough sample of crashes to compute an odds ratio that considered yearly changes. As an alternative, the total crashes in the before period were collapsed into a single value for treatment and comparison sites and used to compute the odds ratio. The odds ratio between a treatment and comparison site should be close to 1 to confidently assume the comparison site will be representative of the treatment site.

$$Odds\ Ratio = \frac{N_{Observed,C,B}}{N_{Observed,T,B}}$$

Equation 3-3

Where,

$N_{Observed,C,B}$ = The observed number of crashes in the before period in the comparison group

$N_{Observed,T,B}$ = The observed number of crashes in the before period in the treatment group

Once adequate comparison sites were selected for each treatment site, the expected number of crashes that would have occurred at the group of treatment sites had conversion not taken place was found using Equations 3-4 adapted from the FHWA report, “A Guide to Developing Quality Crash Modification Factors” (Gross et al. 2010). The variance associated with this prediction was calculated using Equation 3-5.

$$N_{Expected,T,A} = N_{Oberved,T,B} * \frac{N_{Observed,C,A}}{N_{Observed,C,B}}$$

Equation 3-4 (Gross et al. 2010)

Where,

$N_{Expected,T,A}$ =The expected number of crashes in the after period in the treatment group

$N_{Observed,C,A}$ = The observed number of crashes in the after period in the comparison group

$$Var\left(N_{Expected,T,A}\right) = N^2_{Expected,T,A}\left(\frac{1}{N_{Observed,T,B}} + \frac{1}{N_{Observed,C,B}} + \frac{1}{N_{Observed,C,A}}\right)$$

Equation 3-5 (Gross et al. 2010)

Next, a CMF that represents the safety effectiveness of each alternative could then be estimated using Equation 3-6. The variance and standard error of the CMF were determined using Equations 3-7 and 3-8.

$$CMF = \frac{\frac{N_{Observed,T,A}}{N_{Expected,T,A}}}{1 + \frac{Var\left(N_{Expected,T,A}\right)}{N^2_{Expected,T,A}}}$$

Equation 3-6 (Gross et al. 2010)

Where,

$N_{Observed,T,A}$ = The observed number of crashes in the after period in the treatment group

$$Var(CMF) = \frac{CMF^2\left[\left(\frac{1}{N_{Observed,T,A}}\right) + \left(\frac{Var\left(N_{Expected,T,A}\right)}{N^2_{Expected,T,A}}\right)\right]}{\left[1 + \left(\frac{Var\left(N_{Expected,T,A}\right)}{N^2_{Expected,T,A}}\right)\right]^2}$$

Equation 3-7 (Gross et al. 2010)

$$SE = \sqrt{Var(CMF)}$$

Equation 3-8 (Gross et al. 2010)

Where,

SE = Standard error

Lastly, a 95% confidence interval was calculated using Equation 3-9 to determine the range of potential CMF values for each alternative intersection based on the standard error (Gross et al. 2010). If the computed confidence interval did not include 1.00, the CMF was significant at a 95% confidence level (Gross et al. 2010). If the CMF is insignificant at a 95% confidence level, that means that alternative intersection implementation may result in an increase, decrease, or have no effect on crash rates (Gross et al. 2010). At a 95% confidence level, the cumulative probability, also commonly referred to as the z-statistic, is equal 1.96 (Gross et al. 2010). If Equation 3-9 resulted in a negative value, then that value was adjusted to equal zero due to a negative CMF being undefined.

$$Confidence\ Interval = CMF\ \pm (Cumulative\ Probability * Standard\ Error)$$

Equation 3-9 (Gross et al. 2010)

The roundabout located at the intersection of Lime Quarry Road/Graphics Dr & Intergraph Way was removed from the comparison group analysis due to missing volume data on all approaches. Also, RCUTs located at US 82 & AL 219 and US 82 & Timberlane Dr were both removed due to a lack of before-period crash data at comparison sites. The before period for both

RCUTs was January 1, 2013- December 31, 2015, and ALDOT provided the data for these treated sites, but reliable data was not available to match comparison sites. Lastly, the RCUT at US 280 & Tattersall Blvd was removed due to difficulty finding adequate comparison sites. The through and left turn movements on one minor approach were already restricted in the before period which are the main movements RCUTs are implemented to prevent. The comparison group analysis consisted of 21 roundabouts with 29 comparison sites, 12 RCUTs with 24 comparison sites, and 6 CGTs with 13 comparison sites. A final list of all comparison sites is in Appendix B.

3.4. Summary

This chapter began with outlining the data collection procedure that was followed to evaluate the safety effectiveness of roundabouts, RCUTs, and CGTs. The necessary data to perform an analysis on each alternative intersection included dates of construction, crash data, volume data, geometrics, and location information. Geometric and location data was obtained using historical satellite imagery from Google Maps and Google Earth. Construction dates were provided by the associated ALDOT region or local agency. Lastly, Crash data was collected from the CARE portal managed by the Center for Advanced Public Safety at the University of Alabama and volume data was collected from the TDM Public Portal.

The analysis methods selected were a simple before-after and a before-after using a comparison group. The change in total and FI crashes per year that occurred after the implementation of each alternative was determined utilizing both methodologies. The simple before-after analysis is subject to potential bias since variables such as traffic volume, geometric changes, and natural historical crash fluctuations are not considered. The comparison group analysis aims to reduce the chance of bias by incorporating control sites with similar traffic volume, geometrics, and crash rates. Additional evaluations utilizing both methodologies were conducted to determine how prior control type and area type may influence these crash changes. Also, to determine how collision types, specifically those that typically lead to a more severe outcome, are impacted after the installation of each alternative intersection design, the distribution of crash types during the before period and after periods of analysis were assessed and CMFs were developed utilizing the comparison group approach.

Chapter Four: Results

4.1. Introduction

The chapter presents the results from the analysis methods described in Chapter 3. First, the findings of the simple before-after analysis will be presented. The components of this methodology included the mean percent change in total and FI crashes per year across all sites for each alternative. A paired means hypothesis test was then conducted to determine if the total and FI crash reduction was statistically significant at a 0.05 significance level. This was done for all three alternative intersections. Additionally, an unrelated means hypothesis test was performed to determine if sites with 1 to 3 years of crash data in either the before or after period resulted in a statistically significant difference in the observed change in mean crashes per year compared to sites with 3-5 years of data. The simple before-after procedure was repeated to further evaluate roundabouts and RCUTs based on area type and roundabouts based on prior control type. Next, the CMFs for total and FI crashes at each alternative utilizing the before-after analysis with a comparison group will be discussed. CMFs were also developed based on prior control type for roundabouts and based on area type for roundabouts and RCUTs. Lastly, the findings of the changes in the proportion of certain crash types between the before and after periods are explained with a focus on collision types that lead to more severe outcomes, such as left turn, head-on, and angle collisions.

4.2. Manner of Crash Evaluation

An assessment was made of the changes in the manner of crash distribution across all sites after the implementation of each alternative. It is important to consider the manner of crash changes since certain types of collisions such as angle, side impact, and left turn often result in more severe injuries than other crash types. These collision types are often associated with crossing conflict points, which are reduced through the implementation of roundabouts and RCUTs. CGTs also reduce the risk of these crash types. Drivers merging in the continuous direction from the minor road are provided an acceleration lane and physical separation that reduces the angle of potential collisions as well as provides drivers with more time to make decisions on acceptable gaps. This analysis was solely based on the distribution of crash types and did not consider variables such as traffic volume or number of years. The complete results of this analysis can be found in Appendix C.

For roundabouts, the most notable differences in the manner of crash distribution were for side impact, single-vehicle, and rear-end collisions. In the before period, side impacts, angled or 90 degrees, made up approximately 49% of the total crashes across all sites while only accounting for about 25% in the after period. The percentage of rear-end crashes increased from 25% to 36% and like previous research, an increase in the proportion of single-vehicle crashes was observed (6% to 19%). The implementation of roundabouts had little effect on the relative proportions of angle collisions while head-on collisions slightly decreased and sideswipes slightly increased. The manner of crash distribution before and after roundabout implementation can be seen in Figures 4-1 and 4-2 below.

