GEORGIA DOT RESEARCH PROJECT 15-07

FINAL REPORT

SAFETY EVALUATION OF ROUNDABOUTS IN GEORGIA

Georgia Department of Transportation

OFFICE OF PERFORMANCE-BASED MANAGEMENT
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GDOT Research Project 15-07

Final Report

SAFETY EVALUATION OF ROUNDABOUTS IN GEORGIA

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16. Abstract: Several previous studies have documented significant safety benefits of roundabouts in the United Sates. However, the safety benefits for a given roundabout may vary depending on factors such as the familiarity of the driving population to roundabout operation, site-specific geometric features, weather conditions, etc. To help inform GDOT's roundabout implementation investment decisions, the current study provides a safety evaluation of 27 Georgia roundabouts. A time-dependent form of the Highway Safety Manual predictive (empirical Bayes) method was used to estimate potential crash reductions across all crashes and all injury/fatal crashes. The findings provide further evidence that roundabouts are an effective crash countermeasure. Specifically, the results show the following crash reductions: (a) A 37 to 48 percent reduction in average crash frequency for all crashes and a 51 to 60 percent reduction in average crash frequency for injury/fatal crashes at four-leg roundabouts converted from stop-controlled and conventional intersections (b) A 56 and 69 percent reduction in average crash frequency for all crashes and injury/fatal crashes, respectively, at three-leg and four-leg roundabouts converted from stop-controlled and conventional intersections The study did not consider five-leg roundabouts due to small sample size and concerns about the form of the SPF.			
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EXECUTIVE SUMMARY

The modern roundabout is one of nine proven-effective crash countermeasures endorsed by the Federal Highway Administration. Roundabout studies have safety benefits ranging from a reduction in all crashes of 9 to 72 percent. Roundabouts have even greater safety benefits for more severe crashes, with injury crash rates reduced by 52 to 88 percent and fatal and incapacitating injury crashes reduced by more than 90 percent. While informative, published findings may not be directly applicable to Georgia and the southeastern United States due to regional differences in roundabout application, population, driver, design, and weather.

This study evaluates the safety effectiveness of roundabouts in Georgia, analyzing before-and-after data at 27 roundabouts located in Georgia that were converted from prior conventional stop-controlled intersections. The research team selected additional reference sites from conventional stop-controlled intersections with similar traffic (i.e., 1000–20,000 average annual daily traffic [AADT]), physical characteristics (i.e., three and four legs), and driver populations (i.e., the same counties) as the study roundabouts. A total of 49,960 three-leg intersections and 8510 four-leg intersections were used as reference sites. Researchers checked all reference and study sites against the annual GDOT Road Characteristics Link database to exclude sites with any kind of signal device, multi-lane approaches, missing traffic information within the analysis period, or more than one type of traffic control within the analysis period.

Similar to most U.S. states, Georgia does not have a long history of roundabouts. As such, there is limited archived roundabout crash data and related traffic exposure data (i.e., AADT). Limitations regarding available data required some extensions of the Highway Safety Manual's empirical Bayes predictive method. Consistent traffic volume data were available only for 2010 to 2015; thus, traffic volume estimates for 2006 to 2009 were imputed from 2010 to 2015 trends. Consequently, although overall results are reasonable, predicted crash frequencies for individual sites may be somewhat over- or underestimated. To minimize any potential bias in this approach, the parameters used within the safety performance functions (SPFs) developed in this study were made temporally dependent (similar to a full-Bayesian approach) rather than assumed constant, as in the HSM predictive method. While somewhat more complex, this approach provides an improved method of dealing with temporal trends, regression-to-the-mean issues, and volume trends from the available data.

The safety effectiveness of the roundabouts was estimated as crash modification factors (CMFs). In calculating the CMFs, the researchers assumed that the hazard ratio at each site (i.e., the impacts of other potential influences on crashes at the treatment sites) was constant for each site except for the temporal trend in overall crash rates and changes in traffic volumes that were considered explicitly.

In general, the findings from this study are consistent with previously published studies on the safety evaluations of roundabouts in other areas of the United States. Specific findings of this study are as follows:

- Conventional four-leg intersections with only single-lane approaches that are converted into roundabouts in Georgia experience approximately a *37 percent reduction* in average crash frequency for all crashes and *51 percent reduction* in injury/fatal crashes.
- Conventional four-leg intersections, including both single-lane and multi-lane approaches, can collectively experience approximately *48 percent* and *60 percent*

reductions in average crash frequency for all crashes and injury/fatal crashes, respectively, when converted to a modern roundabout.

- When analyzed as a group, three-leg and four-leg conventional intersections that are converted into roundabouts in Georgia experience an approximately *56 percent* reduction in average crash frequency for all crashes and a *69 percent* reduction in average injury/fatal crash frequency.

These estimated safety benefits range from 37 to 56 percent for all crashes and 51 to 69 percent for injury/fatal crashes. These estimates are comparable to estimates from published U.S. studies: 9 to 72 percent and 52 to 100 percent reduction in average crash frequencies for all crashes and injury/fatal crashes, respectively. Five-leg roundabouts were not considered due to small sample size and concerns regarding the form of the SPF.

The main challenges encountered in performing this safety evaluation of roundabouts in Georgia are the limitations of availability and quality of traffic data and crash data, and the significantly short history for the majority of roundabouts in Georgia, which affects the size and quality of available before-period and after-period data. Since these limitations will continue to decline as more roundabouts are constructed and others remain in service, these analyses should be reexamined at a later date. In addition, ongoing efforts to improve the quality of crash location information in the Georgia crash database should continue. Furthermore, a more consistent inclusion of road names in the Road Characteristics Link database should be examined, and a system should be developed to facilitate the tracking of changes in RCLINK IDs for the same physical location.

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CHAPTER 1: INTRODUCTION

While roundabouts in European countries are numerous and have been widely used for decades— about 25,000 and 30,000 in the United Kingdom and France [*1*], respectively— roundabouts are relatively new in the United States. Since the year 2000, interest in and the implementation of roundabouts has grown significantly across the United States, including Georgia [*2*]. Figure 1 presents the cumulative number of roundabouts in the United States by year.

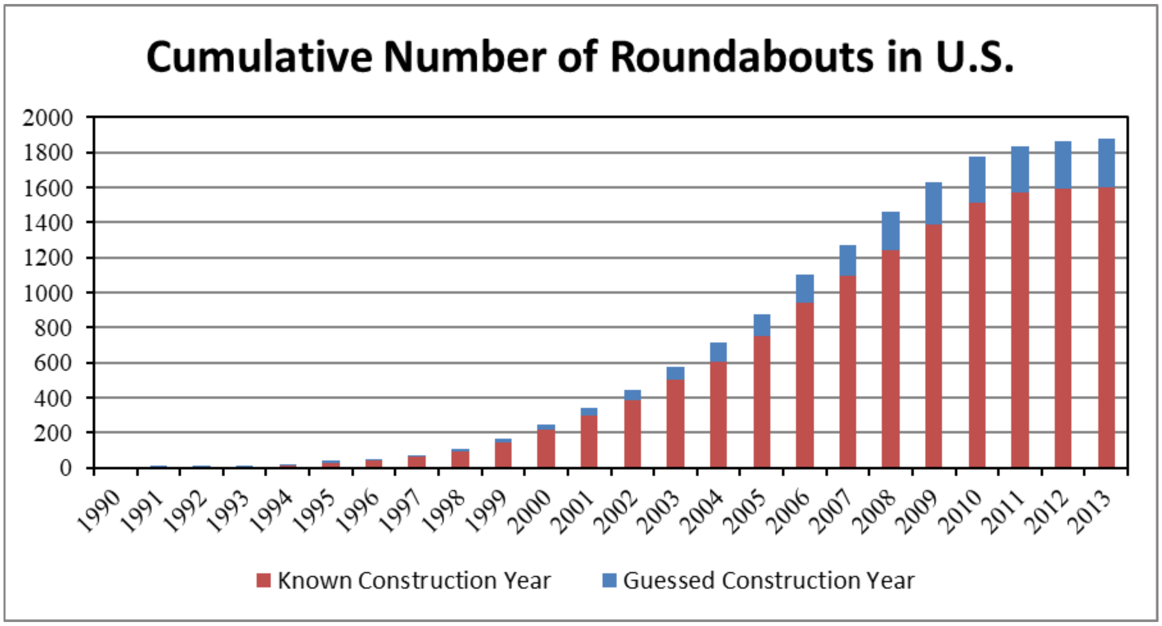


Figure 1 Cumulative Number of Roundabouts in the United States. Reprinted from Gbologah (2015)

In the United States, conventional signalized and stop-controlled intersections are plagued by safety issues [*1*]. Signalized intersections account for about one-third of all U.S. intersection fatalities [*3*]. Nationally, stop-controlled intersections account for fewer total crashes than signalized intersections, but have a significantly higher fatality rate per crash, accounting for over 60 percent of intersection fatalities in 2009 [*4*] in the Fatal Accident Reporting System (FARS). Overall, stop-controlled intersections account for approximately 25 percent of all reported fatalities [*1*]. Due in part to the safety performance of conventional signalized and stop-controlled intersections, the modern roundabout is becoming a favorite among state departments of transportation (DOTs). Many DOTs now consider roundabouts as a viable alternative to uncontrolled and stop-controlled intersections, and, in some cases, an alternative to signalized intersections and complex freeway interchanges [*5*].

The modern roundabout, with its unique geometry, is able to reduce both the number and severity of crashes by altering the vehicle conflict types and reducing entry speeds. Figure 2 shows the number and type of potential conflict points at a conventional intersection and at a roundabout. The Insurance Institute for Highway Safety (IIHS) reports that roundabouts are safer than typical four-leg intersections and typically experience 40 percent fewer vehicle collisions, 80 percent fewer injuries, and 90 percent fewer serious injuries and fatalities than their conventional counterparts in both urban and rural settings [*6*].

However, a roundabout’s safety effectiveness may vary as a result of site-specific geometric features, driver population and familiarity with roundabout operations, regional variations, etc. Therefore, to evaluate the impact of roundabouts as a safety measure in Georgia, a thorough analysis of crash-related safety improvements at roundabout intersections associated with conversions from other intersection types is necessary in a Georgia context.

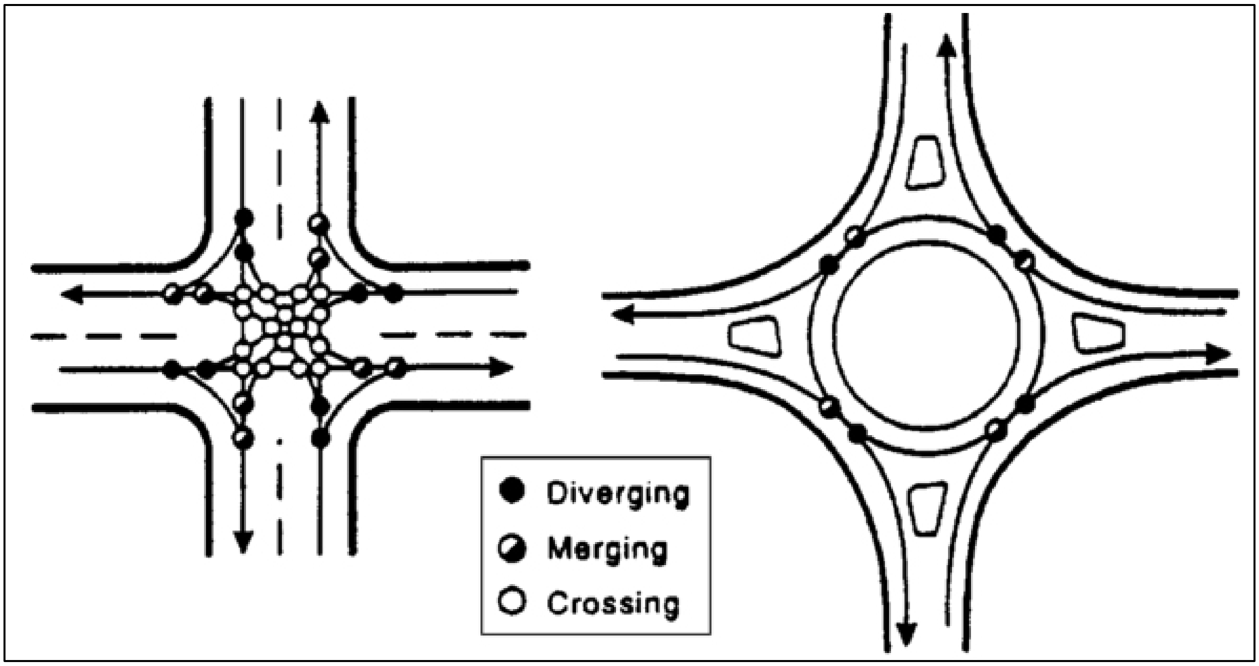


Figure 2 Conflict Points at Conventional Intersections and Roundabouts. Adapted from Flannery (2001)

1.1 Overview of Project

This report presents the findings of a research project sponsored by the Georgia Department of Transportation (GDOT) to evaluate roundabout intersection safety in Georgia. By focusing on Georgia roundabouts, this study reflects regional driving characteristics, weather conditions, previous exposure of the driving population to roundabouts, and other characteristics unique to Georgia and not reflected in roundabout safety evaluations in other states. Due to data limitations described in the methodology section (Chapter 3), this research project adopts a method that extends the standard empirical Bayes (EB) approach outlined in the Highway Safety Manual (HSM) toward a full Bayesian approach and provides an improved method of dealing with temporal trends, regression-to-the-mean issues, and volume trends from the available data. The study uses data from 27 existing roundabouts in Georgia that were converted from other intersection types.