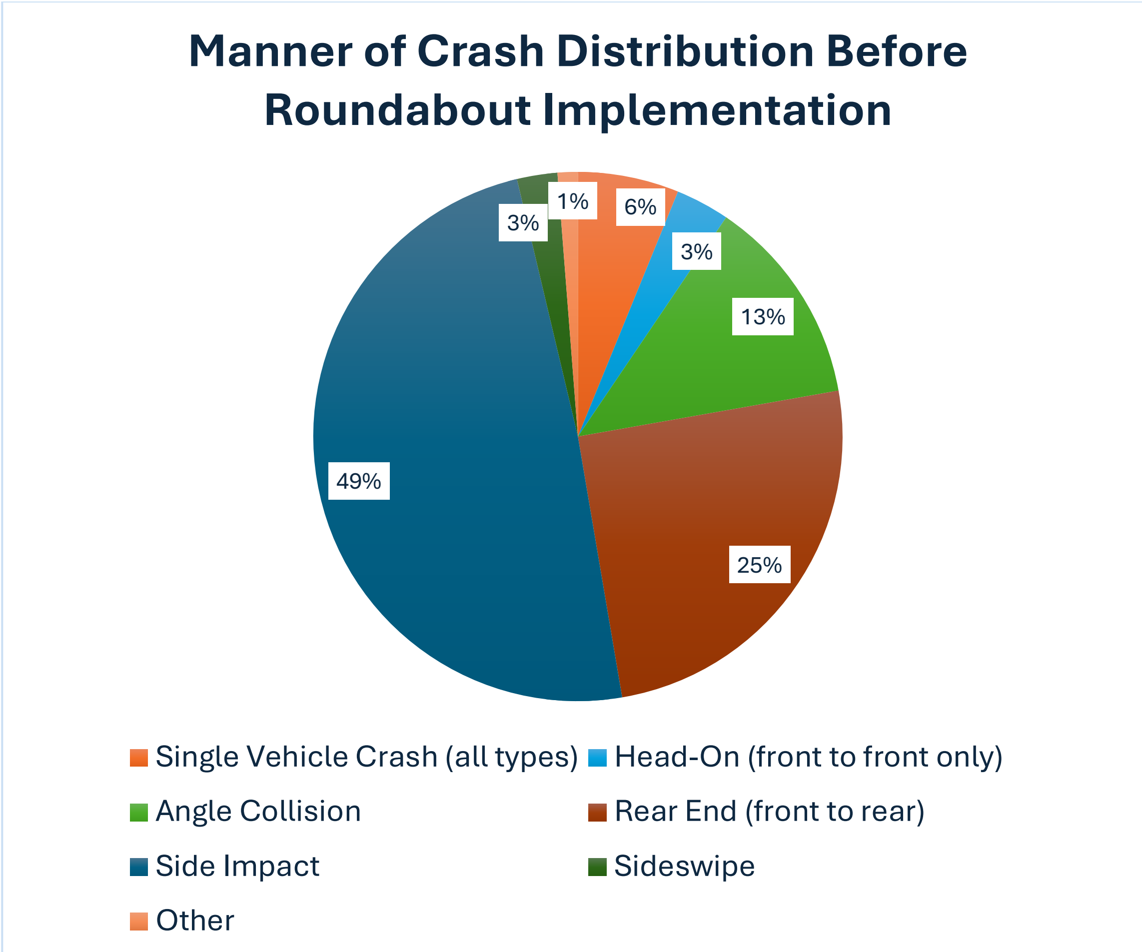

Figure 4-1: Manner of Crash Distribution at Roundabouts in the Before-Period

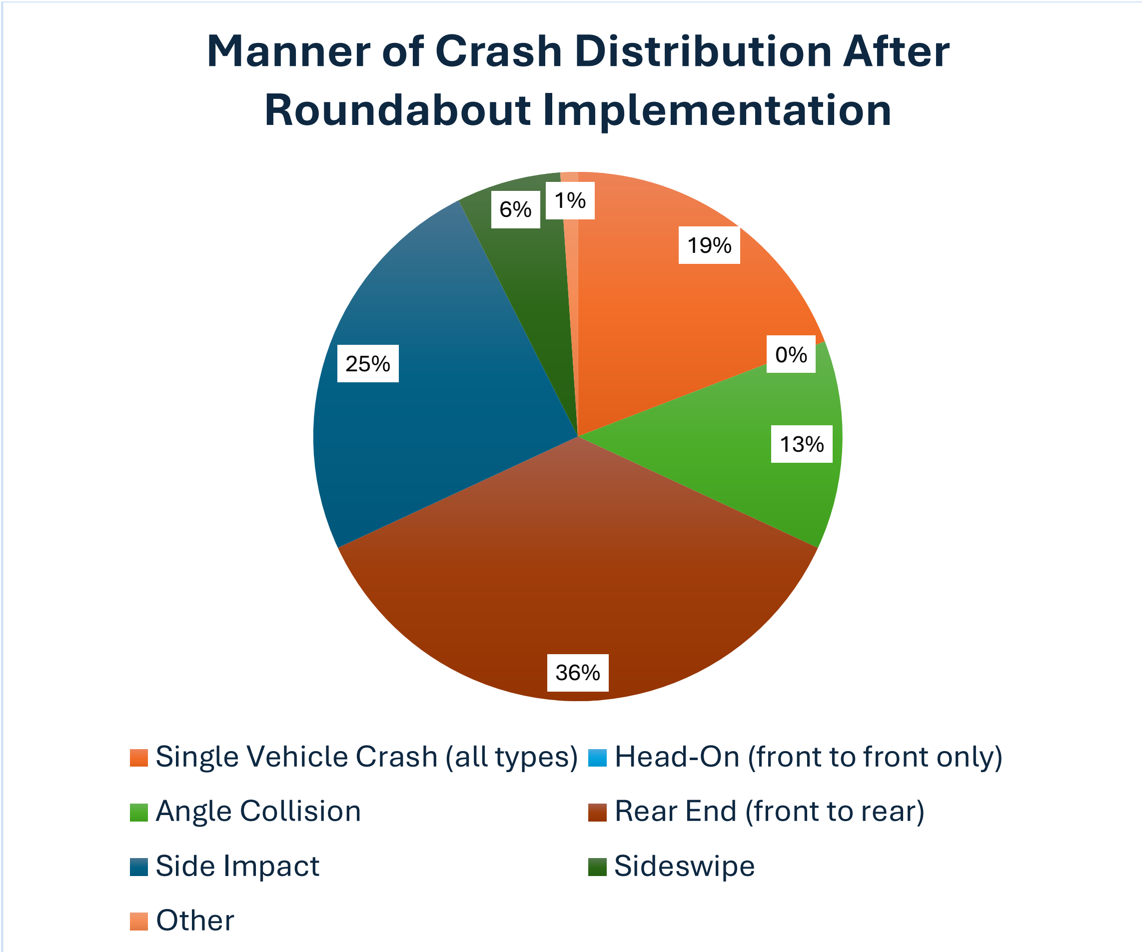

Figure 4-2: Manner of Crash Distribution at Roundabouts in the After-Period

Intersections converted to RCUTs also had a notable reduction in the proportion of side impact collisions between the before and after periods. Side impact collisions, angled or 90 degrees, made up 60% of all crashes in the before period and 28% in the after period. The RCUTs in this research were found to have little impact on the proportion of crashes that are angle and head-on collisions while sideswipes and single-vehicle collisions slightly increased. Lastly, rear-end collisions increased from 20% to 42%. Figures 4-3 and 4-4 show the manner of crash distribution during the before and after periods of analysis for RCUTs.

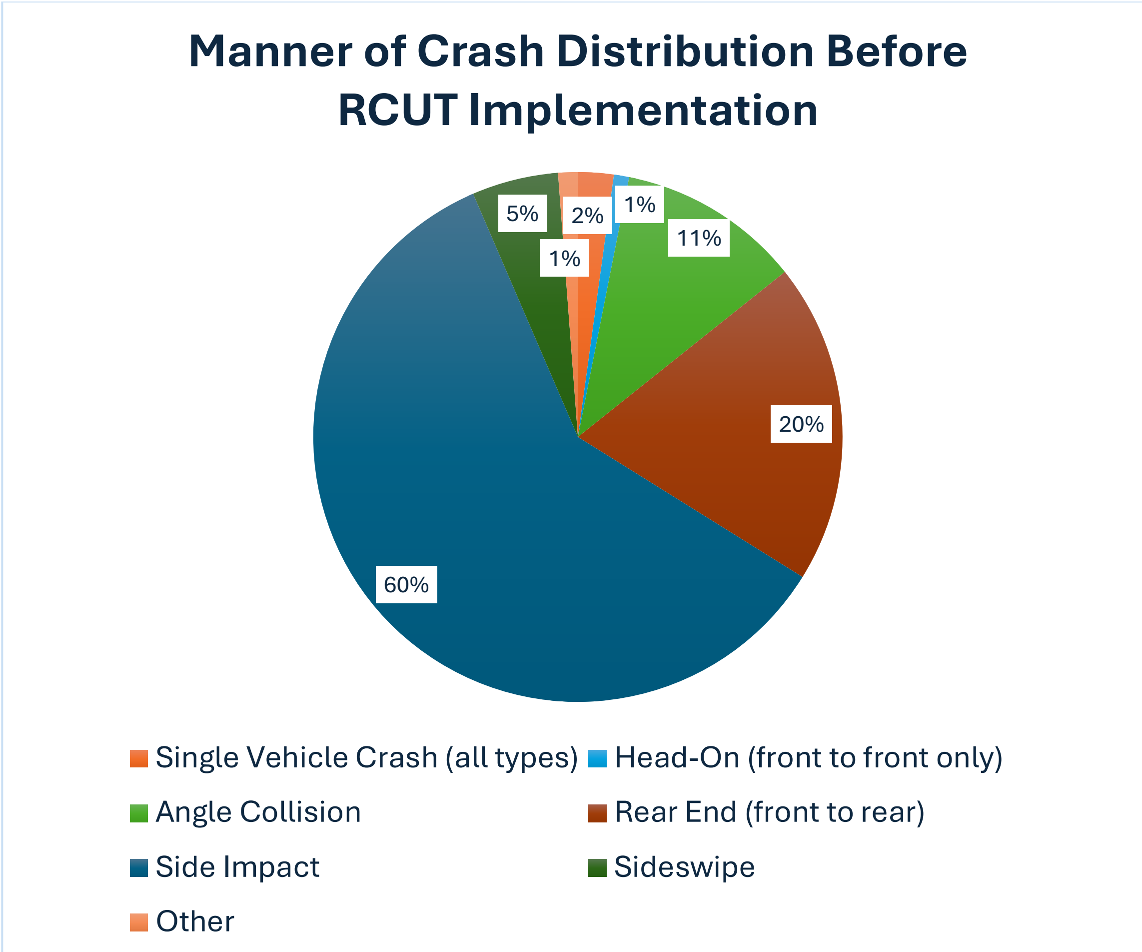

Figure 4-3: Manner of Crash Distribution at RCUTs in the Before-Period

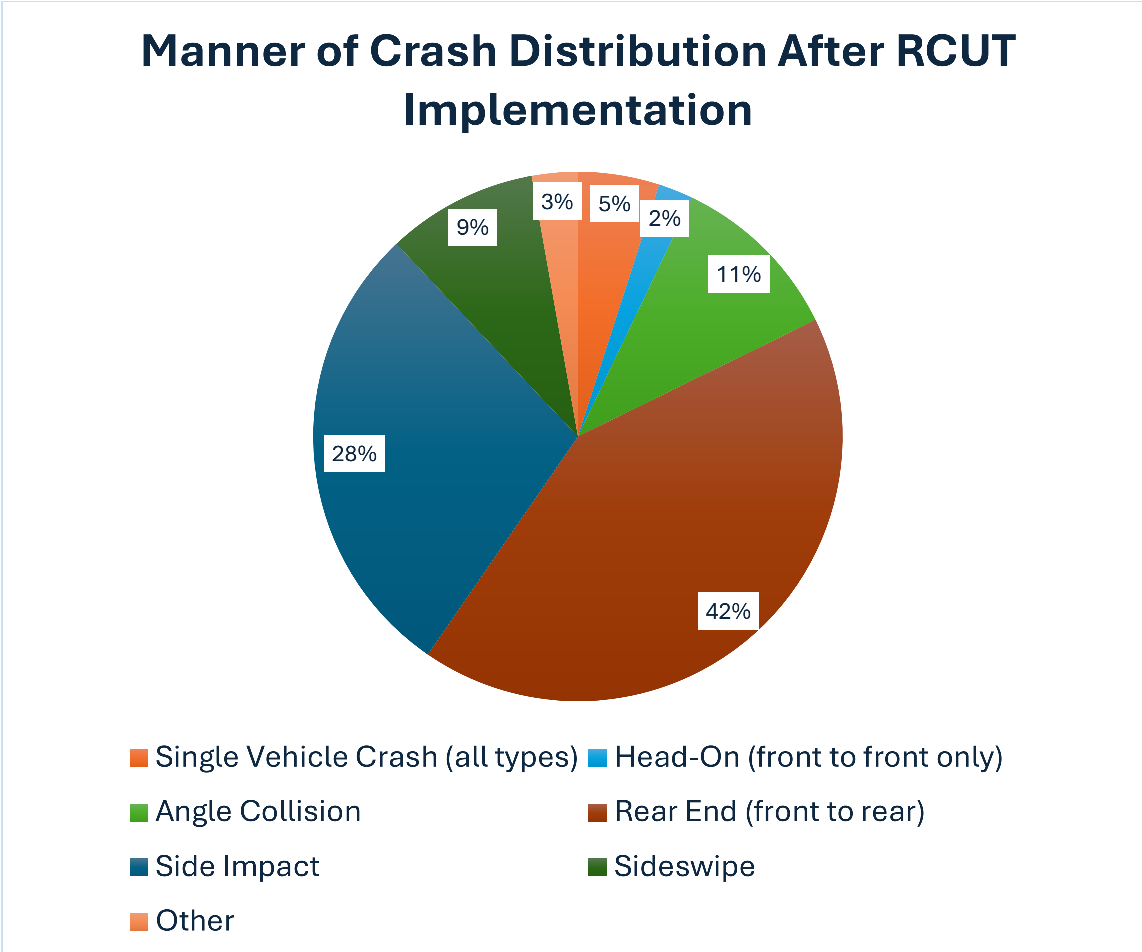

Figure 4-4: Manner of Crash Distribution at RCUTs in the After-Period

Lastly, CGTs also reduced the proportion of total crashes that were side impact collisions, angled or 90 degrees. Side impacts accounted for approximately 48% of all crashes in the before period and only 27% in the after period. This is a considerable reduction since CGTs are often implemented to reduce this type of crash due to the acceleration lane and separation provided to drivers turning left from the minor road. Sideswipe crashes increased from 7% to 14% and rear-end collisions increased from 29% to 43%. CGTs had little impact on the proportion of angle collisions relative to total crashes. The proportions of head-on collisions and single-vehicle collisions slightly increased and decreased, respectively. Figures 4-5 and 4-6 below show the manner of crash distribution at all CGT sites before and after implementation.

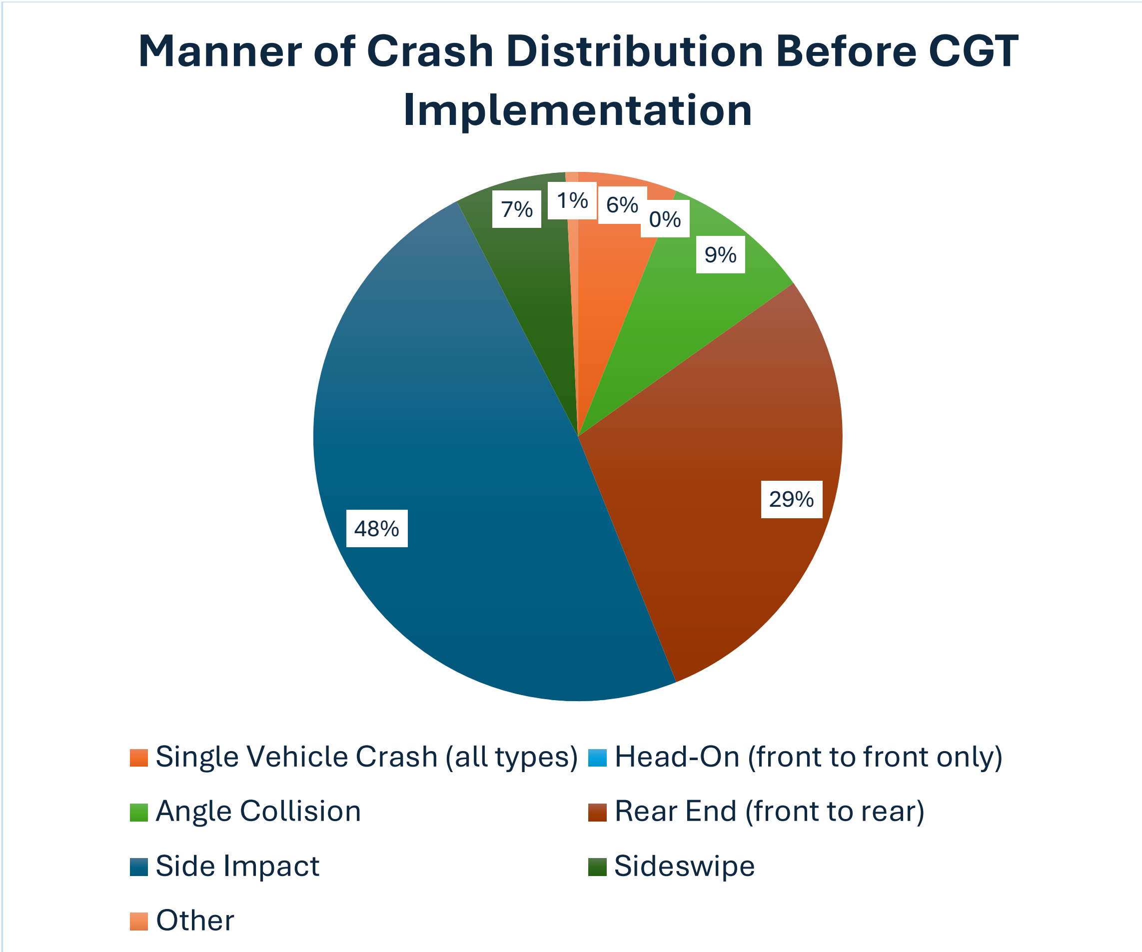

Figure 4-5: Manner of Crash Distribution at CGTs in the Before-Period

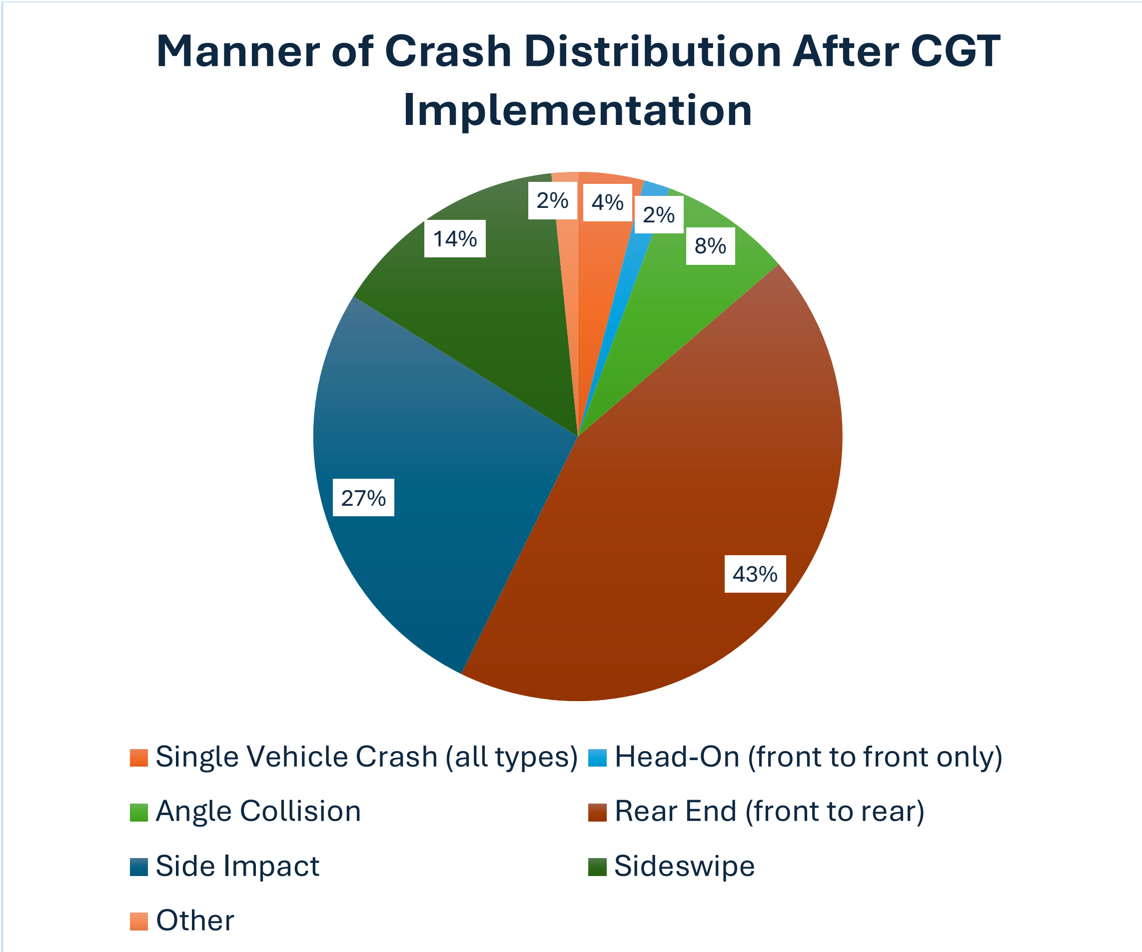

Figure 4-6: Manner of Crash Distribution at CGTs in the After-Period

To determine the significance of the manner of crash changes mentioned previously, a chi-square test of independence was performed. The results from the chi-square test for each alternative are shown in Table 4-1. The null hypothesis was that the different proportions of manner of crash type were independent of the period of analysis, whereas the alternative hypothesis was that the manner of crash proportions were dependent on the analysis period. For each alternative intersection, there were seven different manner of crash types between two categories, the before period and the after period. This means that each alternative intersection had a degree of freedom equal to 6.00, and a significance level of 0.05 was selected. These inputs led to the critical values shown in Table 4-1. The chi-square statistic was then calculated and if the result was greater than the critical value, the null hypothesis was rejected. The chi-square statistic and the degree of freedom were used to determine the p-value. If the p-value was less than the significance level of 0.05, the rejection of the null hypothesis was confirmed. The null hypothesis was rejected for each alternative, meaning that the changes in the manner of crash proportions reported previously were statistically significant at a 0.05 significance level and dependent on the implementation of each design alternative.

Table 4-1: Chi-Square Test Results

	Roundabouts	**RCUTs**	**CGTs**
Degree of Freedom (df)	6	6	6
Significance Level (α)	0.05	0.05	0.05
Critical Value	12.59	12.59	12.59
Chi-square statistic (X^2)	30.17	45.02	18.67
p-value	3.65E-05	4.64E-08	0.005

4.3. Simple Before-After Analysis Results

4.3.1. Mean Percent Change in Crashes

After collecting the crash data during the before and after periods at each site, the mean total and FI crashes per year were calculated for each period. The percent reduction in mean crashes per year at each site was computed. The mean percent reduction across all sites was determined and shown in Figure 4-7.

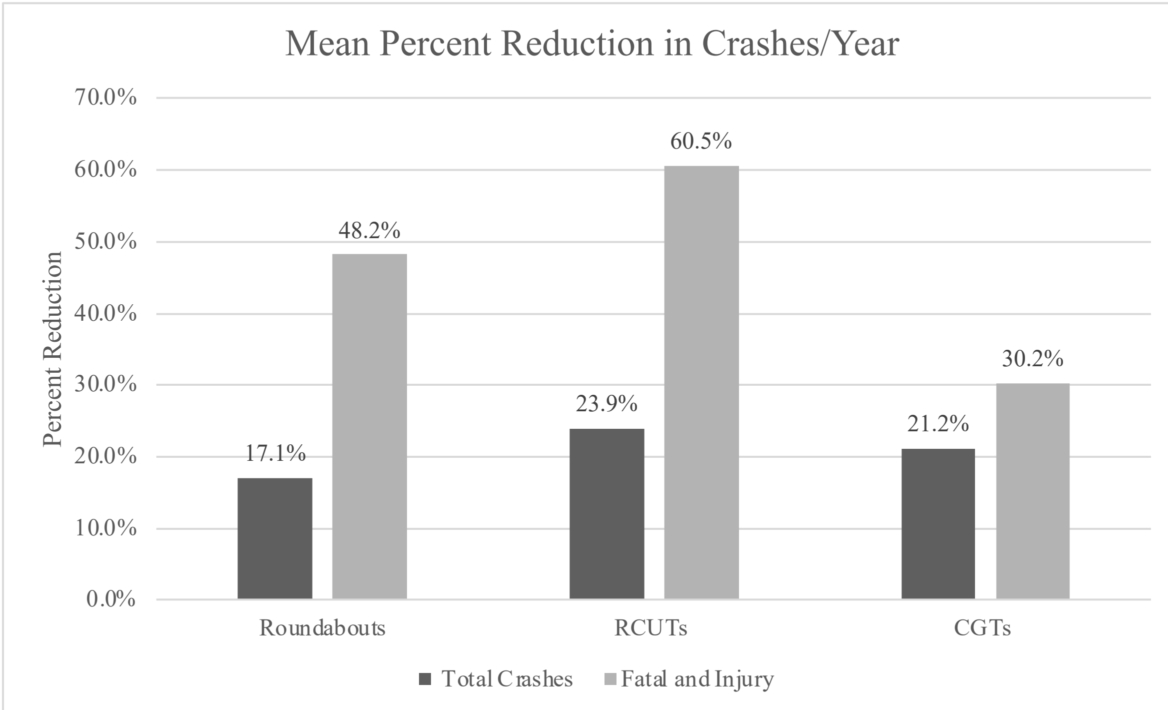

Figure 4-7: Percent Reduction in Mean Crashes/Year Observed at each Alternative Design

Across all 22 roundabouts, a 17.1% reduction in total crashes per year and a 48.2% reduction in FI per year occurred after implementation. The 15 RCUTs resulted in a 23.9% (total) and 60.5% (FI) reduction in crashes per year, and the 6 CGT locations yielded a 21.1% (total) and 30.2% (FI) reduction. Each alternative had a greater impact on the severity of crashes compared to crash frequency, which was expected based on the current literature. It is important to note that this approach does not consider differences in traffic volume between analysis periods or long-term crash fluctuations in the analysis.

4.3.2. Two-Means Hypothesis Test Results

A two-means hypothesis test was conducted to determine if the crash reductions resulting from the simple before-after analysis are statistically significant at a significance level of 0.05. The results of the test for each alternative are presented in Tables 4-2 through 4-4 below. Each table includes details of each hypothesis test, such as the number of sites and the mean total and

FI crashes per year, across all sites, during the before and after periods. The mean percent change in crashes after the implementation of each alternative intersection previously presented in Figure 4-1 are included again. The hypothesis test results shown in each table include the mean difference, across all sites, in total and FI crashes per year before and after implementation and the associated standard deviation. The resultant t-statistics and p-values used to determine if the results were statistically significant are also shown in each table. The 22 roundabouts included in this research had a mean reduction of 2.31 total crashes per year and 0.64 FI crashes per year, which were found to be statistically significant. The results of paired means hypothesis test for roundabouts are shown in Table 4-2 below.

Table 4-2. Paired Mean Hypothesis Test Results for Roundabouts

		Before-Period	After-Period
n	Total FI	22	22
Mean Crashes/Year	Total	3.99	1.71
	FI	0.80	0.17
Mean Percent Change in Crashes/Year	Total	-17.1%	
	FI	-48.2%	
Mean Difference (Standard Deviation)	Total	-2.28 (3.89)	
	FI	-0.64 (0.91)	
t-statistic (Paired t-test p-value)	Total	2.69 (0.0068)	
	FI	3.22 (0.0021)	

The hypothesis test results for the change in total and FI crashes per year across the sample of RCUTs are presented in Table 4-3. Two RCUTs were removed from the FI injury analysis due to a large portion of crashes being reported as an “unknown” severity level. Across 15 RCUTs, the mean reduction in crashes per year was 2.69 and statistically significant at a 0.05 significance level. The 13 RCUTs included in the severity analysis resulted in a mean reduction of 2.35 FI crashes per year, which was also found to be statistically significant.

Table 4-3. Paired Mean Hypothesis Test Results for RCUTs

		Before-Period	After-Period
n	Total	15	15
	FI	13	13
Mean Crashes/Year	Total	7.73	5.04
	FI	3.10	0.75
Mean Percent Change in Crashes/Year	Total	-23.9%	
	FI	-60.5%	
Mean Difference (Standard Deviation)	Total	-2.69 (4.79)	
	FI	-2.35 (1.71)	
t-statistic (Paired t-test p-value)	Total	2.11 (0.0269)	
	FI	4.76 (0.0002)	

Lastly, CGTs experienced a mean percent change in total and FI crashes per year of -21.2% and -30.2%, and the results of the paired means hypothesis test are shown in Table 4-4. The results show notable reductions in total and FI crashes, but they were not statistically significant at a 0.05 significance level.

Table 4-4. Paired Mean Hypothesis Test Results for CGTs

		Before-Period	After-Period
n	Total FI	6	6
Mean Crashes/Year	Total	9.29	8.36
	FI	3.21	2.17
Mean Percent Change in Crashes/Year	Total	-21.2%	
	FI	-30.2%	
Mean Difference (Standard Deviation)	Total	-1.10 (2.71)	
	FI	-1.04 (2.38)	
t-statistic (Paired t-test p-value)	Total	0.91 (0.2033)	
	FI	0.98 (0.1867)	

Ideally, the before and after period of analysis for each site would include 3-5 years of data; however, achieving this was restricted based on the availability of data. An additional unrelated means test was conducted to determine if there was a statistically significant difference in observed crash reductions between sites that had data available within this range and those that did not. Two tests were performed twice for total and FI crashes. The first compared the reduction in mean crashes per year at sites with 3 to 5 years of data in both the before and after period to those with 1 to 3 years of data in the before period. The second compared sites with 3 to 5 years of data in both the before and after periods to those with 1 to 3 years of data in the after period. The hypothesis test for sites with 1 to 3 years of before-period data resulted in p-values of 0.693 and 0.631 for total and FI crashes. For sites with 1 to 3 years of after-period data, the p-values were 0.942 and 0.925 for total and FI crashes. The results from each scenario did not provide evidence to prove that having less than 3 years of data within either the before or after period influenced the results. The results of each unrelated means test are shown in Table 4-5 and includes the t-statistics and p-values. Also included in Table 4-5 for each group is the number of sites and the mean difference in crashes per year between the before and after periods across all sites.