1.2 Project Objectives

This project, *Safety Evaluation of Roundabouts in Georgia,* was designed to provide GDOT with 2 major safety evaluations for conversions from a conventional intersection to a roundabout in Georgia: (1) change in the total number of crashes, and (2) change in injury and fatal crashes. To achieve these objectives, this project had the following key sub-objectives:

- Conduct a review of the literature on previous efforts quantifying the safety impacts of roundabouts
- Identify candidate sites for a before-versus-after study and appropriate control sites
- Obtain data for the chosen sites from the crash database and verify the data against police records
- Perform a safety study using an empirical Bayes analysis and potentially other analysis techniques
- Prepare a final report and make recommendations

1.3 Report Organization

Chapter 1 of this report provides an introductory discussion of roundabouts in the United States, an overview of this project, and the project's objectives. Chapter 2 follows with a literature review of the safety effects of roundabouts on vehicles and other road users, and the safety-influencing features of roundabouts. The analysis methodology is presented in Chapter 3, and the study results are discussed in Chapter 4. The report concludes with a summary of the results and recommendations in Chapter 5.

CHAPTER 2: LITERATURE REVIEW

2.1 Roundabout Impact on Safety

Roundabouts have significantly fewer conflict points than conventional stop-controlled or signalized intersections [*5, 7*]. The roundabout conflict points also tend to have crash types with much lower rates of severe injuries than their conventional intersection counterparts. A roundabout's geometric design and operational features force drivers to reduce speed, regardless of posted speed limits, and promote better driver behavior [*8*]. Their overall safety advantages have made them the preferred alternatives in many instances; for example, in Sweden, major road intersections with high pedestrian and/or cyclist volume are being converted to roundabouts [*9*].

2.1.1 Impact on Vehicle Crashes

The conversion of a stop-controlled or signalized intersection to a roundabout has been found to offer substantial reductions in crash frequency and crash rate [*10*]. One of the earliest studies [*11*] indicated a 74 percent reduction in the injury crash rate after the conversion of 73 conventional intersections in Australia. Similarly, an analysis of 181 converted intersections in the Netherlands [*12*] reported a 47 percent, 71 percent, and 81 percent reduction in all crashes, injury crashes, and severe crashes, respectively. A Swedish study [*13*] investigated the safety, time, and environmental effects of large-scale use of roundabouts in a Swedish urban area. In that study, 21 high-risk signalized and unsignalized intersections were replaced with small roundabouts. The results showed a statistically significant reduction in speeds at the intersections and on road segments between roundabouts; however, there was no change in speeds on the segments not bounded by roundabouts.

Highly significant reductions of 38 percent in all crashes, 76 percent in injury crashes, and 90 percent in fatal and severe injury crashes were estimated in an empirical Bayes study [*10*] of the conversion of 24 stop-controlled and signalized intersections to roundabouts. Similarly, Persaud et al. [*14*] used the EB procedure to analyze the conversion of 19 stop-controlled and 4 signalized intersections. The authors estimated an approximately 40 percent reduction in all crashes, 80 percent reduction in injury crashes, and 90 percent reduction in fatal and incapacitating injury crashes. Further subgrouping analysis of converted single-lane urban stop-controlled intersections indicated a 72 percent reduction in all crashes and an 88 percent reduction in injury crashes. Similar analysis for the conversion of rural single-lane stop-controlled intersections showed a 58 percent reduction in all crashes and an 82 percent reduction in injury crashes, while converted signalized intersections showed a 35 percent reduction in all crashes and a 74 percent reduction in injury crashes.

De Brabander and Vereeck [*15*] evaluated safety at 95 roundabouts and 230 conventional intersections in Belgium. Their results showed that roundabouts reduce injury crashes by 39 percent, severe injury crashes by 17 percent, and light injury crashes by 38 percent. Another study [*16*] reported the results of a before-and-after safety analysis of converted intersections in Australia, France, and the United States. In Australia there was a 41 percent reduction in all crashes, a 45 percent reduction in injury crashes, and a 63 percent reduction in fatal crashes after the conversion of 230 intersections. Similarly, 83 converted intersections in France showed a 78 percent reduction in injury crashes and an 82 percent reduction in fatal crashes. Finally, crash data from converted U.S. intersections showed a 45 percent reduction in all crashes and an 81 percent reduction in injury crashes.

NCHRP Report 572 [*17*] presents the results of an EB analysis of crash data from 55 roundabouts in the United States, indicating a 35 percent and a 76 percent reduction in all and injury crashes, respectively. However, a separate analysis of nine high-speed locations indicated larger safety benefits with a 71 percent reduction in all crashes and an 87 percent reduction in injury crashes. In a similar study, Isebrands [*18*] analyzed 17 high-speed rural intersections that were converted to roundabouts from predominantly two-way stop-controlled intersections. Using an average of 4.6 years of before and 5.5 years of after crash data, the author found reductions of 84 percent and 89 percent for injury crash frequency and crash rate, respectively. Also, angle crashes reduced by 86 percent, while fatal crashes reduced by 100 percent. In another study [*19*], the authors developed a crash prediction model for 19 converted high-speed rural roundabouts from six U.S. states. The before and after data both averaged 5.2 years. Using a negative binomial regression model, the results showed statistically significant reductions of 63 percent for all crashes and 88 percent for injury crashes. A separate EB analysis yielded consistent results of 62–67 percent reduction for all crashes and 85–87 percent reduction for injury crashes.

Uddin et al. [*20*] used the EB procedure with 2.5 years of both before and after data to analyze safety at two previously stop-controlled interchange-terminal roundabouts. The results indicated a 38 percent and 60 percent reduction in all and injury crash frequency, respectively. Jensen [*21*] evaluated crashes at 332 converted roundabouts in Denmark. After correcting for general crash trends and regression-to-the-mean effects, the author estimated overall safety benefits of 27 percent and 60 percent for all and injury crashes, respectively. Also, fatalities reduced by 87 percent, and property damage only (PDO) crashes reduced by 16 percent.

Gross et al. [*22*] analyzed 28 converted signalized intersections using EB as well as negative binomial regression. The EB analysis showed a 21 percent and a 66 percent reduction in all and injury crashes, respectively. However, the safety benefit decreased with increasing entering AADT. The cross-sectional analysis also corroborated decreasing safety benefit with increasing entering AADT. Finally, Qin et al. [*23*] used the EB procedure to analyze the safety performance of 24 converted intersections from Wisconsin. With an average of 3 years of before and after data, an unbiased estimate of a 9.2 percent reduction in all crashes and 52 percent reduction in injury crashes was found.

It is a known and well established characteristic of roundabouts that they force drivers to reduce speed. Isebrands et al. [*8*] undertook a study to verify this phenomenon at high-speed rural locations. They evaluated the change in average approach speed between roundabouts and two-way stop-controlled intersections, as well as between roundabouts with approach rumble strips and those without rumble strips. The study included four roundabouts and two two-way stop-controlled intersections. The findings indicated that the mean speed 100 feet from the roundabout yield line was approximately 2.5 mph lower than the mean speed 100 feet from the stop-controlled intersection stop bar. Mean speeds at roundabout locations with rumble strips were 4.3 and 3.3 mph lower at 100 feet and 250 feet from the yield line, respectively, than roundabouts without rumble strips.

2.1.2 Impact on Non-Vehicle Road Users

De Brabander and Vereeck [*15*] argue that roundabout injury reductions could vary greatly among various subgroups in crashes. They observed that while the total number of crashes involving vulnerable road users reduced by 14 percent on average at all roundabouts, the same statistic went up by 28 percent at roundabout locations that were previously signalized. The authors concluded that signalized intersections protect vulnerable road users more effectively than roundabouts. Vulnerable road users were defined as pedestrians, cyclists, moped drivers, and motorcyclists. Also, Daniels et al. [*24*] evaluated bicyclist safety at 91 roundabouts in Belgium using a before-and-after methodology and found that, after conversion, injuries increased by 27 percent while fatal or serious injuries increased by 41–46 percent. Furthermore, in built-up areas there was a 48 percent and 77 percent increase in injury and fatal or serious crashes, respectively. Outside built-up areas, the results were not statistically significant.

To understand why roundabouts pose a proportionately higher risks to bicyclists, Møller and Hels [*25*] surveyed 1019 bicyclists at 5 roundabouts in Denmark, seeking their perception of risk in roundabouts. The survey respondents were between the ages of 18 and 85. The surveys were administered Tuesdays through Thursdays between 7:30 a.m. and 4:30 p.m. The authors measured risk in two dimensions: (1) perceived risk of being involved in a crash, and (2) perceived danger. These dimensions require cognitive judgment and an emotional response, respectively. The authors found that underestimation of risk and lack of knowledge about traffic rules may be significant contributing factors in vehicle–bicycle crashes at roundabouts. Also, the study showed that perceived risk is influenced by factors such as age and gender of the cyclist, design features, and traffic volume. Finally, the authors observed that roundabouts with a cycle facility are perceived as safer than those without it. However, they note that the possible safety benefits of bicycle facilities may be reduced because cyclists may increase risk-taking behavior given decreased perceived risk.

Daniels et al. [*26*] attempted to shed light on the variation in safety performance of roundabouts by analyzing 90 roundabouts in Flanders, Belgium. The authors used state-of-the-art cross-sectional risk models based on crash data, geometric data, and traffic data. During the analyses, the authors detected underdispersion in the data, so they used gamma modeling techniques in addition to Poisson modeling. The study results indicate that roundabouts with cycle lanes performed worse than those with cycle paths (i.e., dedicated paths for bicyclists at a distance of more than 1 m from the roadway).

2.2 Safety-Influencing Features of Roundabouts

The safety and operational performance of roundabouts can be negatively impacted by inadequate geometric design and site characteristics. Flannery [*5*] used case studies to review the geometric characteristics and safety of roundabouts from Maryland, Florida, and Nevada. That author found that (1) inadequate sight distances hinder the free flow of vehicles into the roundabout, forcing drivers to reduce speeds considerably; (2) lack of adequate deflection encourages drivers not to slow down, with some of them driving over the island apron; and (3) operating roundabouts with low volume/capacity ratio, especially in multilane roundabouts, can encourage high speeds through the roundabout and lane crossings.

Next, Lenters [*7*] explained some geometric design features of roundabouts that influence safety:

- Sharply increasing the angle between arms reduces crash frequency; thus, roundabouts with equally spaced arms may be safer.
- Increasing entry width produces significant increases in crash frequency. A roundabout design that applies entry flaring in combination with moderate entry path curvature can offer improved capacity and balanced safety performance.
- Increasing circulating width increases crash frequency.

- Very small values of entry path radius must be avoided. However, these values are usually large and need to be reduced. Optimum values will depend on entry and circulating flows.
- Increasing the half width provides a very small reduction in crashes.

Figure 3 shows these safety features on a typical roundabout geometric layout.

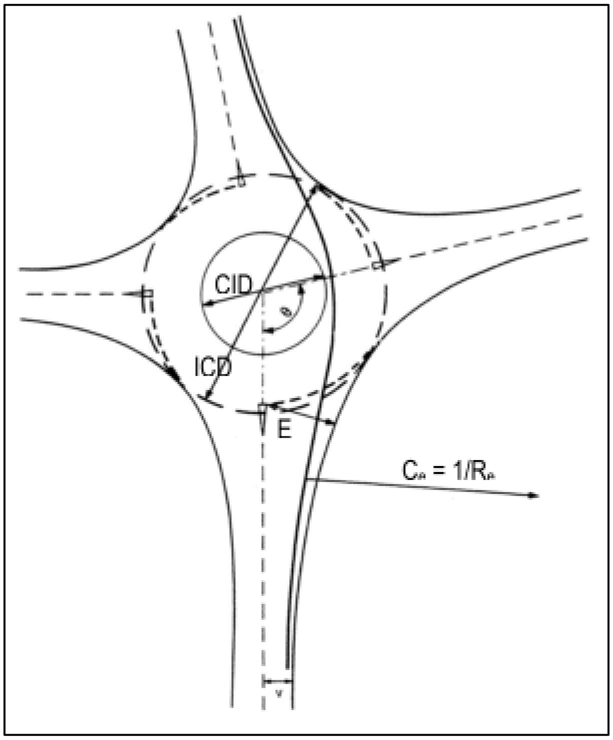


**Figure 3 Geometric Layout of a Roundabout.
Adapted from Lenters (2005)**

The geometry of roundabouts is such that making a change in one geometric element can reduce the probability of one crash type, but can also increase the odds for other crash types. Lenters [*7*] also performed a safety audit of roundabouts in Canada and made the following additional observations about the effect of roundabout geometric elements on crashes.

- Even though a good deflection is desirable for safety, designs with entry path curvatures that are too tight, as with perpendicular or sharply curved entries, can increase crashes resulting from loss of control on the roundabout approaches.
- Inconspicuous central island and/or splitter islands are the primary contributing factors to loss-of-control crashes because drivers that are unfamiliar with the layout often do not receive sufficient visual information to adjust speed and path.
- Inadequate stopping sight distance limits vertical sight and makes it difficult for drivers to see the yield line or the central island and splitter island. This results in drivers overshooting the entry or failing to brake in time. Insufficient sight distance to the left near the entry can result in entry-circulating crashes while providing visibility that is beyond 15 m from the yield line, to the right of the entry, can encourage drivers to compete for gaps.
- Increasing the deflection with small inscribed circles provides better safety for bicycles.
- Improper lane designation contributes to exit crashes.
- Positive contrast lighting and vertical luminance are essential for pedestrian and signage visibility.

In a similar study, Montella [*27*] investigated crash contributory factors and their interdependencies at 15 urban roundabouts located in Naples, Italy, using crash data from 2003 to 2008. The study analyzed 274 crashes, finding that the most common crash contributory factor was geometric design, including: (1) an excessive radius of deflection associated with rear-end and angle crashes at entry, (2) an excessively low angle of deviation associated with angle crashes at entry, and (3) an excessive radius of deflection of the left approach associated with angle crashes. Poor markings contributed to more than half of the crashes, with missing yield lines or symbols being associated with angle crashes at entry, and missing, faded, or poorly located pedestrian crossings being associated with pedestrian crashes at exit. Inadequate pavement friction was found to be the most common pavement contributory factor, being associated with one-third of all crashes.

Zirkel et al. [*28*] evaluated the influence of sight distance on safety at low-volume single-lane roundabouts by analyzing 72 roundabout approaches from 19 single-lane roundabouts. Their findings showed that increasing sight distance increases the risk of crash occurrence as well as the speed differential between the approach and entry to the roundabout. However, the authors acknowledged that other parameters not included in the study could also contribute to the variability in crashes and crash rates.

Hammond et al. [*29*] also investigated the effect of additional lane lengths on roundabout operational characteristics, using delay as the performance measure. The authors defined an additional lane as a lane used to increase the entry and/or exit widths at roundabouts. It may be a flared lane or lane with sufficient taper length. Delay was measured within 250 feet of the yield line. The authors analyzed a hypothetical four-leg, double-lane roundabout with additional lanes at both entry and exit. They varied the lengths of these additional lanes to study their effect on operations. Based on the findings from the hypothetical roundabout, similar additional lane lengths were applied to a calibrated and validated model of an existing roundabout. The findings indicate that shorter lengths of additional lanes (and flares) of 50 to 150 feet provided the best operational performance.

2.3 Summary of Published Roundabout Safety Reduction in U.S. Studies

Table 1 presents the summary findings on roundabout safety effectiveness in a number of published U.S. studies. The table gives the names of authors, the study year, the stated analysis method, the prior intersection control if stated in the published study, and the estimated safety benefit for different crash severity types.

Table 1 Summary Findings on Roundabout Safety Effectiveness in Crash Reductions

Author(s)	Year	Analysis Method	Prior Intersection Control	Estimated Safety Benefit (%)			
				All Crashes	Injury	Fatal	Fatal/Severe Injury
Retting et al.	2001	Empirical Bayes		38	76		90
Persaud et al.	2001	Empirical Bayes	All	40	80		90
			Stop-control (urban)	72	88		
			Stop-control (rural)	58	82		
Rodegerdts et al.	2007	Before/After		45	81		
Rodegerdts et al.	2007	Empirical Bayes		35	76		
Isebrands	2009	Before/After			84	100	
Isebrand & Hallmark	2012	Neg. Binomial		63	88		
		Empirical Bayes		65	86		
Uddin et al.	2012	Empirical Bayes		38	60		
Gross et al.	2013	Empirical Bayes	Signalized	21	66		
Qin et al.	2013	Empirical Bayes	All	9	52		

The data in Table 1 show a wide range in estimated benefits for different crash severities. This may be an indication that findings may be sensitive to site-specific conditions and peculiar characteristics of the driving population.

CHAPTER 3: METHODOLOGY

3.1 Minimum Data Requirements

A successful safety evaluation of roundabouts requires the availability of several types of data: crash data, roadway characteristics, intersection characteristics, and traffic data. Historical sunrise and sunset data may also be required to establish times for civil twilight and to distinguish nighttime crashes from daytime crashes.

The crash data must provide case-by-case information on accidents within the study period. At a minimum, it must include the following information:

- Date of crash
- Crash or case ID
- Time of crash
- Location of crash (roadway and milepost or latitude/longitude, rural/urban designation, road segment or intersection)
- Crash severity (fatal, serious, injury, possible injury, and property damage only).

The roadway characteristics data must include information that allows the identification of different homogenous segments (e.g., county route name, number of lanes, width of lanes, posted speed limits, beginning milepost, and ending milepost). It must also distinguish between one-way and two-way segments for accurate computation of intersection entering volumes. The roadway characteristics data must allow identification of road segments that connect to intersections and segments that are midblock.

In addition, there must be information on the intersections of interest within the study area. As a minimum, the following information must be available:

- Intersection type
- Traffic control mechanism
- Location (rural/urban designation, route, latitude/longitude and/or milepost)
- Traffic volume data in the form of annual average daily traffic (AADT) for every intersection leg or the total daily entry volume for the intersection for all the years of the analysis period

Furthermore, historical sunrise and sunset data with adjustments for daylight savings may be needed to distinguish nighttime crashes from daytime crashes if a temporally segmented analysis is desired. Information about illumination levels or presence of illumination is also highly desirable for accurate deconvolution of contributing factors [*30*].

3.2 Data Sources

This study uses roadway and crash data obtained from the annual GDOT Road Characteristics Link (RC-Link) databases and the Georgia crash database for crash information, respectively. Roadway exposure data (i.e., AADT) that could be translated into daily entry volumes (DEV) for intersections is available in the annual GDOT RC-Link databases for 2010 to 2013. As a longer study period was desirable, the researchers initially selected a 2010–2015 period. The AADT information missing from the 2014 and 2015 RC-Link databases was imputed in two steps. In the first step, some of the missing AADT information was extracted from available annual geospatial data released by the Highway Performance Monitoring System (HPMS). Matching the HPMS road network and the GDOT RC-Link databases was possible because both systems contain inventoried road segments with beginning milepost, ending milepost, and a unique link or segment identification number. The HPMS contains data submitted by individual states on the following roadway classifications:

- Interstate
- Principal arterial—other freeways and expressways
- Principal arterial
- Minor arterial
- Major collector
- Urban minor collector
- Other highways that are designated as part of the National Highway System (NHS)

In the second step of the imputation process, any road segment AADT information still missing was imputed by applying an annual growth factor for its 2013 base value. Since the time period is short (2 years) and the average growth rate is relatively small (of order 2% year) these imputations have a minimal impact on the resulting CMF calculation. Thus, for simplicity of the projection model, the researchers opted for an aggregated annual growth factor for the state (2%/year). This estimate was obtained by comparing the annual vehicle miles traveled (VMT) for Georgia from 2013 to 2015. From the VMT numbers in Table 2 it can be seen that the difference in growth factor across facility types within each analysis year is also fairly minor. The impact of using different rural and urban growth factors was not evaluated but is also expected to be minimal. Annual VMT for states are available from the Federal Highway Administration (FHWA) Office of Highway Policy Information. Table 2 shows the annual VMT for Georgia from 2010 to 2015.

Table 2 Annual Vehicle Miles Traveled in Georgia

Facility Type	Annual Vehicle Miles Traveled in Georgia (Millions)					
	2010	**2011**	**2012**	**2013**	**2014**	**2015**
Interstate	27,242	26,516	26,445	27,065	27,692	28,171
Arterial	53,817	52,171	51,562	52,245	53,089	54,007
Collector	15,438	14,965	14,782	14,995	15,252	15,516
Local	15,225	14,802	14,699	15,049	15,503	15,771
Total	**111,722**	**108,454**	**107,488**	**109,354**	**111,536**	**113,465**
Growth Factor	**n/a**	**0.971**	**0.991**	**1.017**	**1.020**	**1.017**

As the study progressed, it became necessary to expand the study period from 2010–2015 to 2006–2015 to ensure a balance between available before-data and after-data in the final selection of roundabouts. While the Georgia crash database for crash information includes data for the 2006–2009 extension period, there is no roadway exposure information available in the publicly available RC-Link databases for this period. The researchers could not locate any alternative repository for the missing roadway exposure information. Therefore, a regression analysis was used to extrapolate 2006–2009 AADT based on the known AADT data in the 2010–2015 period. Clearly, these extrapolated AADTs could vary from the actual observed AADTs on a site-by-site basis, implying that the developed SPFs could predict lesser or greater crash frequencies for individual sites but, to the extent that long-term trends are consistent, the overall estimate of crash rates should be rational.

3.3 Selection of Candidate Roundabout Sites

3.3.1 Initial Pool of Sites

An initial pool of candidate roundabouts in Georgia was identified from two sources. The first source was a roundabout intersection database developed as part of a previous GDOT research project [*31*, *32*]. This database provides a list of circular intersections including roundabouts, with their latitudes and longitudes, among other attributes. The research team identified a total of 198 potential roundabout sites from this circular intersection database. The second source of roundabout information was the 2015 GDOT RC-Link geographic information system (GIS) shapefile and attribute table. The attribute table contains codes for various intersection types. The codes for roundabouts are:

- CRR: County road roundabout
- CSR: City street roundabout
- PRR: Public road roundabout
- SRR: State route roundabout

The RC-Link IDs (RCLINK) of the identified roundabouts from the attribute table were then used to identify the roundabout in the GIS shapefile and the corresponding latitudes and longitudes were extracted. A total of 163 roundabouts, which were not included in the previously described circular intersections database, were identified from this second source. Therefore, 361 potential sites were included in the initial pool of candidate roundabout sites. This initial selection was further refined using filters for construction year, location, design, and traffic volume, as described below. Figure 4 shows an example of an identified roundabout in the GIS shapefile with one of the approaches selected based on RCLINK data.