Table 4-5: Unrelated Means Test Results

		Sites with 3 to 5 years of data	**Sites 1 to 3 years of after-period data**	**Sites with 1 to 3 years of before-period data**
n	Total	8	25	6
	FI	6	25	6
Mean Difference in Crashes/Year	Total	-1.781	-2.503	-1.653
	FI	-0.931	-1.363	-1.055
t-statistic (Paired t-test p-value)		Total	0.40 (0.6929)	-0.08 (0.9416)
		FI	0.51 (0.6306)	0.096 (0.9252)

4.3.3. Simple Before-After Based on Prior Control Type

Further analysis was performed based on the prior control type for roundabouts. All CGT sites and all except one RCUT site were previously under TWSC; therefore, this analysis could only be performed for roundabouts. The mean percent change in crashes was calculated in the same manner as described in the previous section and a paired means hypothesis test was once again performed to determine if the results were significant at a 0.05 significance level. The results are presented in Table 4-6 at the end of this section. The largest reduction in crashes occurred at roundabouts that were previously TWSC, which is consistent with the findings of the literature review. A 48.9% and 65.2% reduction in total and FI crashes was observed, which were statistically significant. Sites that were previously signalized intersections showed the least improvements, having a 26.2% increase in total crashes per year and a 25% reduction in FI crashes per year. Despite the mean percent change for previously signalized sites showing an increase in total crashes, the mean crashes per year across all sites decreased by approximately 1.23 crashes between the before and after periods. Two out of the six previously signalized sites showed a percent increase in crashes after roundabout implementation, one of which had a 333% increase, which contributed to the mean percent change in crashes across all sites showing an increase. The results for the mean difference in total and FI crashes for previously signalized sites were statistically insignificant. Lastly, previously AWSC intersections showed a reduction of 2.8% and 40.5% for total and FI crashes, the mean reduction in total crashes per year was found to not be statistically significant at a 0.05 significance level.

Table 4-6: Paired Mean Hypothesis Test Results based on Prior Control Type

		Signalized		**TWSC**		**AWSC**	
		Before-Period	**After-Period**	**Before-Period**	**After-Period**	**Before-Period**	**After-Period**
n	Total FI	5	5	10	10	7	7
Mean Crashes/Year	Total	3.37	2.13	4.80	1.00	3.29	2.42
	FI	0.33	0.17	1.28	0.22	0.45	0.10
Mean Percent Change in Crashes/Year	Total	26.2%		-48.9%		-2.8%	
	FI	-25.0%		-65.2%		-40.5%	
Mean Difference (Standard Deviation)	Total	-1.23 (3.86)		-3.80 (4.90)		-0.87 (1.59)	
	FI	-0.17 (0.29)		-1.07 (1.20)		-0.36 (0.46)	
t-statistic (Paired t-test p-value)	Total	0.71 (0.2573)		2.45 (0.0183)		1.45 (0.0989)	
	FI	1.29 (0.1331)		2.81 (0.0103)		2.07 (0.0417)	

4.3.4. Simple Before-After Based on Area Type

A similar analysis was performed to assess performance based on area type, urban or rural. Due to all CGTs except one being rural, this analysis was performed for RCUTs and roundabouts only. The results of the mean percent change in crashes and the two means hypothesis test for each alternative intersection based on area type are presented in Tables 4-7 and 4-8. For roundabouts, sites in urban locations resulted in a larger reduction in total crashes but rural sites had slightly better results for FI crashes. Total crashes were reduced by 39.1% and 4.6% in urban and rural locations while FI crashes were reduced by 44.8% and 50.1%. All results for the mean difference in total and FI crashes per year across sites were significant at a 0.05 significance level.

Table 4-7: Roundabout Paired Mean Hypothesis Test based on Area Type

		Urban		**Rural**	
		Before-Period	**After-Period**	**Before-Period**	**After-Period**
n	Total FI	8	8	14	14
Mean Crashes/Year	Total	4.56	2.21	3.67	1.42
	FI	0.48	0.15	0.99	0.18
Mean Percent Change in Crashes/Year	Total	-39.1%		-4.6%	
	FI	-44.8%		-50.1%	
Mean Difference (Standard Deviation)	Total	-2.35 (2.62)		-2.24 (4.62)	
	FI	-0.33 (0.46)		-0.81 (1.08)	
t-statistic (Paired t-test p-value)	Total	2.37 (0.0247)		1.82 (0.0462)	
	FI	1.90 (0.0495)		2.80 (0.0075)	

For RCUTs, rural sites performed better in terms of total and FI crash reduction compared to urban sites. Rural sites showed a reduction in total and FI crashes by 63.3% and 85.7%. The mean percent change in crashes per year for urban sites showed a 21.1% increase in total crashes and a 38.9% decrease in FI. The mean difference in total crashes per year for urban sites showed a slight reduction of -0.19 crashes, but these results were insignificant. All other results were significant at a 0.05 level and are shown in Table 4-8 below.

Table 4-8: RCUT Paired Mean Hypothesis Test based on Area Type

		Urban		Rural	
		Before-Period	After-Period	Before-Period	After-Period
n	Total FI	7	7	8 6	8 6
Mean Crashes/Year	Total	6.90	6.71	8.46	3.57
	FI	1.81	0.79	4.61	0.71
Mean Percent Change in Crashes/Year	Total	21.1%		-63.3%	
	FI	-38.9%		-85.7%	
Mean Difference (Standard Deviation)	Total	-0.19 (4.22)		-4.89 (4.14)	
	FI	-1.02 (1.12)		-3.90 (0.66)	
t-statistic (Paired t-test p-value)	Total	0.11 (0.4577)		3.12 (0.0084)	
	FI	2.24 (0.0330)		13.14 (2.27E-05)	

4.4 Before-After Analysis with a Comparison Group

4.4.1. Development of Crash Modification Factors

Utilizing the comparison group calculation procedure outlined in Chapter 3, total crash, FI crash, and target crash type CMFs were developed for roundabouts, RCUTs, and CGTs. Confidence intervals were also calculated for each CMF at a 95% confidence level. The roundabout treatment and comparison site groups had an odds ratio of 0.83 and 0.98 for total and FI crashes. RCUT treatment and comparison sites had a total and FI odd ratios of 0.94 and 1.32. Lastly, CGTs had average odds ratios of 0.64 and 0.48 for total crashes and FI crashes.

Based on the results, each alternative intersection design resulted in CMFs that indicated a reduction in total and FI crashes after implementation. Similar to the results of previous research and the simple before-after analysis, each alternative intersection design resulted in a greater reduction in FI crashes compared with the total. The 21 roundabouts yielded the greatest improvements in total crashes and FI crashes. Roundabouts had an approximately 62% and 80%

reduction in total and FI crashes. RCUTs reduced total crashes by 40% and FI by 74%. Lastly, CGTs reduced total and FI crashes by 21% and 42%. The results of the analysis are presented in Table 4-9 below and include the odd ratios, CMFs, variance, and standard error (SE) for each alternative intersection design.

Table 4-9: Comparison Group Analysis CMF Results

	OR		CMF		Variance (CMF)		SE	
	Total	**FI**	**Total**	**FI**	**Total**	**FI**	**Total**	**FI**
Roundabouts	0.83	0.98	0.38	0.20	0.004	0.007	0.059	0.082
RCUTs	0.94	1.32	0.60	0.26	0.007	0.007	0.086	0.085
CGTs	0.64	0.48	0.79	0.58	0.022	0.038	0.149	0.194

Table 4-10 shows the confidence interval for each CMF. For roundabouts and RCUTs the value of 1.0 does not fall within the confidence interval, meaning that each alternative resulted in a reduction in total and FI crashes at a 95% confidence level. Roundabouts resulted in total and FI CMFs ranging from 0.26 to 0.50 and 0.04 to 0.36 at a 95% confidence level. RCUTs at a 95% confidence level resulted in total and FI CMFs ranging from 0.43 to 0.77 and 0.10 to 0.43. For CGTs, the upper limit for total crashes was 1.08, meaning that it cannot be stated at a 95% confidence level that CGT conversion resulted in a reduction in crashes. Despite this, CGT locations yielded a FI crash CMF ranging from 0.19 to 0.96 at a 95% confidence level.

Table 4-10: Comparison Group Analysis CMF Confidence Intervals

	Total Crashes		FI Crashes	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Roundabouts	0.26	0.50	0.04	0.36
RCUTs	0.43	0.77	0.10	0.43
CGTs	0.50	1.08	0.19	0.96

4.4.2. Crash Modification Factors Based on Prior Control Type

The same comparison group methodology was utilized to assess the safety performance of each alternative based on prior control type. As previously mentioned, due to sample size this additional evaluation was only performed for roundabouts. Out of the 21 roundabouts included in the comparison group analysis, 5 were previously signalized, 9 were previously TWSC, and 7 were previously AWSC. The results are shown in Table 4-11. Similar to the simple before-after evaluation, roundabouts converted from a TWSC intersection had the greatest reduction in total crashes (79%) and also experienced an 82% reduction in FI crashes, Previously AWSC intersections yielded a reduction in total and FI crashes of approximately 58% and 89%. Lastly, previously signalized intersections showed a decrease of total crashes of about 11% and a 70% reduction in FI crashes. The odds ratios, CMFs, variance, and SE results are presented in Table 4-11.

Table 4-11: CMF Results at Roundabouts Based on Prior Control Type

	OR		CMF		Variance (CMF)		SE	
	Total	**FI**	**Total**	**FI**	**Total**	**FI**	**Total**	**FI**
Signalized	1.17	1.00	0.89	0.30	0.076	0.039	0.276	0.197
TWSC	0.64	0.97	0.21	0.18	0.004	0.010	0.060	0.100
AWSC	1.05	1.00	0.42	0.11	0.011	0.005	0.103	0.074

The confidence intervals for each CMF based on prior control type are presented in Table 4-12 below. TWSC and AWSC confidence intervals indicate that roundabout conversion resulted in a reduction in total and FI crashes at a 95% confidence level. The total crash changes due to signalized intersection to roundabout conversion are not as clear with a 95% confidence interval ranging from 0.35 to 1.44. The results in terms of FI crashes resulted in a CMF ranging from 0.00 to 0.69 at a 95% confidence level.

Table 4-12: Roundabout CMFs by Prior Control Type Confidence Intervals

	Total Crashes		FI Crashes	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Signalized	0.35	1.44	0.00	0.69
TWSC	0.10	0.33	0.00	0.38
AWSC	0.22	0.62	0.00	0.25

4.4.3. Crash Modification Factors Based on Area Type

The comparison group methodology was also used to assess safety performance based on area type for Roundabouts and RCUTs. The results for each are shown in Tables 4-13 and 4-15. Seven roundabouts included in the comparison group analysis were in an urban area while 14 were in a rural area. The odds ratios, CMFs, variance, and SE for roundabouts in urban and rural areas are shown in Table 4-13. Both groups experienced reductions in total and FI crashes, but the rural sites had larger safety improvements. Rural sites reduced total and FI crashes by approximately 70% and 86% while urban sites resulted in a 45% and 61% reduction.

Table 4-13: CMF Results at Roundabouts Based on Area Type

	OR		CMF		Variance (CMF)		SE	
	Total	**FI**	**Total**	**FI**	**Total**	**FI**	**Total**	**FI**
Urban	0.88	1.18	0.55	0.39	0.018	0.056	0.133	0.237
Rural	0.80	0.92	0.30	0.14	0.004	0.005	0.060	0.070

The confidence intervals for each CMF based on area type are shown in Table 4-14 below. Urban sites resulted in CMFs ranging from 0.29 to 0.81 for total crashes and 0.00 to 0.85 for FI crashes at a 95% confidence level. Rural sites also resulted in CMFs that indicate a reduction in total and FI crashes at a 95% confidence level ranging from 0.18 to 0.42 and 0.005 to 0.28, respectively.

Table 4-14: Roundabout CMFs by Area Type Confidence Intervals

	Total Crashes		FI Crashes	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Urban	0.29	0.81	0.00	0.85
Rural	0.18	0.42	0.005	0.28

For RCUTs, 6 sites were in a rural area while 6 were in an urban area. Like roundabouts, rural locations resulted in a greater reduction in total (67%) and FI crashes (86%). Urban sites increased total crashes by approximately 20%, but FI crashes were still reduced by 40%. Despite there being an increase in total crashes at urban sites the severity of the crashes that occurred were still reduced. The results for RCUTs in urban and rural areas are shown in Table 4-15 below.

Table 4-15: CMF Results at RCUTs Based on Area Type

	OR		CMF		Variance (CMF)		SE	
	Total	**FI**	**Total**	**FI**	**Total**	**FI**	**Total**	**FI**
Urban	1.04	0.94	1.20	0.60	0.064	0.074	0.253	0.272
Rural	0.85	0.82	0.33	0.14	0.004	0.003	0.066	0.051

The confidence intervals for each RCUT CMF based on area type are presented in Table 4-16 below. Rural sites resulted in a CMF that indicates a reduction in total (0.20 to 0.46) and FI (0.04 to 0.24) at a 95% confidence level. For urban sites, the confidence intervals for total and FI crashes includes the value of 1.0, meaning that it cannot be determined at a 95% confidence level whether urban RCUT conversion resulted in a reduction, increase, or had no impact of crash rates.