Figure 4 Identification of a Roundabout from the GIS Shapefile based on an Identified Approach RC-Link ID.

3.3.2 Construction Year Selection Filter

To ensure at least one data year in the after period, roundabouts constructed later than 2014 were omitted. The application of this construction year filter reduced the number of candidate sites from 361 to 290. Construction year information for each roundabout was verified from Google Earth® satellite images. In addition, the year in which the roundabout was first seen on the satellite images was omitted from the analysis as the exact bounds of the construction period could not be conclusively established. Figure 5 shows results of a Google Earth analysis of satellite images to identify the construction year of a roundabout.

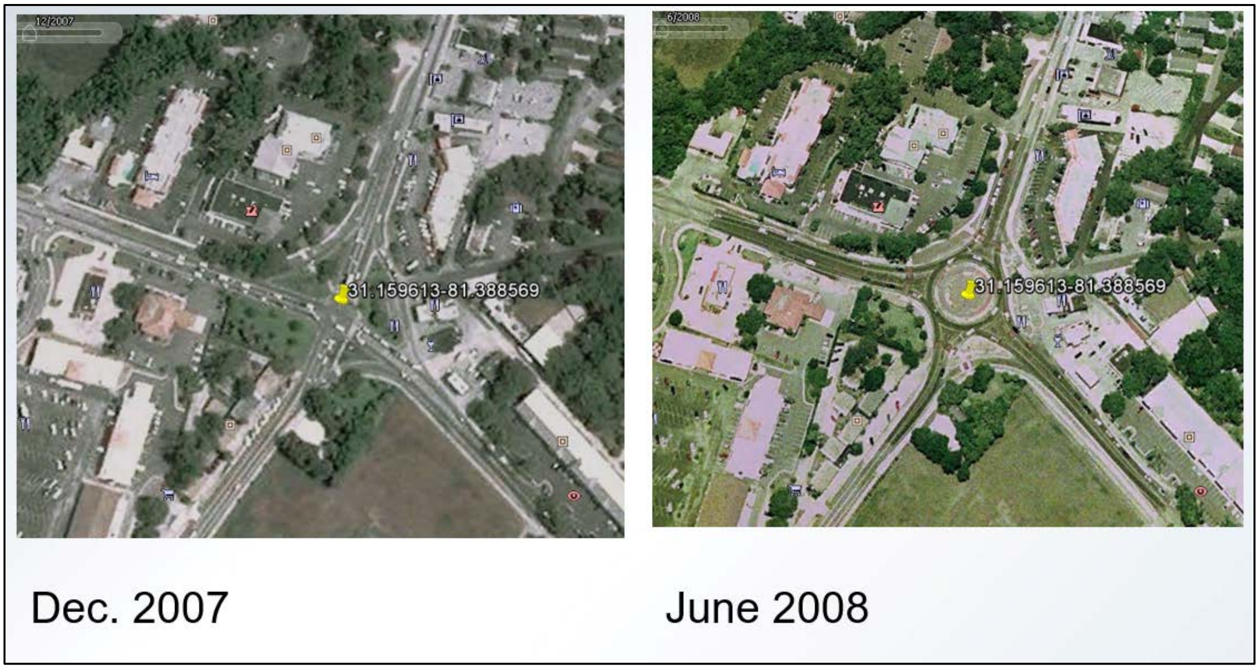
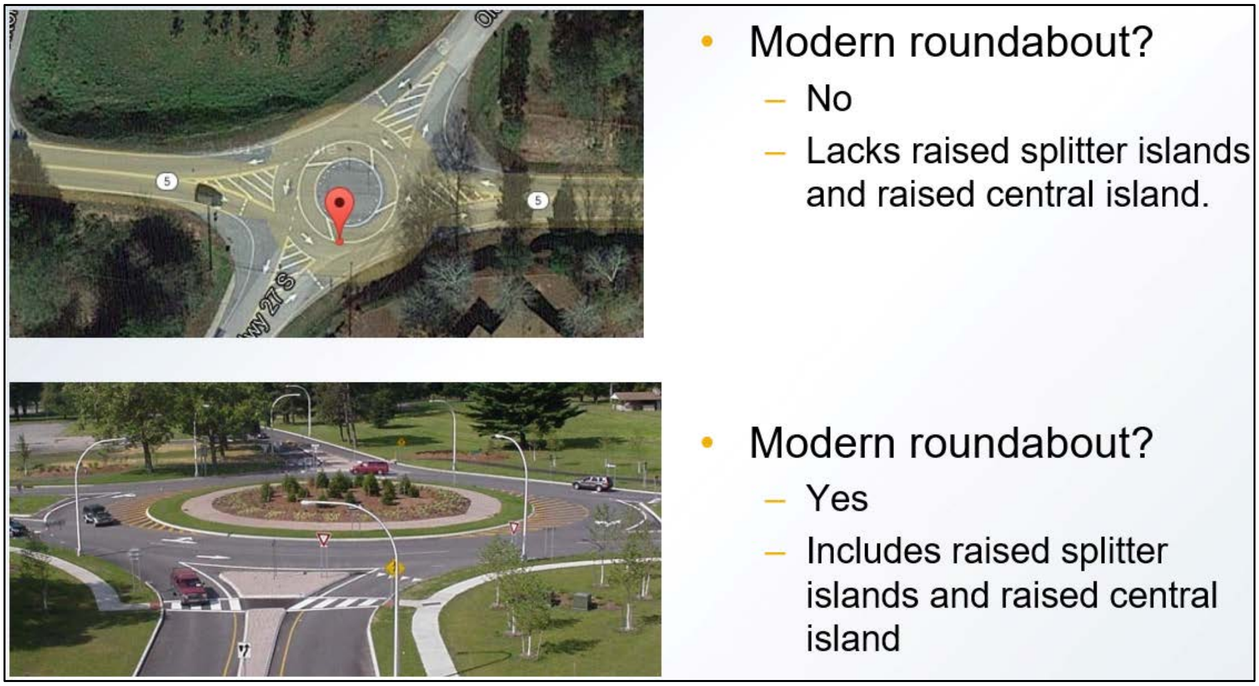


Figure 5 Roundabout with Verified Construction Year of 2008 in Saint Simons Island, GA.

3.3.3 Location and Design Selection Filters

Next, all roundabouts on dead-end roads or in subdivisions were omitted from the candidate pool. This filter was applied because these roundabouts are typically too low a volume to make a meaningful contribution to determining crash rates. Furthermore, roundabouts that do not comply with the modern roundabout design were omitted. These two filters further reduced the number of potential candidates to 70 sites. The modern roundabout in this context was defined as a roundabout with raised splitter islands and a raised central island. Figure 6 shows a roundabout that does not meet the modern roundabout design requirement and another roundabout that meets the modern roundabout design requirement as defined in this study.



- Modern roundabout?
  - No
  - Lacks raised splitter islands and raised central island.

- Modern roundabout?
  - Yes
  - Includes raised splitter islands and raised central island

Figure 6 Comparison of a Non-Modern Roundabout and a Modern Roundabout.

3.3.4 Selection of Final Candidate Sites

The research team then held a consultative meeting with GDOT staff and presented the list of 70 candidate sites. Based on the input from GDOT staff regarding site characteristics of the roundabouts (e.g., location on private/limited access roadways), a pre-final list of 50 candidate sites was selected and subjected to the final traffic volume selection filter. For each of these 50 sites, researchers compiled AADTs for each analysis year (2010–2015) and selected for the final analysis only the roundabouts without missing AADTs. This traffic volume selection filter resulted in a final list of 27 roundabouts. Figure 7 shows the location of the roundabouts on a map. Table 3 provides summary data, including location, open year, number of legs, number of lanes, and years of before and after data for the selected 27 roundabouts.

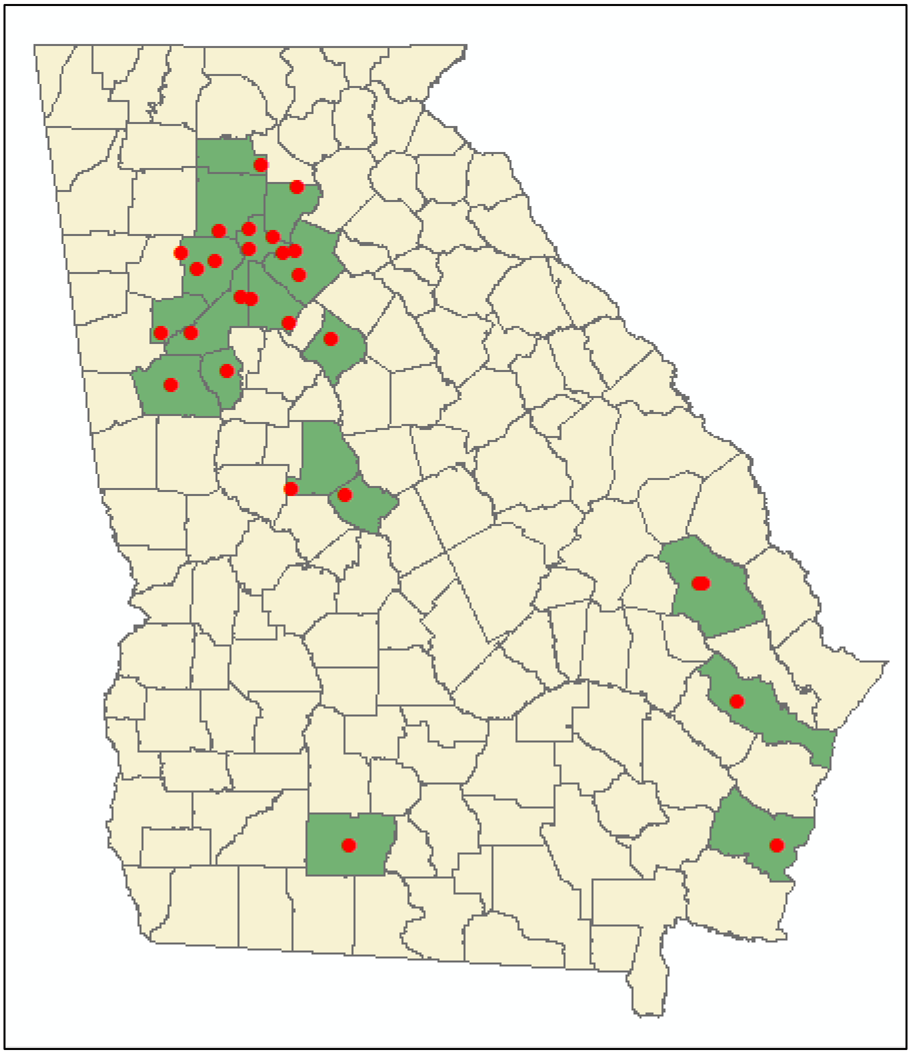


Figure 7 Map of 27 Final Roundabouts in 17 Georgia Counties.

Table 3 Final Selected Roundabouts

ID	No. of Legs	Year Opened	Before Data Years	After Data Years	Average Obs All Crashes in Before	Average Predicted All Crashes in Before	Average Obs All Crashes in After	Average Predicted All Crashes in After	Average Obs Injury/Fatal Crashes in Before	Average Predicted Injury/Fatal Crashes in Before	Average Obs Injury/Fatal Crashes in After	Average Predicted Injury/Fatal Crashes in After	Estimated CMF All Crashes	Estimated CMF Injury/Fatal Crashes
15	4	2007	1	8	0.00	0.19	1.00	0.39	0.00	0.09	0.25	0.14	n/a	n/a
18	4	2008	2	7	1.50	0.14	3.14	0.30	0.00	0.04	0.29	0.12	0.97	n/a
24	5	2011	5	4	10.40	0.12	13.00	0.32	1.60	0.02	2.00	0.16	0.46	0.15
25	4	2009	3	6	3.67	0.24	2.17	0.34	0.33	0.07	1.00	0.15	0.43	1.44
29	4	2007	1	8	6.00	0.10	4.25	0.26	2.00	0.02	1.00	0.11	0.27	0.08
30	4	2011	5	4	5.00	2.13	3.75	1.92	1.40	0.98	1.00	0.85	0.83	0.82
35	5	2011	5	4	8.60	0.15	9.75	0.33	2.40	0.03	1.50	0.16	0.51	0.13
42	4	2009	3	6	6.33	0.69	6.83	1.03	2.00	0.17	2.00	0.46	0.72	0.38
44	4	2011	5	4	4.00	1.30	3.75	1.44	0.20	0.43	0.25	0.68	0.85	0.80
45	4	2010	4	5	0.00	0.20	0.00	0.44	0.00	0.08	0.00	0.16	n/a	n/a
53	4	2007	1	8	1.00	0.20	1.25	0.46	1.00	0.11	0.00	0.16	0.55	0.00
54	4*	2008	2	7	42.50	0.08	11.29	0.23	5.50	0.01	0.71	0.11	0.09	0.01
56	4	2009	3	6	2.00	0.12	2.83	0.29	0.00	0.02	0.17	0.13	0.56	n/a
81	4	2009	3	6	0.00	0.13	1.83	0.33	0.00	0.03	0.00	0.14	n/a	n/a
903	5	2014	8	1	4.13	3.11	6.00	0.92	1.13	3.55	0.00	0.37	4.92	0.00
930	4	2012	6	3	1.83	0.15	3.33	0.35	0.17	0.03	1.33	0.19	0.76	1.35
931	4	2012	6	3	5.83	0.14	10.00	0.35	0.67	0.03	1.33	0.18	0.67	0.30
932	5	2012	6	3	0.00	3.05	0.00	3.04	0.00	1.92	0.00	1.19	n/a	n/a
954	4*	2014	8	1	17.13	0.20	3.00	0.46	3.50	0.05	1.00	0.26	0.08	0.06
955	4	2014	8	1	0.88	0.99	0.00	1.08	0.50	0.47	0.00	0.46	0.00	0.00
975	4	2011	5	4	17.80	0.16	5.25	0.34	4.40	0.04	0.75	0.16	0.14	0.04
1046	4	2012	6	3	1.33	0.30	2.67	0.48	0.17	0.18	1.00	0.18	1.25	6.03
8	3	2010	4	5	0.25	2.33	2.00	26.16	0.00	0.58	0.20	7.44	0.71	n/a
14	3	2007	1	8	0.00	0.18	0.00	0.26	0.00	0.04	0.00	0.06	n/a	n/a
953	3	2014	8	1	0.63	0.25	1.00	0.36	0.25	0.06	1.00	0.08	1.15	2.78
959	3	2012	6	3	0.33	0.43	3.00	0.25	0.00	0.08	0.67	0.07	15.78	n/a
979	3	2009	3	6	2.33	0.30	1.50	0.27	1.33	0.06	0.33	0.07	0.71	0.22

Note 1: * means a multi-lane roundabout

Note 2: Injury/Fatal includes fatal crashes as well as all types of injury crashes: complaint, visible, and serious

3.4 Selection of Control Intersection Sites

The 2015 GDOT RC-Link GIS shapefile contains the Georgia road network. The shapefile also includes an attribute table, which provides various link-related variables, such as road name, county, AADT, and a unique link ID called INV_ROUTE. INV_ROUTE is the same link ID (i.e., RCLINK) used in the annual GDOT RC-Link database files. Therefore, INV_ROUTE may be used to match data between the annual RC-Link database and the shapefile's attribute table. Unfortunately, an efficient, fully automated matching process was not possible as several links or segments can have the same ID (INV_ROUTE or RCLINK) if they are on the same route (i.e., they have the same route number) and are within the same county. Additionally, neither the GIS attribute table nor the annual RC-Link database has a variable to identify the individual legs of an intersection. Therefore, the analysis had to first identify the individual intersection legs as shown on the GIS shapefile. Next, the analysis had to match and extract these links in the annual RC-Link database files. Parts of this process required significant man-hours for matching and verification. In some cases, it was not possible to match links, as a link's route number may have changed within the analysis period but the annual RC-Link database files, as well as the GIS attribute table, do not track such changes.

3.4.1 Identification of Intersection Link/Segment Sets from GIS Shapefile Attributes

The GIS RC-Link shapefile contains lines representing the road network in Georgia. The shapefile does not directly identify the crossing point of two lines as an intersection location. Therefore, the first step the researchers undertook was to generate a shapefile of nodes (points) at intersection locations. Any node outside the counties containing the selected roundabouts was omitted to streamline the analysis. Figure 8 shows a map of the 17 analysis counties.

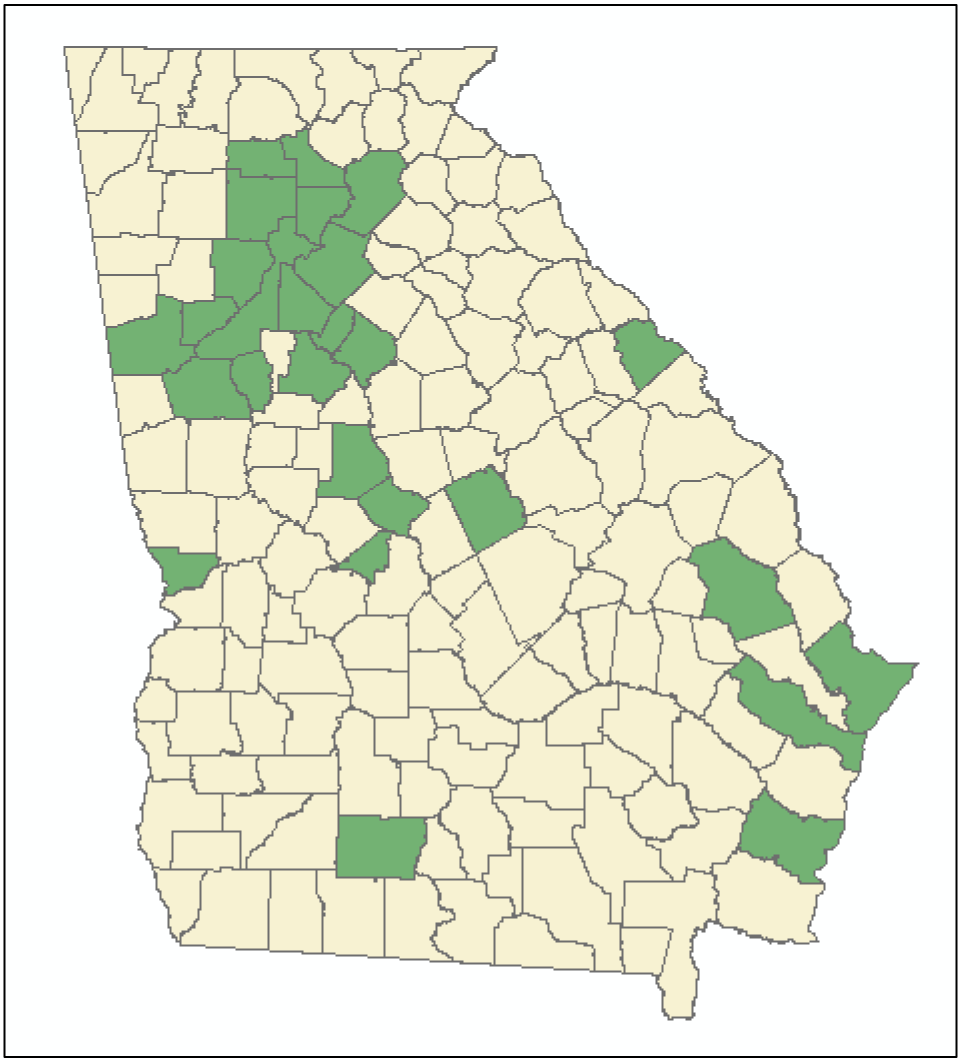


Figure 8 Map of the 17 Analysis Counties in Georgia.

Subsequently, the generated nodes were spatially joined to the links, appending the link attributes to the nodes in a new attribute file. This process duplicates the node as many times as there are connecting single-lane roads. Thus, at a four-leg intersection with single-lane roads, the node will be duplicated four times and each duplicate will have a link ID corresponding to one of the connecting links. However, for links that represent two-way travel, the node will be duplicated for both paths. For example, for a four-leg intersection with a two-way route and a crossing one-way route, the node will be duplicated six times after the spatial join operation.

Two-way roads have two link IDs in the RC-Link database files. One ID is a numeric 10-digit number. The other ID is an alphanumeric number in which the fourth digit is replaced with the letter D. Therefore, to avoid double counting, the analysis deleted all alphanumeric link IDs containing the letter “D”. Then, dead end links on private property were identified and removed by omitting alphanumeric link IDs containing the letter “U”. These data quality checks removed 81,802 node-links from an original 672,014 node-link data. Furthermore, all links containing the word “Interstate” as part of the road name were removed to avoid including on-ramp, exit-ramp, and interchange connections in the analysis. This process removed an additional 4790 links.

3.4.2 Identifying Intersection Legs from GIS Shapefile Attribute Table and Matching to Annual RC-Link Database Files

As mentioned in the previous section, the spatial analysis to append link attributes to the nodes duplicates the nodes as many times as their connected links in the GIS shapefile. Therefore, to extract the relevant three-leg and four-leg intersections, all unique nodes with less than three entries in the appended node-link data were removed. Nodes with only one entry are nodes at the ends of links that are not connected to other roads (e.g., cul-de-sac, dead ends). Nodes with two entries are usually nodes created in mid-block locations where there is a break in the original link representing the road or route. Also, the number of legs for each intersection (i.e., the number of entries in the node-link data) was computed and appended as a new field to each connecting link (leg). A total of 392,964 node-link data entries were identified as three- and four-leg intersections from the results of the spatial join process.

The identified intersection legs in the node-link data had to be matched to the corresponding intersections in the annual RC-Link database files. However, as mentioned previously, the annual RC-Link database files do not identify the legs of any individual intersection. For links that connect to an intersection, the RC-Link database files contain an entry for intersecting road names (INT_ROADNAME). Unfortunately, these road names were also unreliable for matching because of missing values and inconsistencies in the use of primary road names, secondary road names, alternative road names, prefixes, and suffixes. Fortunately, for links that connect to an intersection, the RC-Link database files contain a field called DESC. DESC is an alphanumeric code containing the last six digits of the crossroad's RCLINK ID. Therefore, the analysis was able to perform the required matching using the following two-step process. In the first step, the link ID of any identified intersection leg (from the GIS node-link data) was used to extract DESC information of matching links in the RC-Link database files. In the second step, the analysis compares alphanumeric codes in the extracted DESC information to the link IDs of the other legs in the intersection. This two-step process enabled the researchers to correctly identify an intersection leg from the node-link data to the correct link (out of many possible links with the same link ID) in the RC-Link database using the DESC information to match the correct crossroad link ID. The process is performed for each of the six annual RC-Link databases covering the 2010–2015 analysis period. Any intersection that could not be identified for each analysis year was omitted from the analysis. There are several reasons an intersection may not be in all six annual databases, including jurisdictional changes and/or route number changes.

Furthermore, intersections that did not have only one type of control within the analysis period (e.g., it changed from uncontrolled to all-way stop before being converted into a roundabout) were omitted. The intersection control type was identified from the SIGNAL field in the RC-Link database. Also, any intersection with the following "SIGNAL" codes was omitted in the analysis:

- Code B – Beacon (Overhead Flashing Amber)
- Code R – Beacon (Overhead Flashing Red)
- Code F – Flasher (Other than Overhead Beacon)
- Code S – Traffic Control Device (Red, Amber, Green)
- Code L – Traffic Control Device (Left Turn Arrow)
- Code P – Traffic Control Device (Pedestrian Signalization)

Additional selection filters were further applied to omit any intersection with a multilane approach. The intersections that passed all the prior-mentioned selection processes were analyzed to compute the entry AADT. A maximum intersection entry volume of 20,000 AADT and a minimum of 1000 AADT were also applied as a cut-off filter in order to pick the intersections whose AADTs fall within the observed range for the selected roundabouts.