Table 4-16: RCUT CMFs by Area Type Confidence Intervals

	Total Crashes		FI Crashes	
	Lower Limit	**Upper Limit**	**Lower Limit**	**Upper Limit**
Urban	0.70	1.69	0.06	1.13
Rural	0.20	0.46	0.04	0.24

4.4.4. Crash Modification Factors for Target Crash Types

Lastly, CMFs were developed to determine how effective each alternative intersection is at reducing the occurrence of crash types that often lead to a more severe outcome. Crash types considered include side impact (angle or 90 degrees), angle collisions, and head on collisions. The results are shown below in Table 4-17 and include the odds ratio, CMF, variance, and standard error. Roundabouts, RCUTs, and CGTs resulted in a reduction in target crash types of approximately 81%, 68%, and 61%. For roundabouts and RCUTs this is likely due to the reduction of conflict points, specifically crossing conflicts. While for CGTs, this reduction in target crashes is likely due to the use of acceleration lane and separation provided to drivers turning left from the minor road.

Table 4-17: Comparison Group Analysis Target Crash Types CMF Results

	OR	**CMF**	**Variance (CMF)**	**SE**
Roundabouts	0.66	0.19	0.002	0.043
RCUTs	0.85	0.32	0.004	0.062
CGTs	0.39	0.39	0.012	0.109

Confidence intervals were also developed for each CMF at a 95% confidence level. Based on the results each alternative resulted in a reduction in left turn, angle, and head on collisions at a 95% confidence level. The results displayed in Table 4-18 show CMFs ranging from 0.10 to 0.27 at roundabouts, 0.19 to 0.44 at RCUTs, and 0.17 to 0.60 at CGTs.

Table 4-18: Comparison Group Analysis CMF Confidence Intervals

	Total Crashes	
	Lower Limit	**Upper Limit**
Roundabouts	0.10	0.27
RCUTs	0.19	0.44
CGTs	0.17	0.60

4.5. Summary

This chapter consisted of the key analysis findings related to the safety effectiveness of roundabouts, RCUTs, and CGTs. This chapter began with the results of the assessment on the changes in manner of crash distribution across sites before and after the implementation of each alternative. It was concluded that each alternative reduced the proportion of side impact crashes that occur at an intersection relative to other crash types. This is an important result since side impacts have a higher probability of a severe outcome compared to other crash types. The proportion of head-on and angle collisions was not affected by implementation. Each alternative intersection also experienced an increase in the proportion of rear-end collisions, roundabouts and RCUTs had an increase in single-vehicle collisions, and RCUTs and CGTs had an increase in sideswipe collisions. These changes in the distribution of manner of crash were found to be statistically significant at a 0.05 significance level. Next, the results of the simple before-after analysis and the various hypothesis tests utilized to determine if the observed crash changes were statistically significant at a 0.05 significance level were presented. It was determined that each alternative intersection resulted in a reduction in total and FI crashes per year with RCUTs the having largest improvements. All results were statistically significant except for CGTs. The comparison group analysis yielded similar results, but the largest reduction in total and FI crashes was observed at roundabouts. Each methodology had similar results for the assessment based on prior control type, with TWSC to roundabout conversion showing the greatest safety improvements. RCUTs and roundabouts in rural locations had better crash reductions than in urban locations. The results for urban RCUTs were inconclusive indicating a potential decrease, increase, or no change in total and FI crashes as evidenced by the 95% confidence interval of the CMFs shown in Table 4-16. CMFs developed from the comparison group analysis showed that each alternative design effectively reduced target crash types which included side impact, angle, and head on collisions at a 95% confidence level. The results of each analysis led to the same conclusion that the implementation of roundabouts, RCUTs, and CGTs in Alabama has led to a reduction in the number of total and FI crashes occurring at intersections as well as a reduction in the occurrence of side impact collisions that often led to a higher severity crash.

Chapter Five: Conclusions and Recommendations

5.1. Introduction

Improving intersection safety remains a focus area of FHWA due to the frequency and severity of crashes occurring at intersections throughout the United States (FHWA Highway Safety Program, 2024). FHWA supports the push towards the "Vision Zero Approach" and emphasizes that intersection safety is an important component to achieving the goal of minimizing traffic fatalities (FHWA Highway Safety Program, 2024). Alternative intersections such as roundabouts, RCUTs, and CGTs are often implemented to improve the safety of an intersection. The safety performance of these alternatives has been discussed nationally and in other states, but there is a lack of research on how these alternatives are currently performing in Alabama in terms of safety. The objective of this research is to determine the change in a) the total number of crashes per year, b) the number of fatal and injury (FI) crashes per year, and c) the manner of crash distribution after alternative intersection installation in Alabama, specifically roundabouts, RCUTs, and CGTs. Another goal of this thesis was to gain a better understanding of how these alternatives are performing in terms of variables such as prior control type and area type to guide future implementation. Lastly, the changes in manner of crash distribution were assessed to determine how each alternative impacted the occurrence of severe collision types.

These objectives were achieved by evaluating the historical crash data at a sample of treatment sites before and after implementation. Data collection consisted of gathering the necessary dates of construction, geometric and location information, crash data, and volume data at each site. Two analysis methods were used to assess the safety performance of each alternative, a simple before-after analysis and a comparison group analysis. A paired means hypothesis test was also conducted to confirm the statistical significance of the results of the simple before-after analysis. The comparison group analysis incorporated control sites similar to treatment sites in terms of major and minor road traffic volume, number of lanes, number of approaches, area type, and crashes in the before period to more accurately determine the total and FI crash reductions attributed to alternative intersection implementation.

5.2. Conclusions

5.2.1. Manner of Crash Evaluation

The evaluation of the manner of crash distribution between the before and after periods results showed that each alternative reduced the proportion of side impact crashes related to total crashes. This is a substantial reduction since side impacts are one of the main crash types that roundabouts, RCUTs, and CGTs are implemented to reduce due to the probability of a severe outcome. For RCUTs and roundabouts, this is likely due to the reduction in crossing conflict points. Despite CGTs having the same conflict points as a conventional T-intersection, drivers utilize an acceleration lane and are provided separation before merging which reduces the angle of potential collisions. The proportion of head-on and angle collisions, which also typically have a more severe outcome compared to other crash types, were unaffected by the implementation of each alternative intersection design. Roundabouts also increased the percentage of single-vehicle crashes in the after period compared to the before period, which corresponds to the existing research. RCUTs resulted in an increase in single-vehicle crash types and CGTs had a higher proportion of sideswipes crashes. Also, each alternative intersection type had a larger proportion of rear-end collisions, which are typically not severe. Lastly, a chi-square test of independence was performed to determine if the change in the manner of crash proportions before and after alternative intersection implementation was statistically significant at a 0.05 significance level. The results showed that the observed proportion of crashes was dependent on the analysis period, meaning the presence of each alternative intersection design influenced the manner of crash changes.

5.2.2. Simple Before-After Analysis

The simple before-after analysis showed that sample sites of each alternative, roundabouts, RCUTs, and CGTs, have resulted in a reduction in mean percent reduction in total crashes per year of 17.1%, 23.9%, and 21.2%. Each alternative not only reduced the occurrence of crashes but greatly improved the severity of those that do occur. The results yielded a 48.2%, 60.5%, and 30.2% mean percent reduction in FI crashes per year at roundabouts, RCUTs, and CGTs. The mean reduction in total and FI crashes per year at each alternative intersection was found to be statistically significant at a 0.05 significance level except for CGTs. The analysis based on the prior control type before roundabout conversion showed that intersections converted from TWSC showed the greatest improvements in safety while previously signalized intersections showed the least. For signalized intersection conversion, the mean percent change in crashes across all sites showed an increase in total crashes and a reduction in FI crashes, while the mean difference in crashes per year indicated a reduction for both total and FI crashes but was not statistically significant. Conversion of AWSC intersections to roundabouts also resulted in improvements in terms of total and FI crashes per year, but they were also statistically insignificant at a 0.05 significance level. The analysis based on area type showed that roundabouts in urban locations had greater reductions in total crashes per year, but rural sites showed a greater improvement in terms of reduction in FI crashes per year, both results were statistically significant. Lastly, RCUTs in rural areas overall had greater improvements after implementation in terms of the frequency and severity of crashes compared to those in more urban locations. All results were statistically significant except for the reduction in the mean total crashes per year observed at urban sites. The mean percent change in crashes across all sites indicated that urban sites experienced an increase in total crashes, but FI crashes were still reduced. This is likely due to RCUTs eliminating more difficult minor road driver maneuvers, through and left turn movements, that often lead to more severe outcomes.

5.2.3. Before-After Analysis with a Comparison Group

The comparison group analysis had similar results to the simple before-after, showing that each alternative reduced total and FI crashes at intersections throughout Alabama. For this analysis, comparison sites and treatment sites were matched based on traffic volume, number of approaches, number of lanes, prior control type, area type, and crash history. Based on the CMF across all sites for each alternative intersection, total crashes were reduced at roundabouts, RCUTs, and CGTs by approximately 62%, 40%, and 21%, respectively. Also based on the developed CMFs, roundabouts, RCUTs, and CGTs yielded greater reductions in terms of FI crashes of 80%, 74%, and 42%, respectively. Confidence intervals were developed for each CMF at a 95% confidence level. The 95% confidence interval for each CMF indicated a reduction in total and FI crashes at each alternative intersection design except the results for the change in total crashes after CGT implementation were inconclusive. Roundabouts were evaluated further based on prior control type and it was found that previous TWSC intersections resulted in the greatest reduction in total and FI crashes, and a reduction in crashes was observed for prior AWSC and signalized sites. Based on the CMF confidence intervals, it cannot be stated at a 95% confidence level that signalized intersection to roundabout conversion will result in a reduction in total crashes. Roundabouts and RCUTs in rural areas both had greater safety improvements compared to urban. Total and FI crashes were reduced at rural RCUTs, rural roundabouts, and urban roundabouts at a 95% confidence level. The impact on total crashes after the implementation of an RCUT in an urban location were inconclusive at a 95% confidence level while FI crashes were reduced. Lastly, based on the CMFs developed that considered side impact, angle, and head-on collisions showed that roundabouts, RCUTs, and CGTs effectively reduce target crash types by 81%, 68%, and 61%, respectively. The observed reductions in crash types that often lead to a higher severity result is achieved at roundabouts and RCUTs through reducing total and crossing conflict points while CGTs minimize the angle of potential collisions due to drivers turning left from the minor road utilizing a separated acceleration lane.

5.3. Recommendations for Future Research

This work is anticipated to support future researchers looking to further evaluate the safety performance of these alternative intersection designs as well as any other alternatives or countermeasures. Due to having limited data available prior to 2016, the sites included in this research were constructed in recent years and skewed towards having less available after-period data. Additional research should be done as more after-period data becomes available for these sites and drivers become more familiar with these alternatives. Also, as the implementation of these alternatives continues to grow, further research should be conducted as sample size increases. As more RCUTs and CGTs are constructed throughout the state, further analysis should be conducted to assess the safety performance of each based on prior control type as well as in terms of area type for CGTs.

5.4. Recommendations for Practice

This research was performed to provide insight to the Alabama Department of Transportation on how roundabouts, RCUTs, and CGTs are currently performing in terms of safety throughout the state. Research conducted nationally and in other states may support the implementation of these design alternatives in Alabama, but having data-driven benefits specific to the state is preferable for gaining public support and motivating future projects. The results of this research showed that the implementation of these alternative intersection designs led to a reduction in total and FI crashes per year, making them a practical treatment method for intersections in Alabama. It is important to note that the implementation of each alternative intersection had greater reductions in FI crashes compared to total crashes, meaning they may be most effective in a location with a high frequency of severe crashes. Further insight was also provided on what locations, based on prior control type and area type, are best suited for future implementation. The results showed that roundabouts that were previously TWSC intersections had the greatest reductions in total and FI crashes per year, whereas those that were previously signalized had the least. Also, roundabouts and RCUTs in rural locations overall had better safety performance compared to those in urban locations. Lastly, the evaluation of the distribution of the manner of crashes showed that the implementation of each alternative intersection reduced the proportion of side impact collisions relative to other crash types. This means that each alternative intersection type is an appropriate treatment method for intersections experiencing a high frequency of side-impact collisions. In conclusion, roundabouts, RCUTs, and CGTs are effective design alternatives when it comes to improving intersection safety in Alabama due to their ability to reduce the frequency of crashes as well as the severity of those that do occur.

References

1. Al-Omari, M. M. A., Abdel-Aty, M., Lee, J., Yue, L., and Abdelrahman, A. (2020). “Safety Evaluation of Median U-Turn Crossover-Based Intersections.” *Transportation Research Record, 2674(7)*, 206-218. https://doi.org/10.1177/0361198120921158.
2. American Association of State Highway and Transportation Officials. (2010). *Highway Safety Manual* (Vol. 1). Washington, DC.
3. Coffey, S., Park, S., and Zoccoli, N. (2016). “Roundabout Safety Analysis in the Context of Time Series: Case Study in the State of Pennsylvania.” *International Conference on Transportation and Development 2016*. pp. 907-918. Houston, Texas.
4. Donnell, E., Wood, J., and Eccles, K. (2016). "Safety Evaluation of Continuous Green T Intersection.” *Report No. FHWA-HRT-16-036*. Federal Highway Administration.
5. Edara, P., Breslow, S., Sun, C., and Claros, B. R. (2015). “Empirical Evaluation of J-Turn Intersection Performance: Analysis of Conflict Measures and Crashes.” *Transportation Research Record, 2486(1)*, 11-18. https://doi.org/10.3141/2486-02.
6. Federal Highway Administration Highway Safety Program (2024). *About Intersection Safety*. U.S. Department of Transportation. Federal Highway Administration. Retrieved September 2024, from https://highways.dot.gov/safety/intersection-safety/about.
7. Ferguson, E., Bonneson J., Rodegerdts, L., and Foster, N. (2018). *NCHRP Research Report 888: Development of Roundabout Crash Prediction Models and Methods*. National Academies of Sciences, Engineering, and Medicine, Transportation Research Board, National Cooperative Highway Research Program.