The 2010–2012 RC-Link database files contain 13 functional class codes, while the 2013–2015 RC-Link database files contains 7 functional class codes, Therefore, the analysis recoded the 2010–2012 functional class codes to match the 2013–2015 codes. This made it possible to identify any interstate links that were still within the data. In addition, it helped to compute the minor road AADT, the major road AADT, and the AADT split (which is defined as minor road AADT / major road AADT) for the intersections. Also, any links with unknown functional classes were omitted. Table 4 shows how the 2010–2013 functional class codes were used to match the 2013–2015 functional class codes.

This selection process for the control intersections resulted in 58,543 intersections for each analysis year. Of these, 49,962 were three-leg intersections and 8581 were four-leg intersections.

Table 4 Functional Class Matching between the 2010–2012 and 2013–2015 RC-Link Datasets

Recoded 2010–2012 Functional Class Codes		**Adopted 2013–2015 Functional Class Codes**	
Code	Functional Class Name	Code	Functional Class Name
0	Rural Interstate Principal Arterial	1	Interstate
1	Rural Principal Arterial	3	Principal Arterial – Other
2	Rural Minor Arterial	4	Minor Arterial
6	Rural Major Collector	5	Major Collector
7	Rural NFA Minor Collector	6	Minor Collector
8	Rural Local	7	Local
9	Urban Interstate Arterial	1	Interstate
11	Urban Freeway and Expressway	2	Principal Arterial – Other Freeways & Expressways
12	Principal Arterial	3	Principal Arterial – Other
14	Urban Minor Arterial Street	4	Minor Arterial
16	Urban Collector Street	5	Major Collector
17	Urban Local	7	Local
19	Rural Interstate Principal Arterial	1	Interstate

3.5 Computation of Intersection Daily Entry Volume

The daily entry volume was computed for each intersection by summing up all the approach AADTs. AADTs on one-way legs that exit the intersection were omitted. AADT on two-way approaches were split into two, and only one half was included in the analysis. The 50/50 split assumption was necessary because the actual split of traffic between the two directions on the two-way roads was not available in the RC-Link files.

3.6 Identification of Intersection-Related Crashes

GDOT's crash database contains about 46 tables, which can be electronically merged through the incident ID variable. One of these is the *Incident Table*, which primarily contains information on incident ID; incident date; incident location variables (city, county, latitude, longitude); main road on which crash occurred; nearest intersecting road; distance to nearest intersection; and a variable indicating whether the crash occurred at an intersection, near an intersection, at an interchange, or on a private property. There is also a *Collision Table* that gives further information on each incident (e.g., the type of injury severity, and number of people involved).

Similar to most crash databases, the GDOT database has some data quality issues. It is to be noted that the GDOT database is simply an archive of the original crash documentation provided by law enforcement. Therefore, any inaccuracies in location information is not due to any processing of the police crash reports by GDOT. The primary issues in the data are due to missing variable information and possibly miscoded location information. Identification of incident records with missing variable information can be easily accomplished with a simple database query. However, deciphering and correcting the incident records with wrongly entered data would require a rigorous manual quality assurance/quality control (QA/QC) procedure for the over 3.42 million crash records within the analysis period of 2006–2015. In addition, for each of the 3.42 million crash records, 58,543 candidate intersections would have to be manually checked before a crash could be assigned to an intersection. This would require an extremely large number of man-hours that is beyond the resources available on this research project.

A possible solution would have been to create a smaller control group out of the 58,543 intersections for use in the analysis. However, the selection of the control group might introduce additional biases if it is not truly representative of the population. Furthermore, using a smaller control group of intersections also means that some crashes could be excluded from the analysis. Therefore, the research team adopted a method that is inclusive of as many intersections and crashes as possible (based on limitations of available data) with a reasonable degree of accuracy. Analysis of the crash data showed that, overwhelmingly, the latitude and longitude of crash locations is more likely to be available than the RCLINK ID of the crash location. Therefore, a shortest distance algorithm that makes assignments based on the latitude/longitude of intersections, latitude/longitude of crashes, and a given buffer distance was adopted. Buffer distances of 250 feet and 325 feet were adopted for control intersections and roundabouts, respectively. This method could be limited by the accuracy of the coded latitude and longitude information; however, it offers the most pragmatic approach for this study.

3.7 Development of Safety Performance Functions

This project developed separate safety performance functions (SPFs) for all crashes and injury/fatal crashes at the three-leg and four-leg intersections. Injury/fatal crashes includes fatal crashes as well as all types of injury crashes: complaint, visible, and serious. For each intersection type and crash type, researchers developed two SPFs: (1) one SPF for the "before case" scenario that represents conditions before the roundabouts were installed, and (2) an "after case" SPF scenario that represents the conditions predicted to exist without the installation of the roundabouts. The data used to develop the after-case SPFs do not include data on the roundabout sites. Therefore, there were SPFs for each crash and intersection type and data period, resulting in the development of eight SPFs.

Having a large set of intersections and their related crashes, as is the case in this research, helps ensure that the analysis includes and captures the crash experience that is more representative of the intended population. However, for these intersections covering 17 Georgia counties, many are expected to have zero observed crashes, and these intersections need to be included in determining the state's overall crash rate estimate.

3.7.1 Treatment of SPF Data

The SPFs were developed with intersection crash data from 2010 to 2015. Each annual dataset was further subdivided into three-leg intersection crashes and four-leg intersection crashes. Thus, there were 12 datasets: six for three-leg intersections and another six for four-leg intersections. Each three-leg intersection dataset contained 49,962 entries, while 8581 entries were in each of the four-leg intersection datasets. Before developing the SPFs, each of these 12 datasets were normalized using the process described below.

First, each dataset was sorted by AADT and then split into 10 equal binned subsets to account for the impact of AADT and to avoid mixing low- and high-volume sites. Therefore, there were 10 binned subsets, each containing 4996 individual intersection data from each annual three-leg intersection dataset. Similarly, there were 10 binned subsets for the annual four-leg intersection data with each containing data from 858 individual intersections. Therefore, at this stage, 60 data subsets were created for three-leg intersections and another 60 data subsets were created for four-leg intersections.

From each of the 120 data bins, 25 samples were created by a random (exclusive) selection process, and the mean crash frequency for each of the 25 samples was calculated. The ensemble average of these 25 samples means was used to obtain the final mean crash frequency for each of the 10 AADT bins for each intersection type for each analysis year. This sampling process provides independent equally weighted crash rate estimates for an AADT bin that includes results from those intersections with zero crashes. Consequently, each intersection type had 60 crash rate estimates to be included for the analysis. In addition, the daily entry volume corresponding to each of the 60 samples was calculated. Each DEV estimate for a three-leg intersection and a four-leg intersection was an average over the data for the 4996 and 858 intersections, respectively. This process enabled the analysis to include as many intersections as possible and avoid potential biases introduced by omitting intersections with zero observed crashes.

3.7.2 The Developed SPFs

Based on the data treatment process described in the previous section, the analysis had available 10 paired estimates (mean crash frequency and average daily entry volume) per-intersection-type per-analysis-year per-crash-type (all crashes and injury/fatal crashes) to develop the SPFs. SPFs are regression equations that estimate the average crash frequency for a specific site type as a function of traffic volume and roadway characteristics. They are generally based on the negative binomial distribution, which is better suited for modeling the high natural variability of crash data compared to the normal distribution [*33-35*]. Equation 1 is the general form of the adopted SPF:

$$N = e^{[\alpha + \beta_1 * \ln(AADT_{major\ road}) + \beta_2 * \ln(AADT_{minor\ road})]} \quad \text{........................} \ \textbf{(1)}$$

where N is the number of predicted crashes for an intersection.

3.7.2.1 Estimating Beta1 (β_1)

The Beta1 ($\beta_{1)}$ parameter in the SPF equation was first estimated for each analysis year, crash type, and intersection type. This was done by regressing the natural log of the observed crashes (N) against the natural log of the major road AADT. The SPF can be rewritten by taking a natural log on both sides of Equation 1, as shown in Equation 2:

$$\ln(N) = \gamma + \beta_1 * \ln(AADT_{major\,road}) \ldots\ldots \quad \textbf{(2)}$$

where $\gamma = \alpha + \beta_2 * \ln(\mathrm{AADT}_{\mathrm{minor\ road}})$ and the slope of the plotted line is β_1. Next, for each intersection type and crash type, regression analysis was used to develop a time-dependent equation to predict Beta1 for any given year over the analysis period. Table 5 shows the estimated Beta1 values for three-leg intersections, while Table 6 shows the estimated Beta1 values for four-leg intersections. Figure 9 shows a typical output of the regression analysis to estimate Beta1 as a function of time. Table 7 shows the estimated equations to estimate Beta1 for crashes at three-leg intersections in the before and after periods. Table 8 presents estimated equations to estimate Beta1 for crashes at four-leg intersections in the before and after periods.

Table 5 Annual Estimates of Beta1 (β_1) Values for 3-Leg Intersections

Year	3-Leg Intersections			
	All Crashes		Injury/Fatal Crashes	
	Before	After	Before	After
2010	1.149	1.149	1.233	1.234
2011	1.083	1.079	1.208	1.206
2012	1.049	1.049	1.168	1.169
2013	0.972	0.973	1.092	1.095
2014	0.941	0.941	1.090	1.088
2015	0.956	0.956	1.120	1.117

Table 6 Annual Estimates of Beta1 (β_1) Values for 4-Leg Intersections

Year	4-Leg Intersections			
	All Crashes		Injury/Fatal Crashes	
	Before	After	Before	After
2010	1.274	1.267	1.343	1.341
2011	1.306	1.311	1.384	1.352
2012	1.081	0.959	1.125	1.037
2013	0.866	0.876	0.938	0.935
2014	0.784	0.782	0.901	0.900
2015	0.773	0.775	0.919	0.920

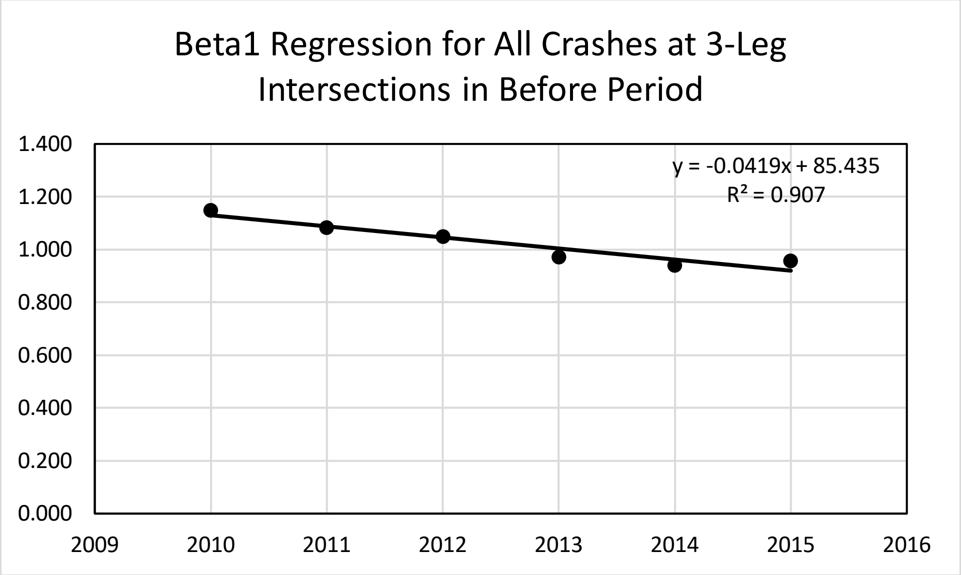


Figure 9 Typical Results of Regression Analysis to Estimate Beta1 (β_1) as a Function of Time.

Table 7 Beta1 Equations for 3-Leg Intersections

	Before Scenario	After Scenario
All Crashes	85.43 – 0.0419*Year	84.69 – 0.0416*Year
Injury/Fatal Crashes	58.36 – 0.0284*Year	59.40 – 0.0289*Year

Table 8 Beta1 Equations for 4-Leg Intersections

	Before Scenario	**After Scenario**
All Crashes	247.5 – 0.1225*Year	238.5 – 0.1180*Year
Injury/Fatal Crashes	217.1 – 0.1073*Year	206.0 – 0.1018*Year

3.7.2.2 Estimating Beta2 (β_2)

The Beta2 (β_2) parameter in the SPF equation was also estimated for each analysis year, crash type, and intersection type. To accomplish this, the already-estimated Beta1 equations were inserted into the SPF, and Beta2 was estimated from the rewritten form of the SPF shown in Equation 3.

$$\ln\left(\frac{N}{e^{[\beta_1 * \ln(AADT_{major\ road})]}}\right) = \alpha + \beta_2 * \ln(AADT_{minor\ road}) \;\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \textbf{(3)}$$

The slope of the plotted line is β_2. Similar to the Beta1 values, the estimated Beta2 values were regressed to develop time-dependent equations to estimate Beta2 for any given year, intersection type, crash type, and before or after period. Table 9 shows the estimated Beta2 values for three-leg intersections, while Table 10 shows the estimated Beta2 values for four-leg intersections. Figure 10 shows a typical output of the regression analysis to estimate Beta2 as a function of time. Table 11 shows the regression equations for estimating Beta2 for a three-leg intersection in the before and after periods. Table 12 shows the regression equations for estimating Beta2 for a four-leg intersection in the before and after periods.

Table 9 Annual Estimates of Beta2 (β_2) Values for 3-Leg Intersections

Year	3-Leg Intersections			
	All Crashes		Injury/Fatal Crashes	
	Before	After	Before	After
2010	−0.932	−0.930	−1.057	−1.089
2011	−0.470	−0.480	−0.415	−0.433
2012	−1.457	−1.472	−1.738	−1.781
2013	−1.050	−1.062	−1.010	−1.036
2014	−1.158	−1.173	−1.120	−1.153
2015	−1.064	−1.081	−0.991	−1.030

Table 10 Annual Estimates of Beta2 (β_2) Values for 4-Leg Intersections

Year	4-Leg Intersections			
	All Crashes		Injury/Fatal Crashes	
	Before	After	Before	After
2010	−1.960	−2.062	−2.527	−2.455
2011	−1.106	−1.153	−1.293	−1.212
2012	−1.038	−1.265	−1.377	−1.491
2013	−1.017	−1.091	−1.338	−1.296
2014	−1.030	−1.115	−1.033	−1.021
2015	−0.812	−0.905	−0.979	−0.945

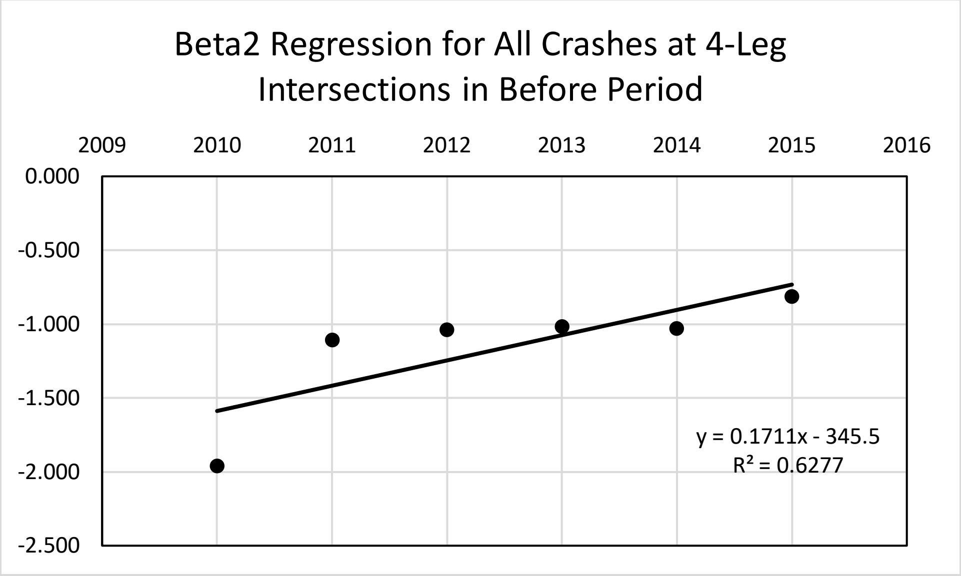


Figure 10 Typical Results of Regression Analysis to Estimate Beta2 (β_2) as a Function of Time.

Table 11 Beta2 Equations for 3-Leg Intersections

	Before Scenario	**After Scenario**
All Crashes	132.2 − 0.0662*Year	138.3 − 0.0693*Year
Injury/Fatal Crashes	59.72 − 0.0302*Year	63.31 − 0.0320*Year

Table 12 Beta2 Equations for 4-Leg Intersections

	Before Scenario	**After Scenario**
All Crashes	−345.5 + 0.1711*Year	−350.5 + 0.1735*Year
Injury/Fatal Crashes	−493.6 + 0.2445*Year	−479.7 + 0.2377*Year

3.7.2.3 Estimating Alpha (α)

The Alpha (α) parameter in the SPF equation was also estimated for each analysis year, crash type, and intersection type. The Alpha values were directly estimated by inserting the estimated Beta1 and Beta2 equations into a rewritten form of the SPF as shown in Equation 4.

$$\ln\left(\frac{N}{\left[e^{[\beta_1 * \ln(AADT_{major\ road})]}\right] * \left[e^{[\beta_1 * \ln(AADT_{minor\ road})]}\right]}\right) = \alpha \quad \textbf{..............................} \quad \textbf{(4)}$$

For each intersection type and crash type, a regression analysis of the estimated Alpha values was used to develop a time-dependent equation to predict Alpha for any given year, intersection type, crash type, and before or after period. Table 13 shows the estimated Alpha values for three-leg intersections, while Table 14 shows the estimated Alpha values for four-leg intersections. Figure 11 shows a typical output of the regression analysis to estimate Alpha as a function of time. Table 15 shows the regression equations for estimating Alpha for a three-leg intersection in the before and after periods, while Table 16 presents the regression equations for estimating Alpha for a four-leg intersection in the before and after periods.

Table 13 Annual Estimates of Alpha (α) Values for 3-Leg Intersections

	3-Leg Intersections			
	All Crashes		**Injury/Fatal Crashes**	
Year	**Before**	**After**	**Before**	**After**
2010	−3.790	−3.440	−4.980	−4.880
2011	−2.835	−2.480	−4.489	−4.380
2012	−2.046	−1.670	−4.020	−3.890
2013	−1.071	−0.670	−3.362	−3.220
2014	−0.232	0.190	−2.938	−2.780
2015	0.672	1.110	−2.363	−2.180

Table 14 Annual Estimates of Alpha (α) Values for 4-Leg Intersections

Year	4-Leg Intersections			
	All Crashes		Injury/Fatal Crashes	
	Before	After	Before	After
2010	1.147	2.140	2.845	1.450
2011	0.911	1.810	1.830	0.450
2012	0.582	1.420	0.904	−0.480
2013	0.473	1.270	0.097	−1.250
2014	0.145	0.890	−0.890	−2.240
2015	−0.059	0.640	−1.734	−3.060

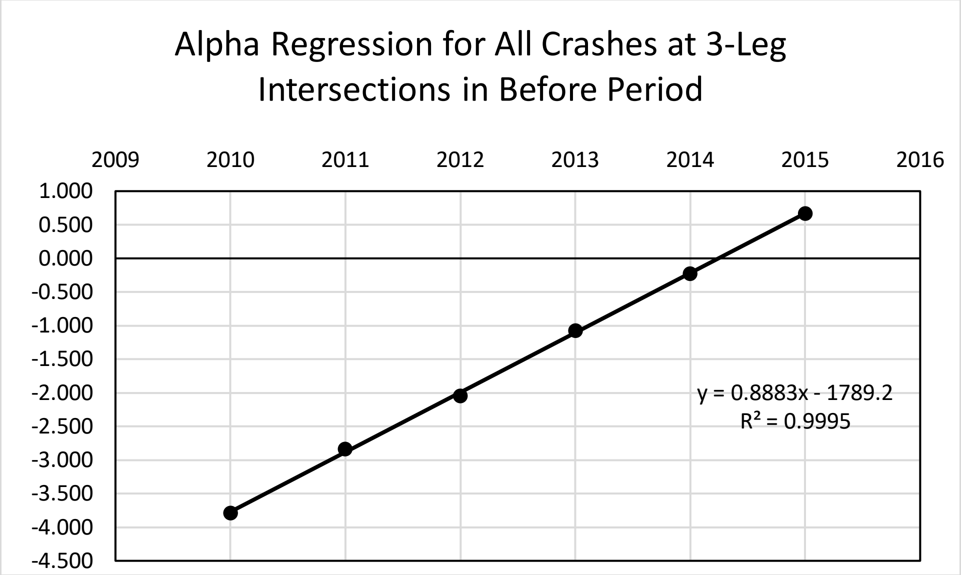


Figure 11 Typical Results of Regression Analysis to Estimate Alpha (α) as a Function of Time.

Table 15 Alpha Equations for 3-Leg Intersections

	Before Scenario	After Scenario
All Crashes	−1789 + 0.8884*Year	−1827 + 0.9074*Year
Injury/Fatal Crashes	−1061 + 0.5256*Year	−1094 + 0.542*Year

Table 16 Alpha Equations for 4-Leg Intersections

	Before Scenario	After Scenario
All Crashes	485.7 – 0.2411*Year	599.9 – 0.2974*Year
Injury/Fatal Crashes	1833 – 0.9103*Year	1804 – 0.8966*Year

3.8 Crash Modification Factor Analysis

3.8.1 The Standard Empirical Bayes Approach

The empirical Bayes analysis is a procedure for analyzing road safety data to estimate the effectiveness of a safety treatment without incurring the range of complexities of a full Bayesian analysis. Notably, the method explicitly addresses changes in observed crash frequencies before and after a treatment that may be due to time trends, regression-to-the-mean issues, and traffic volumes by incorporating crash information from other but similar (i.e., reference) sites into the evaluation. This is done by developing safety performance functions, with constant parameter estimates (unlike the estimates described in the previous sections) to predict average crash frequency in the before case (prior to installation of safety treatment) at the treatment sites, and in the after case (what would have been in the absence of the installed safety treatment) based on reference sites with similar traffic and physical characteristics. The effectiveness of the treatment can be estimated by a process that weighs the observed crash frequencies with SPF-predicted crash frequencies to obtain an expected average frequency. Treatment effectiveness is generally presented in the form of a crash modification factor (CMF). A CMF represents the relative change in crash frequency due to a change in one specific condition (when all other conditions and site characteristics remain constant). The CMF is a ratio of the crash frequency of a site, or group of sites, under two different conditions (in this case, before and after roundabout installation). Therefore, it serves as an estimate of the effect of the treatment in crash frequency [*33*].

The values of CMFs are determined for a specific set of base conditions, and under the base condition, the value is 1.00. If the base condition is modified by application of a treatment, CMF values less than 1.00 indicate a reduction in the estimated crash frequency. CMF values greater than 1.00 indicate an increase in the estimated crash frequency with treatment in comparison to the base condition. The CMF is related to the expected change in crash frequency as in Equation 5:

$$Change\ in\ Crash\ Frequency\ (CFF) = 100 * (1.00 - CMF) \quad \text{.........................} \quad (5)$$

Therefore, the empirical Bayes analysis procedure could be outlined in five steps:

1. Development of the SPFs
2. Estimation of before-and-after case crash frequency for treatment sites
3. Correction of time trends and volume trends effects by weighting the observed and predicted crashes into estimated expected crashes
4. Estimation of treatment effectiveness—CMFs
5. Estimation of the precision of the effectiveness

3.8.2 The Adopted Approach

The standard empirical Bayes approach described above requires that the SPFs are developed with data covering the entire analysis period. Due to the previously discussed data availability challenges, it was not possible to meet this requirement. This study’s SPFs were developed with data from 2010 to 2015, while the analysis period covers 2006 to 2015. Therefore, to estimate the safety benefits, this research needed to extend the standard empirical Bayes approach to incorporate a full time-dependence for the SPF parameters (as for a full Bayesian approach) rather than constant values (as for the standard empirical Bayes approach) while retaining the other aspects of the empirical Bayes approach.