8. Gross, F., Lyon, C., Persaud, B., and Srinivasan, R. (2013). "Safety Effectiveness of Converting Signalized Intersections to Roundabouts." *Accident Analysis & Prevention, 50*, 234-241.
9. Gross, F., Persaud, B., and Lyon, C. (2010). "A Guide to Developing Quality Crash Modification Factors." *Report No. FHWA-SA-10-032.* U.S. Department of Transportation. Federal Highway Administration.
10. Guin, A., Rodgers, M., and Gbologah, F. (2018). "Safety Evaluation of Roundabouts in Georgia." *Report No. FHWA-GA-18-1507*. Georgia Tech Research Corporation. Georgia Department of Transportation.
11. Hauer, E., Harwood, D. W., Council, F. M., and Griffith, M. S. (2002). "Estimating Safety by the Empirical Bayes Method: A Tutorial." *Transportation Research Record, 1784(1)*, 126-131. https://doi.org/10.3141/1784-16.
12. Herbel, S., Laing, L., McGovern, C. (2010). "Highway Safety Improvement Program (HSIP) Manual." *Report No. FHWA-SA-09-029*. U.S. Department of Transportation. Federal Highway Administration.
13. Hughes, W., Jagannathan, R., Sengupta, D., and Hummer, J. (2010). "Alternative Intersections/Interchanges: Informational Report (AIIR)." *Report No. FHWA-HRT-09-060*. Federal Highway Administration.
14. Hummer, J. E., Haley, R. L., Ott, S. E., Foyle, R. S., and Cunningham, C. M. (2010). "Superstreet Benefits and Capacities." *Report No. 2009 – 06*. North Carolina State University. North Carolina Department of Transportation.

15. Hummer, J. E., and Rao, S. (2017). "Safety Evaluation of Signalized Restricted Crossing U-Turn Intersections." *Report No*. *FHWA-HRT-17-082*. U.S. Department of Transportation. Federal Highway Administration.

16. Hummer, J., Ray, B., Daleiden, A., Jenior, P., Knudsen, J., and Kittelson & Associates, Inc. (2014). "Restricted Crossing U-Turn Intersection Informational Guide." *Report No. FHWA-SA-14-070*. U.S. Department of Transportation. Federal Highway Administration Office of Safety.

17. Inman, Vaughan W., and Haas, R. (2012). "Field Evaluation of a Restricted Crossing U-Turn Intersection." *Report No. FHWA-HRT-11-067*. Science Applications International Corporation. U.S. Department of Transportation. Federal Highway Administration.

18. Lee, J., Abdel-Aty, M., and El-Urfali, A. (2020). "Safety Implications of Converting Continuous Green T-intersections back to Conventional T-intersections." *Journal of Transportation Engineering, Part A: Systems, 146(4)*. https://doi.org/10.1061/jtepbs.0000322.

19. Leuer, D. (2017). *A Study of the Traffic Safety at Roundabouts in Minnesota*. Minnesota Department of Transportation Office of Traffic, Safety and Technology. Retrieved from rosap.ntl.bts.gov/view/dot/35084.

20. Litsas, S. and Rakha, H. (2013). "Evaluation of Continuous Green T-Intersections on Isolated Undersaturated Four-Lane Highways." *Transportation Research Record, 2348(1)*, 19-29. https://doi.org/10.3141/2348-03.

21. Mamlouk, M. and Souliman, B. (2019). "Effect of Traffic Roundabouts on Accident Rate and Severity in Arizona." *Journal of Transportation Safety & Security, 11*(4), 430-442. https://doi.org/10.1080/19439962.2018.1452812.

22. Mishra, R and Pulugurtha, S. S. (2021). "Safety Evaluation of Unsignalized and Signalized Restricted Crossing U-Turn (RCUT) Intersections in Rural and Suburban Areas Based on Prior Control Type." *IATSS Research, 46*(2), 247-257. The University of North Carolina at Charlotte.
23. Ngo, C. (2023). *Zero Deaths and Safe System.* U.S. Department of Transportation. Federal Highway Administration. Retrieved January 2024, from highways.dot.gov/safety/zero-deaths.
24. Park, L., & Pierce, D. (2013). "Accommodation of Large Trucks in Roundabouts: Motor Carrier Perspective." *Transportation Research Record*, *2388*(1), 10-13. https://doi.org/10.3141/2388-02.
25. Qin, X., Khan, G., Bill, A., and Noyce, D. (2011). "Comprehensive Safety Evaluation of Roundabouts in Wisconsin." *Journal of Transportation Safety & Security, 3(4)*, 289-303, https://doi.org/10.1080/19439962.2011.624290.
26. Rice, E. and Znamenacek, Z. (2010). "Continuous Green T-Intersections." *Report No. FHWA-SA-09-016*. U.S. Department of Transportation. Federal Highway Administration.
27. Robinson, B., Rodegerdts, L., Scarborough, W., Kittelson, W., Troutbeck, R., Brilon, W., Bondzio, L., Courage, K., Kyte, M., Mason, J., Flannery, A., Myers, E., Bunker, J., Jacquemart, G., & Kittelson & Associates, Inc (2000). "Roundabouts: An Informational Guide." *Report No. FHWA-RD-00-067*. U.S. Department of Transportation. Federal Highway Administration.
28. Rodegerdts, L., Knudsen, J., & Kittelson & Associates, Inc. (2023). *NCHRP Research Report 1043: Guide for Roundabouts*. National Cooperative Highway Research Program, Transportation Research Board.

29. Rodegerdts, L., Persaud, B., and Lyon, C. (2007). *NCHRP Report 572: Roundabouts in the United States*. National Cooperative Highway Research Program, Transportation Research Board. Retrieved from http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_572.pdf.

30. Sando, T., Chimba, D., Kwigizile, V., and Walker, H. (2011). “Safety Analysis of Continuous Green Through Lane Intersections.” *Journal of the Transportation Research Forum, 50*(1), 5–17.

31. Savolainen, P. T., Gates, T. J., Gupta, N., Megat-Johari, M., Cai, Q., Imosemi, S., Ceifetz, A., McArthur, A., Hagel, E. C., and Smaglik, E. (2023). “Evaluating the Performance and Safety Effectiveness of Roundabouts- An Update.” *Report No. SPR-1725*. Michigan Department of Transportation.

32. Steyn, H., Griffin, A., and Rodegerdts, L. A. (2015). “Accelerating Roundabout Implementation in the United States - Volume IV of VII: Review of Fatal and Severe Injury Crashes at Roundabouts.” *Report No. FHWA-SA-15-072*. U.S. Department of Transportation. Federal Highway Administration. Retrieved from https://rosap.ntl.bts.gov/view/dot/49389.

33. Sun, X. and Ashifur, R. M. (2019). “Investigating Safety Impact of Center Line Rumble Strips, Lane Conversion, Roundabout, and J-Turn Features on Louisiana Highways*.”* *Report No. FHWA/LA.18/597*. University of Louisiana at Lafayette. Louisiana Transportation Research Center.

34. Sun, X., Rahman, M. A., and Sun, M. (2019). "Safety Analysis of RCUT Intersection," *2019 6th International Conference on Models and Technologies for*

Intelligent Transportation Systems (MT-ITS), 1-6. Cracow, Poland. https://doi.org/10.1109/MTITS.2019.8883332.

35. Ulak, M. B., Ozguven, E. E., Karabag, H. H., Ghorbanzadeh, M., Moses, R., Dulebenets, M. (2020). “Development of Safety Performance Functions for Restricted Crossing U-turn Intersections.” *Journal of Transportation Engineering, Part A: Systems, 146*(6). https://doi.org/10.1061/jtepbs.0000346.
36. Van Sluijs, S. M., Linsenmayer, M., and CTC & Associates LLC. (2018). “Use of Continuous Green T-Intersections.” *Report No. TRS 1809*. Minnesota Department of Transportation. Retrieved from https://rosap.ntl.bts.gov/view/dot/64603.
37. Virginia Department of Transportation. (2023). *Innovative Intersections: Continuous Green-T*. Retrieved October 2024, from https://www.vdot.virginia.gov/about/our-system/highways/innovative-intersections/continuous-green-t/.
38. Wang, J. and Cicchino, J. B. (2022). “Safety Effects of Roundabout Conversions in Carmel, Indiana, the Roundabout City.” *Journal of Safety Research, 82,* 159-165. https://doi.org/10.1016/j.jsr.2022.05.007.
39. Wisconsin Department of Transportation. *Restricted Crossing U-Turn (RCUT).* Retrieved January 2024, from https://wisconsindot.gov/Pages/safety/safety-eng/rcut.aspx.

Appendix A: Treatment Site List

Table A-1: Roundabout Site List

Latitude	Longitude	Major Road	Minor Road(s)	County	Area Type	Prior Control Type	Construction Start Date	Construction Completion Date
32.66587	-85.48995	AL-147	CR-72	Lee	Rural	TWSC	Nov 2020	Nov 2021
34.812372	-86.930456	AL-251	CR-83	Limestone	Rural	Signal	Jan 2021	March 2023
33.98382	-86.58768	AL-79	AL-160	Blount	Rural	Signal	April 2019	Jan 2021
32.67426	-85.33410	W Point Pkwy	Anderson Rd / SportPlex Pkwy	Lee	Rural	TWSC	July 2022	March 2023
32.57765	-85.52445	Wire Rd	Cox Rd	Lee	Urban	TWSC	July 2021	Sept 2022
32.61098	-85.39179	Society Hill Rd	Gateway Dr	Lee	Rural	AWSC	Dec 2019	July 2020
33.78182	-86.278447	US-411	CR-33/US-231	St. Clair	Rural	TWSC	Feb 2019	Jan 2021
32.507095	-86.128508	CR-8	CR-59	Elmore	Rural	TWSC	June 2021	Oct 2022
30.47255	-87.86933	CR-13	CR-32	Baldwin	Rural	TWSC	~2021	~2022
30.651981	-88.246712	Dawes Rd	Jeff Hamilton Road	Mobile	Urban	Signal	Dec 2020	Dec 2022
34.72891	-86.768076	Balch Rd	Gillespie Rd	Madison	Urban	AWSC	~2021	~2021
33.314557	-86.782335	CR-35	Oak Mountain Park Rd	Shelby	Rural	AWSC	~2022	~2023
30.68429	-88.052809	Broad St	Canal Street City	Mobile	Urban	Signal	~2020	~2022
31.186807	-85.4081	Campbellton Hwy	Taylor Rd	Houston	Rural	TWSC	~2021	~2022
34.676691	-86.742094	Lime Quarry Road/Graphics Dr	Intergraph Way	Madison	Urban	TWSC	~2022	~2022
33.173319	-86.779075	CR-87	Weather Vane Rd	Shelby	Rural	AWSC	~2021	~2021
34.80366	-87.65835	S Royal Ave	Huntsville Rd	Lauderdale	Urban	TWSC	May 2018	April 2020
30.602675	-88.258676	McFarland Rd	Dawes Rd / McLeod Rd	Mobile	Rural	TWSC	Aug 2018	Oct 2020
32.61583	-85.40719	Interstate Dr	Enterprise Dr / Hamilton Rd	Lee	Urban	AWSC	Aug 2018	April 2019
32.95329	-87.17341	AL-5	CR-58	Bibb	Rural	AWSC	July 2018	Nov 2019
32.63642	-85.38391	Auburn St	Frederick Rd / Martin Luther King St	Lee	Urban	Signal	Sept 2017	Oct 2018
30.530934	-87.869187	Gayfer Rd Ext	Oberg Rd	Baldwin	Rural	AWSC	~2017	~2017

Note: ~ Construction date estimated from Google Earth/Google Maps

Table A-2: RCUT Site List

Latitude	Longitude	Major Road	Minor Road(s)	County	Area Type	Prior Control Type	Construction Start Date	Construction Completion Date
34.3007889	-86.1449859	AL-75	AL-68 / Hustleville Rd	Marshall	Rural	TWSC	Dec 2021	Dec 2021
34.621435	-86.096837	US-72	AL-79	Jackson	Rural	TWSC	Nov 2020	Aug 2021
34.75867477	-86.47443773	US 72	Dug Hill Rd	Madison	Rural	TWSC	Sept 2019	Sept 2019
33.46056	-86.103078	AL-275	Jackson Trace Road	Talladega	Rural	TWSC	Feb 2022	April 2022
32.92649	-85.963209	US-280	Recreation Dr	Tallapoosa	Urban	TWSC	Nov 2021	Dec 2021
33.417878	-86.668969	US-280	Tattersall Blvd	Shelby	Urban	TWSC	July 2021	May 2023
33.414907	-86.665869	US-280	Greystone Highlands Dr	Shelby	Urban	TWSC	July 2021	May 2023
33.408388	-86.664361	US-280	Bowling Drive	Shelby	Urban	TWSC	July 2021	May 2023
33.347682	-86.636605	US-280	Chesser Rd/CR-280	Shelby	Urban	TWSC	Late 2021	Early 2022
32.46725949	-87.59401366	US-80	AL-25	Marengo	Rural	TWSC	July 2020	Jan 2022
31.235253	-85.431753	US-231	Forest Dr	Houston	Urban	TWSC	~2021	~2022
31.23271	-85.431905	US-231	Kent Dr	Houston	Urban	TWSC	~2021	~2022
32.958601	-87.147718	US-82	AL-219	Bibb	Rural	Signal	~2016	~2017
32.959311	-87.151065	US-82	Timberlane Dr	Bibb	Rural	TWSC	~2016	~2017
31.195316	-85.329173	US-84	Forrester Road/Glen Lawrence Rd	Houston	Rural	TWSC	May 2022	April 2023

Note: ~ Construction date estimated from Google Earth/Google Maps

Table A-3: CGT Site List

Latitude	Longitude	Major Road	Minor Road(s)	County	Area Type	Prior Control Type	Construction Start Date	Construction Completion Date
32.67644	-85.48625	US-280	AL-147	Lee	Rural	TWSC	Jan 2021	May 2022
32.300477	-86.443181	US-80	Mitchell Young Rd	Montgomery	Rural	TWSC	Oct 2021	July 2022
34.1515	-86.833976	US-31	Olive Street SW	Cullman	Urban	TWSC	March 2020	June 2021
32.45622	-86.170861	CR-8	CR-4	Elmore	Rural	TWSC	June 2021	April 2023
33.147735	-87.523509	US-82	AL-215	Tuscaloosa	Rural	TWSC	April 2017	Oct 2018
33.148299	-87.525933	AL-215	Bear Creek Cutoff Rd	Tuscaloosa	Rural	TWSC	~2017	~2018

Note: ~ Construction date estimated from Google Earth/Google Maps

Appendix B: Comparison Site List

Table B-1: Roundabout Comparison Site List

Lat	Long	Major Road	Minor Road(s)	County
34.872837	-87.660514	Helton Dr	Kendall Dr	Lauderdale
32.63861	-85.437537	Veterans Pkwy	Academy Dr	Lee
32.642916	-85.504887	N Donahue Dr	Miracle Rd	Lee
33.817158	-87.33072	AL-69	AL-124	Walker
34.552688	-86.990537	Cedar Lake Rd SW	Sandlin Rd SW	Morgan
32.650227	-85.385442	N 10th St	4th Ave	Lee
34.72905	-86.796586	Huntsville Brownsferry Rd	Burgreen Rd	Limestone
30.567397	-87.750786	CR-54	CR-55	Baldwin
31.160134	-85.344629	E Cottonwood Rd	Eddins Rd	Houston
34.768883	-87.404641	AL-101	CR-314/Foster Mill Rd	Lawrence
33.874967	-86.29866	US-231	US-11	St. Clair
33.76253	-86.279111	US-231	CR-22	St. Clair
30.443209	-87.852406	AL-181	CR-24	Baldwin
32.442363	-86.129668	Rifle Range Rd	Dozier Rd/Albritton Ln	Elmore
34.500877	-86.855033	AL-67	Friendship Rd	Morgan
32.533908	-85.374532	AL-51	CR-47	Lee
30.421338	-87.869319	US-98	CR-13	Baldwin
30.523662	-87.835487	CR-48	Lawrence Rd	Baldwin
33.772036	-86.475088	US-11	Murphrees Valley Rd	St. Clair
30.443248	-87.86931	CR-24	CR-13	Baldwin
30.565395	-88.343242	Grand Bay Wilmer Rd South	Dawes Rd	Mobile
34.5767	-87.052942	CR-61	Shady Grove Ln SW	Morgan
34.561555	-87.072638	CR-61	Modaus Rd SW	Morgan
30.669549	-88.113623	Cottage Hill Rd	S Sage Ave	Mobile
30.646666	-88.258352	CR-25	Jeff Hamilton Rd	Mobile
32.643437	-85.372065	Torbert Boulevard	McCoy St/South 7th Street	Lee
32.643996	-85.386807	1st Ave	14th Street North	Lee

Lat	Long	Major Road	Minor Road(s)	County
33.330083	-86.981623	CR-55	CR-6	Jefferson
32.786521	-85.192147	US-29	Fairfax Bypass	Chambers

Table B-2: RCUT Comparison Site List

Lat	Long	Major Road	Minor Road(s)	County
33.287974	-86.810759	Pelham Pkwy	Cummings St	Shelby
33.410989	-86.664745	US-280	Turtlelake Dr	Shelby
33.406551	-86.664087	US-280	Cedar Ln	Shelby
33.402666	-86.663552	US-280	Eagle Point Pkwy	Shelby
33.240682	-87.582812	US-82	26th Ave	Tuscaloosa
31.253192	-85.407106	Ross Clark Circle	Zenith Rd	Houston
31.198841	-85.370153	Ross Clark Circle	Oppert Dr	Houston
33.334857	-86.791583	Pelham Pkwy	Bowling Ln	Shelby
32.327172	-86.25181	US-82	US 80 Service Rd	Montgomery
31.204277	-85.420422	US-231	Timbers Dr	Houston
34.308145	-86.11269	AL-75	McVille Rd	Marshall
34.589073	-87.42426	AL-157	AL 101	Lawrence
34.312922	-86.503046	US-231	3rd Ave SW	Marshall
34.608883	-86.270539	US-72	CR-63	Jackson
31.175835	-85.238838	US-84	CR-55	Houston
34.696952	-86.377704	US-72	Gurley Pike	Madison
34.7553	-86.468121	US-72	Wall Rd	Madison
31.201232	-85.368084	US-431	Hedstrom Dr	Houston
34.704727	-87.652417	US-72	Elledge Rd	Colbert
34.308142	-86.11269	AL-75	McVille Rd	Marshall
32.460111	-86.382056	Cobbs Ford Rd	S Edgewood Dr	Elmore
34.490087	-87.672876	AL-24	CR-77	Franklin
31.160651	-85.402252	US-231	Saunders Rd	Houston
31.207743	-85.352812	US-84	N Beverlye Rd	Houston

Table B-3: CGT Comparison Site List

Lat	Long	Major Road	Minor Road(s)	County
34.153882	-86.834248	US-31	Broadway Dr SW	Cullman
33.580262	-86.127159	AL-77	Speedway Blvd	Talladega
32.410871	-86.256923	Cong W L Dickinson Dr	Emory Folmar Blvd	Montgomery
32.90611	-85.900952	US-280	Dadeville Rd	Tallapoosa
32.8455	-85.780266	US-280	AL-49	Tallapoosa
32.65062	-85.441974	US-280	Waverly Pkwy	Lee
32.664918	-85.472918	US-280	Farmville Rd	Lee
32.270197	-86.512625	US-80	AL-21	Lowndes
33.47525	-86.626783	Grants Mill Rd	Eastern Valley Rd	Jefferson
33.265177	-87.543984	Martin Rd E	Union Chapel Rd E	Tuscaloosa
32.506268	-87.69489	US-80	AL-69	Hale
33.526116	-86.930727	Birmingport Rd	Panama Pl	Jefferson
30.642792	-88.326059	Airport Blvd	CR-11	Mobile

Appendix C: Manner of Crash Distribution Analysis Results

Table C-1: Manner of Crash Proportions Before and After Implementation

	Roundabouts		RCUTs		CGTs	
	Before	**After**	**Before**	**After**	**Before**	**After**
Single Vehicle Crash (all types)	6.2%	19.1%	2.2%	5.0%	6.1%	4.0%
Head-On (front to front only)	3.3%	0.0%	0.9%	2.1%	0.0%	1.6%
Angle Collision	12.9%	12.8%	11.2%	10.6%	9.1%	8.1%
Rear End (front to rear)	24.9%	36.2%	19.6%	41.8%	28.8%	43.5%
Side Impact	49.0%	24.5%	59.6%	28.4%	48.5%	26.6%
Sideswipe	2.5%	6.4%	5.3%	9.2%	6.8%	14.5%
Other	1.2%	1.1%	1.2%	2.8%	0.8%	1.6%

Table C-2: Roundabout Chi-Square Test of Independence Results

Roundabouts			
Observed			
	Before	**After**	**Sum**
Single Vehicle Crash (all types)	15.0	18.0	33
Head-On (front to front only)	8.0	0.0	8
Angle Collision	31.0	12.0	43
Rear End (front to rear)	60.0	34.0	95
Side Impact	118.0	23.0	142
Sideswipe	6.0	6.0	12
Other	3.0	1.0	4
Total	241	94	335
Expected			
	Before	**After**	**Sum**
Single Vehicle Crash (all types)	23.7	9.3	33
Head-On (front to front only)	5.8	2.2	8
Angle Collision	30.9	12.1	43
Rear End (front to rear)	67.6	26.4	94
Side Impact	101.4	39.6	141
Sideswipe	8.6	3.4	12
Other	2.9	1.1	4
Total	241	94	335
Degrees of Freedom (df)	6		
Significance Level (α)	0.05		
Critical Value	12.59		
Chi-square statistic (X^2)	30.17		
p-value	3.65E-05		

Table C-3: RCUT Chi-Square Test of Independence Results

RCUT			
Observed			
	Before	**After**	**Total**
Single Vehicle Crash (all types)	7.0	7.0	14
Head-On (front to front only)	3.0	3.0	6.0
Angle Collision	36.0	15.0	51
Rear End (front to rear)	63.0	59.0	122
Side Impact	192.0	40.0	232
Sideswipe	17.0	13.0	30
Other	4.0	4.0	8
Total	322	141	463
Expected			
	Before	**After**	**Total**
Single Vehicle Crash (all types)	9.7	4.3	14
Head-On (front to front only)	4.2	1.8	6
Angle Collision	35.5	15.5	51
Rear End (front to rear)	84.8	37.2	122
Side Impact	161.3	70.7	232
Sideswipe	20.9	9.1	30
Other	5.6	2.4	8
Total	322	141	463
Degrees of Freedom (df)	6		
Significance Level (α)	0.05		
Critical Value	12.59		
Chi-square statistic (X^2)	45.02		
p-value	4.64E-08		

Table C-4: CGT Chi-Square Test of Independence Results

CGT			
Observed			
	Before	**After**	**Total**
Single Vehicle Crash (all types)	8.0	5.0	13
Head-On (front to front only)	0.0	2.0	2
Angle Collision	12.0	10.0	22
Rear End (front to rear)	38.0	54.0	92
Side Impact	64.0	33.0	97
Sideswipe	9.0	18.0	27
Other	1.0	2.0	3
Total	132	124	256
Expected			
	Before	**After**	**Total**
Single Vehicle Crash (all types)	6.7	6.3	13
Head-On (front to front only)	1.0	1.0	2
Angle Collision	11.3	10.7	22
Rear End (front to rear)	47.4	44.6	92
Side Impact	50.0	47.0	97
Sideswipe	13.9	13.1	27
Other	1.55	1.45	3
Total	132	124	256
Degrees of Freedom (df)	6		
Significance Level (α)	0.05		
Critical Value	12.59		
Chi-square statistic (X^2)	18.67		
p-value	0.005		

Appendix D: Simple Before-After Analysis Results

Table D-1: Roundabout Simple Before-After Calculations

Site ID	Major Rd	Minor Rd (s)	Mean Crashes/Year				Percent Change in Mean Crashes/Year		Difference in Mean Crashes/Year	
			Before-Period		After-Period					
			Total	FI	Total	FI	Total	FI	Total	FI
1	AL-147	CR-72	7.67	2.67	0.50	0.00	-93.5%	-100.0%	-7.17	-2.67
2	AL-251	CR-83	2.50	0.00	0.00	0.00	-100.0%	0.0%	-2.50	0.00
3	AL-79	AL-160	1.00	0.33	4.33	0.33	333.3%	0.0%	3.33	0.00
4	W Point Pkwy	Anderson Rd / SportPlex Pkwy	16.67	4.33	1.00	1.00	-94.0%	-76.9%	-15.67	-3.33
5	Wire Rd	Cox Rd	6.33	1.00	0.50	0.00	-92.1%	-100.0%	-5.83	-1.00
6	Society Hill Rd	Gateway Dr	4.00	0.67	3.33	0.33	-16.7%	-50.1%	-0.67	-0.33
7	US-411	CR-33/US-231	5.00	2.00	2.00	0.50	-60.0%	-75.0%	-3.00	-1.50
8	CR-8	CR-59	3.67	0.67	1.00	0.00	-72.7%	-100.0%	-2.67	-0.67
9	CR-13	CR-32	2.00	1.50	0.00	0.00	-100.0%	-100.0%	-2.00	-1.50
10	Dawes Rd	Jeff Hamilton Road	7.00	0.67	0.00	0.00	-100.0%	-100.0%	-7.00	-0.67
11	Balch Rd	Gillespie Rd	7.00	1.00	5.50	0.00	-21.4%	-100.0%	-1.50	-1.00
12	CR-35	Oak Mountain Park Rd	0.33	0.00	0.00	0.00	-100.0%	0.0%	-0.33	0.00
13	Broad St	Canal Street City	3.33	0.67	4.00	0.50	20.0%	-25.0%	0.67	-0.17
14	Campbellton Hwy	Taylor Rd	2.33	0.33	0.00	0.00	-100.0%	-100.0%	-2.33	-0.33
15	Lime Quarry Road/Graphics Dr	Intergraph Way	1.00	0.00	1.00	0.00	0.0%	0.0%	0.00	0.00
16	CR-87	Weather Vane Rd	0.67	0.00	2.50	0.00	274.8%	0.0%	1.83	0.00
17	S Royal Ave	Huntsville Rd	2.33	0.00	1.33	0.33	-42.9%	0.0%	-1.00	0.33
18	McFarland Rd	Dawes Rd / McLeod Rd	1.00	0.33	2.67	0.33	166.7%	-0.1%	1.67	0.00
19	Interstate Dr	Enterprise Dr / Hamilton Rd	6.50	0.50	3.00	0.33	-53.8%	-33.4%	-3.50	-0.17
20	AL-5	CR-58	3.50	1.00	2.25	0.00	-35.7%	-100.0%	-1.25	-1.00
21	Auburn St	Frederick Rd / Martin Luther King St	3.00	0.00	2.33	0.00	-22.2%	0.0%	-0.67	0.00
22	Gayfer Rd Ext	Oberg Rd	1.00	0.00	0.33	0.00	-66.7%	0.0%	-0.67	0.00

Table D-2: RCUT Simple Before-After Calculations

Site ID	Major Rd	Minor Rd (s)	Mean Crashes/Year				Percent Change in Mean Crashes/Year		Difference in Mean Crashes/Year	
			Before-Period		After-Period					
			Total	FI	Total	FI	Total	FI	Total	FI
1	AL-75	AL-68 / Hustleville Rd	12.33	3.67	13.50	0.50	9.5%	-86.4%	1.17	-3.17
2	US-72	AL-79	10.33	4.67	1.00	0.50	-90.3%	-89.3%	-9.33	-4.17
3	US 72	Dug Hill Rd	11.33	5.67	1.75	0.75	-84.6%	-86.8%	-9.58	-4.92
4	AL-275	Jackson Trace Road	9.00	4.33	1.50	1.00	-83.3%	-76.9%	-7.50	-3.33
5	US-280	Recreation Dr	2.00	0.33	5.50	0.00	175.0%	-100.0%	3.50	-0.33
6	US-280	Tattersall Blvd	3.00	1.00	5.00	0.00	66.7%	-100.0%	2.00	-1.00
7	US-280	Greystone Highlands Dr	6.00	0.67	11.00	2.00	83.3%	199.9%	5.00	1.33
8	US-280	Bowling Drive	13.67	2.33	8.00	1.00	-41.5%	-57.1%	-5.67	-1.33
9	US-280	Chesser Rd/CR 280	12.00	3.33	15.00	1.50	25.0%	-55.0%	3.00	-1.83
10	US-80	AL-25	5.33	3.33	1.00	0.00	-81.2%	-100.0%	-4.33	-3.33
11	US-231	Forest Dr	4.67	2.67	0.50	0.50	-89.3%	-81.3%	-4.17	-2.17
12	US-231	Kent Dr	7.00	2.33	2.00	0.50	-71.4%	-78.6%	-5.00	-1.83
13	US-84	Forrester Road/Glen Lawrence Rd	13.00	6.00	4.50	1.50	-65.4%	-75.0%	-8.50	-4.50
14	US-82	AL-219	6.00	-	5.33	-	-11.1%	-	-0.67	-
15	US-82	Timberlane Dr	0.33	-	0.00	-	-100.0%	-	-0.33	-

Table D-3: CGT Simple Before-After Calculations

Site ID	Major Rd	Minor Rd (s)	Mean Crashes/Year				Percent Change in Mean Crashes/Year		Difference in Mean Crashes/Year	
			Before-Period		After-Period					
			Total	FI	Total	FI	Total	FI	Total	FI
1	US-280	AL-147	5.3	2.3	5.0	1.0	-4.8%	-55.6%	-0.25	-1.25
2	US-80	Mitchell Young Rd	6.7	2.7	5.0	2.0	-25.0%	-25.0%	-1.67	-0.67
3	US-31	Olive Street SW	10.0	2.5	13.5	4.0	35.0%	60.0%	3.50	1.50
4	CR-8	CR-4	3.3	0.3	0.0	0.0	-100.0%	-100.0%	-3.33	-0.33
5	US-82	AL-215	15.0	8.0	10.0	2.0	-33.3%	-75.0%	-5.00	-6.00
6	AL-215	Bear Creek Cutoff Rd	15.5	3.5	15.7	4.0	1.1%	14.3%	0.17	0.50

Appendix E: Before-After Analysis with a Comparison Group Calculations

Table E-1: Roundabout Comparison Group Calculations Part 1

Group ID	Major Road	Minor Road(s)	Treatment Group				Comparison Group			
			Before		After		Before		After	
			Total	FI	Total	FI	Total	FI	Total	FI
1	AL-147	CR-72	23	8	1	0	20	13	15	9
2	AL-251	CR 83	5	0	0	0	4	0	2	0
3	AL-79	AL-160	3	1	13	1	13	3	18	2
4	W Point Pkwy	Anderson Rd / SportPlex Pkwy	50	13	1	1	9	4	1	1
5	Wire Rd	Cox Rd	19	3	1	0	18	5	5	0
6	Society Hill Rd	Gateway Dr	12	2	10	1	15	1	16	1
7	US-411	US-231 / CR-33	15	6	4	1	15	6	21	5
8	CR-8	Firetower Rd / Dozier Rd	11	2	1	0	7	2	8	2
9	CR-13	CR-32	4	3	0	0	5	2	1	1
10	Dawes Rd	Jeff Hamilton Road	21	2	0	0	19	1	2	0
11	Balch Rd	Gillespie Rd	21	3	11	0	17	2	28	3
12	CR-35	Oak Mountain Park Rd	1	0	0	0	1	0	1	0
13	Broad St	Canal Street City	10	2	8	1	10	1	9	1
14	Campbellton Hwy	Taylor Rd	7	1	0	0	5	1	4	0
16	CR-87	Weather Vane Rd	2	0	5	0	8	1	4	1
17	S Royal Ave	Huntsville Rd	7	0	4	1	7	2	1	0
18	McFarland Rd	Dawes Rd / McLeod Rd	3	1	8	1	3	1	2	1
19	Interstate Dr	Enterprise Dr / Hamilton Rd	13	1	9	1	9	2	14	2
20	AL-5	CR-58	7	2	9	0	9	2	41	7
21	Auburn St	Frederick Rd / Martin Luther King St	3	0	7	0	3	0	3	1
22	Gayfer Rd Ext	Oberg Rd	1	0	1	0	1	0	4	0
All Sites			238	50	93	8	198	49	200	37
Urban Sites			94	11	40	3	83	13	62	7
Rural Sites			144	39	53	5	115	36	138	30
Previously Signalized			42	5	28	2	49	5	34	4
Previously TWSC			139	37	20	4	89	36	58	19
Previously AWSC			57	8	45	2	60	8	108	14

Table E-2: Roundabout Comparison Group Calculations Part 2

	OR		Nexpected =		Var(Nexpected) =		CMF =		Var(CMF) =		SE =	
	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI
All Sites	0.83	0.98	240.404	37.755	823.692	96.125	0.38	0.20	0.004	0.007	0.059	0.082
Urban Sites	0.88	1.18	70.217	5.923	191.376	10.900	0.55	0.39	0.018	0.056	0.133	0.237
Rural Sites	0.80	0.92	172.800	32.500	683.386	91.632	0.30	0.14	0.004	0.005	0.060	0.070
Previously Signalized	1.17	1.00	29.143	4.000	62.534	10.400	0.90	0.30	0.076	0.039	0.276	0.197
Previously TWSC	0.64	0.97	90.584	19.528	292.703	40.969	0.21	0.18	0.004	0.010	0.060	0.100
Previously AWSC	1.05	1.00	102.600	14.000	457.596	63.000	0.42	0.11	0.011	0.005	0.103	0.074

Table E-3: Roundabout Confidence Interval Calculations

	Cumulative Probability (95% Confidence Level)	Total Crashes		FI Crashes	
		Upper Limit	Lower Limit	Upper Limit	Lower Limit
All Sites	1.96	0.26	0.50	0.04	0.36
Urban Sites	1.96	0.29	0.81	0.00	0.85
Rural Sites	1.96	0.18	0.42	0.00	0.28
Previously Signalized	1.96	0.35	1.44	0.00	0.69
Previously TWSC	1.96	0.10	0.33	0.00	0.38
Previously AWSC	1.96	0.22	0.62	0.00	0.25

Table E-4: RCUT Comparison Group Calculations Part 1

Group ID	Major Road	Minor Road(s)	Treatment Group				Comparison Group			
			Before		After		Before		After	
			Total	FI	Total	FI	Total	FI	Total	FI
1	Alabama Highway 75	AL 68 / Hustleville Rd	37	11	27	1	28	16	17	9
2	US-72	AL-79	31	14	2	1	31	11	19	10
3	US 72	Dug Hill Rd	34	17	7	3	34	13	48	23
4	AL 275	Jackson Trace Road	27	13	3	2	29	15	13	6
	US 80	AL 25	16	10	2	0				
5	US 280	Recreation Dr	6	1	11	0	9	1	3	0
6	US 280	Greystone Highlands Dr	18	2	11	2	57	9	24	5
	US 280	Bowling Drive	41	7	8	1				
7	US 280	Chesser Rd / CR 280	36	10	30	3	34	15	7	2
8	US 231	Forest Dr	14	8	1	1	42	8	21	4
	US 231	Kent Dr	21	7	4	1				
9	US 84	Forrester Road / Glen Lawrence Rd	13	6	9	3	12	3	28	8
All Sites			294	69	116	14	276	91	180	67
Urban Sites			136	35	65	8	142	33	55	11
Rural Sites			158	71	50	10	134	58	125	56

Table E-5: RCUT Comparison Group Calculations Part 2

	OR		Nexpected =		Var(Nexpected) =		CMF =		Var(CMF) =		SE =	
	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI
All Sites	191.739	50.802	462.494	104.285	0.60	0.26	0.007	0.007	0.086	0.085	191.739	50.802
Urban Sites	52.676	11.667	90.394	20.387	1.19	0.60	0.064	0.074	0.253	0.272	52.676	11.667
Rural Sites	147.388	68.552	473.389	231.128	0.33	0.14	0.004	0.003	0.066	0.051	147.388	68.552

Table E-6: RCUT Confidence Interval Calculations

	Cumulative Probability (95% Confidence Level)	Total Crashes		FI Crashes	
		Upper Limit	Lower Limit	Upper Limit	Lower Limit
All Sites	1.96	0.43	0.77	0.10	0.43
Urban Sites	1.96	0.70	1.69	0.06	1.13
Rural Sites	1.96	0.20	0.46	0.04	0.24

Table E-7: CGT Comparison Group Calculations Part 1

Group ID	Major Road	Minor Road(s)	Treatment Group				Comparison Group			
			Before		After		Before		After	
			Total	FI	Total	FI	Total	FI	Total	FI
1	US-280	AL-147	21	9	10	2	21	3	16	6
2	US-80	Mitchell Young Rd	20	8	10	4	17	4	14	6
3	US-31	Olive Street SW	20	5	27	8	17	8	11	3
4	CR-8	CR-4	10	1	0	0	7	2	0	0
5	US-82	AL-215	30	16	30	6	23	5	57	9
	AL-215	Bear Creek Cutoff Rd	31	7	47	12				
All Sites			132	46	124	32	85	22	98	24

Table E-8: CGT Comparison Group Calculations Part 2

	OR		Nexpected =		Var(Nexpected) =		CMF =		Var(CMF) =		SE =	
	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI	Total	FI
All Sites	0.64	0.48	152.188	50.182	684.289	274.134	0.79	0.58	0.022	0.038	0.149	0.194

Table E-9: CGT Confidence Interval Calculations

	Cumulative Probability (95% Confidence Level)	Total Crashes		FI Crashes	
		Upper Limit	Lower Limit	Upper Limit	Lower Limit
All Sites	1.96	0.50	1.08	0.19	0.96

Table E-10: Comparison Group Target Crash Type Calculations Part 1

	Total Target Crash Types			
	Treatment Sites		Comparison Sites	
	Before	After	Before	After
Roundabouts	152	34	100	116
RCUTs	208	46	176	121
CGTs	76	45	30	43

Table E-11: Comparison Group Target Crash Type Calculations Part 2

	OR	Nexpected =	Var(Nexpected) =	CMF =	Var(CMF) =	SE =
Roundabouts	0.66	176.320	783.425	0.188	0.002	0.043
RCUTs	0.85	143.000	383.500	0.32	0.004	0.062
CGTs	0.39	108.933	827.651	0.39	0.012	0.109

Table E-12: Target Crash Type Confidence Interval Calculations

	Cumulative Probability (95% Confidence Level)	Target Crash Types	
		Upper Limit	Lower Limit
Roundabouts	1.96	0.10	0.27
RCUTs	1.96	0.19	0.44
CGTs	1.96	0.17	0.60