The effects of time trends and regression-to-the-mean issues become pronounced when a single SPF is used to predict crash frequencies over a range of analysis years. Consequently, the researchers developed the SPF so that the traffic activity parameters (β_1 and β_2) were a function of time (in this case, year). Furthermore, the Alpha (α) parameter, which really drives the crash predictions, was estimated as a function of time. The estimated Alpha values were also normalized by the traffic volume. Therefore, predicted crash is based on time-specific parameters for traffic activity and Alpha for that specific year and period (before or after). This process enabled this research to address the issue of volume and time trends more effectively than the standard EB similar to that in the full Bayesian approach.

Another important requirement of empirical Bayes is that the controlling variables should be representative of the area being analyzed. The research methodology satisfies this requirement by:

- using only reference sites from the same counties as the treatment sites (roundabouts),
- using only reference sites with the same entry AADT range as the treatment sites, and
- using only reference sites that match either the three-leg or four-leg orientation of the treatment sites.

The effectiveness of the treatment was estimated by assuming that with everything else controlled (including the effects of volume and time trend), the ratio of the observed crash frequency to the predicted crash frequency in the before-period and after-period would remain the same in the absence of the treatment (in this case, roundabout installation). This means that the ratio in the after period is a direct effect of the safety treatment (roundabouts, in this case) on the before period ratio. Therefore, the following equation can be used to estimate the crash modification factors:

$$CMF * \frac{\#\ of\ observed\ crashes\ before}{\#\ of\ predicted\ crashes\ before} = \frac{\#\ of\ observed\ crashes\ after}{\#\ of\ predicted\ crashes\ after} \ldots\ldots\ldots \quad (6)$$

CHAPTER 4: RESULTS AND DISCUSSIONS

The results and discussions presented in this section are for the estimated crash reduction factors developed with the data that were available for this research as outlined in Chapter 3. The analysis and results omit data from the year the roundabout was installed/opened to public use. In addition to results for all crash severities, results are also presented for injury/fatal crash severities only. As mentioned prior, injury/fatal crashes includes fatal crashes as well as all types of injury crashes: complaint, visible, and serious. Table 17 presents some descriptive statistics of the final 27 roundabouts available for the analysis.

Table 17 Characteristics of Final Study Roundabouts

Physical Characteristic	No. of Single Lane Roundabouts	No. of Multi-Lane Roundabouts	Total
3-Legs	5	0	5
4-Legs	16	2	18
5-Legs	4	0	4

4.1 Initial Results

The change in crash frequency was estimated for all 27 roundabouts even though the data used to develop the SPFs did not include five-leg intersections and intersections with multi-lane approaches. Table 18 shows the analysis results for each roundabout site.

CMFs for all crashes and injury/fatal crashes could not be estimated for some roundabout sites. In Table 18, these are the sites with zero observed all crashes and/or injury/fatal crashes in the before period.

Table 18 Estimated Change in Crash Frequency (CMF) at Each Treatment Site

ID	No. of Legs	Year Opened	Before Data Years	After Data Years	Average Obs All Crashes in Before	Average Predicted All Crashes in Before	Average Obs All Crashes in After	Average Predicted All Crashes in After	Average Obs Injury/Fatal Crashes in Before	Average Predicted Injury/Fatal Crashes in Before	Average Obs Injury/Fatal Crashes in After	Average Predicted Injury/Fatal Crashes in After	Estimated CMF All Crashes	Estimated CMF Injury and Fatal Crashes
15	4	2007	1	8	0.00	0.19	1.00	0.39	0.00	0.09	0.25	0.14	n/a	n/a
18	4	2008	2	7	1.50	0.14	3.14	0.30	0.00	0.04	0.29	0.12	0.97	n/a
24	5	2011	5	4	10.40	0.12	13.00	0.32	1.60	0.02	2.00	0.16	0.46	0.15
25	4	2009	3	6	3.67	0.24	2.17	0.34	0.33	0.07	1.00	0.15	0.43	1.44
29	4	2007	1	8	6.00	0.10	4.25	0.26	2.00	0.02	1.00	0.11	0.27	0.08
30	4	2011	5	4	5.00	2.13	3.75	1.92	1.40	0.98	1.00	0.85	0.83	0.82
35	5	2011	5	4	8.60	0.15	9.75	0.33	2.40	0.03	1.50	0.16	0.51	0.13
42	4	2009	3	6	6.33	0.69	6.83	1.03	2.00	0.17	2.00	0.46	0.72	0.38
44	4	2011	5	4	4.00	1.30	3.75	1.44	0.20	0.43	0.25	0.68	0.85	0.80
45	4	2010	4	5	0.00	0.20	0.00	0.44	0.00	0.08	0.00	0.16	n/a	n/a
53	4	2007	1	8	1.00	0.20	1.25	0.46	1.00	0.11	0.00	0.16	0.55	0.00
54	4*	2008	2	7	42.50	0.08	11.29	0.23	5.50	0.01	0.71	0.11	0.09	0.01
56	4	2009	3	6	2.00	0.12	2.83	0.29	0.00	0.02	0.17	0.13	0.56	n/a
81	4	2009	3	6	0.00	0.13	1.83	0.33	0.00	0.03	0.00	0.14	n/a	n/a
903	5	2014	8	1	4.13	3.11	6.00	0.92	1.13	3.55	0.00	0.37	4.92	0.00
930	4	2012	6	3	1.83	0.15	3.33	0.35	0.17	0.03	1.33	0.19	0.76	1.35
931	4	2012	6	3	5.83	0.14	10.00	0.35	0.67	0.03	1.33	0.18	0.67	0.30
932	5	2012	6	3	0.00	3.05	0.00	3.04	0.00	1.92	0.00	1.19	n/a	n/a
954	4*	2014	8	1	17.13	0.20	3.00	0.46	3.50	0.05	1.00	0.26	0.08	0.06
955	4	2014	8	1	0.88	0.99	0.00	1.08	0.50	0.47	0.00	0.46	0.00	0.00
975	4	2011	5	4	17.80	0.16	5.25	0.34	4.40	0.04	0.75	0.16	0.14	0.04
1046	4	2012	6	3	1.33	0.30	2.67	0.48	0.17	0.18	1.00	0.18	1.25	6.03
8	3	2010	4	5	0.25	2.33	2.00	26.16	0.00	0.58	0.20	7.44	0.71	n/a
14	3	2007	1	8	0.00	0.18	0.00	0.26	0.00	0.04	0.00	0.06	n/a	n/a
953	3	2014	8	1	0.63	0.25	1.00	0.36	0.25	0.06	1.00	0.08	1.15	2.78
959	3	2012	6	3	0.33	0.43	3.00	0.25	0.00	0.08	0.67	0.07	15.78	n/a
979	3	2009	3	6	2.33	0.30	1.50	0.27	1.33	0.06	0.33	0.07	0.71	0.22

Note 1: * means a multi-lane roundabout

Note 2: Injury/Fatal includes fatal crashes as well as all types of injury crashes: complaint, visible, and serious

Similarly, some roundabout locations with low average frequency of crashes in the before period have CMFs that indicate an adverse effect on crashes. This result illustrates why researchers seek to incorporate many sites into the analysis, as these results, as well as those from the zero crash sites, can be averaged to produce a more robust CMF estimate. Note that site 903 has only one year of after period data, and that is driving the high CMF value.

In the sections that follow, the results are presented as an average for three scenario groupings and intersection types. The three scenarios are shown in Table 19. These scenarios test the sensitivity of the results to sites with low average crash frequencies and sites with single data-year in either the before or after period. For the scenario analysis, the research team defines a low crash frequency roundabout as one with less than four observed average crashes per year in the before period. Note that the Manual of Uniform Traffic Control Devices (MUTCD) requires an average crash frequency of five for traffic signals to be installed. Therefore, an average crash frequency of four is a good threshold to distinguish a low crash frequency site for roundabouts, which can be used to replace a traffic signal in some cases.

The results are also presented for single-lane four-leg roundabouts only, and four-leg and three-leg intersections combined.

Table 19 Results Reporting Scenarios

Item	Scenario Definition
Scenario 1	a. Combine roundabout locations with less than four average observed crashes per year in before period as one sample. b. Include roundabout locations with just a single data-year of crashes in before or after period. c. Include roundabout locations with zero observed crashes in the before period.
Scenario 2	a. Combine roundabout locations with less than four average observed crashes per year in before period as one sample. b. Include roundabout locations with just a single data-year of crashes in before or after period. c. Omit all roundabout locations with zero observed crashes in the before period.
Scenario 3	a. Omit roundabout locations with less than four average observed crashes per year in before period. b. Omit roundabout locations with just a single data-year of crashes in before or after period. c. Omit roundabout locations with zero observed crashes in the before period.

4.2 Results for Single-Lane Four-Leg Roundabouts Only

Table 20 presents the average CMF for single-lane four-leg intersections under each of the three scenarios. The CMF results for all crash severities remain largely constant under the three scenarios. The implied safety benefit for converting a four-leg conventional intersection into a single-lane four-leg roundabout based on the available data is about a 35.8 to 38.7 percent reduction in all crashes. In the case of injury/fatal crash severities at single-lane four-leg roundabouts, the results indicate about a 48.8 to 53.3 percent reduction in crashes.

Table 20 Estimated Average CMFs for Single-Lane 4-Leg Roundabouts Only

	Scenario 1	**Scenario 2**	**Scenario 3**
4 Legs (All Crashes)*	0.623	0.613	0.642
4 Legs (Injury/Fatal Crashes)*	0.509	0.512	0.467

Note: * no multi-lanes

Table 21 presents the results of estimated CMFs when the two double-lane four-leg roundabouts are included in the analysis. It can be inferred from Table 21 that the estimated safety benefits are comparatively higher, about 45.1–50.5 percent reduction in all crash severities and 59.1–60.9 percent reduction in injury/fatal crash severities. This observation is intuitive because intersections with multi-lane approach(es) can be expected to experience higher crash frequencies than those with single lanes. Therefore, the roundabout (even if multi-lanes) could have a higher safety effect when installed in place of a double-lane conventional intersection.

Table 21 Estimated Average CMFs for All 4-Leg Roundabouts

	Scenario 1	Scenario 2	Scenario 3
4 Legs (All Crashes)	0.503	0.495	0.549
4 Legs (Injury/Fatal Crashes)	0.403	0.405	0.391

4.3 Results for All Three- and Four-Leg Roundabouts

The estimated CMF results for combined three- and four-leg roundabouts are shown in Table 22. Note that there is no result for Scenario 3; based on the available data, a Scenario 3 analysis for combined three- and four-leg roundabouts ends up being the same as the Scenario 3 results presented in Table 21 for all four-leg roundabouts. Again, from the data in Table 22, the estimated CMFs do not vary much across the scenarios, regardless of the crash severity type. Also, based on the available data, the expected safety benefit for converting either a three-leg or four-leg conventional intersection into a roundabout with the same number of legs is a crash reduction in the range of 56.1–56.7 percent for all crash severities and 68.7–69.1 percent for injury/fatal crashes.

Table 22 Estimated Average CMFs for All 3- and 4-Leg Roundabouts

	Scenario 1	Scenario 2
3 & 4 Legs (All crashes)	0.439	0.433
3 & 4 Legs (Injury/Fatal Crashes)	0.313	0.309

4.4 Results for All Roundabouts including Five-Leg Roundabouts

The results of the analysis with all roundabouts combined, including the five-leg roundabouts, is presented in Table 23. However, given the limited number of available five-leg roundabouts, and the fact that the five-leg roundabouts were not included in the SPF development, these results are not recommended for use.

Table 23 Estimated Average CMFs for All Roundabouts

	Scenario 1	Scenario 2	Scenario 3
3,4,5 Legs (All Crashes)	0.83	0.815	0.533
3,4,5 Legs (Injury/Fatal Crashes)	0.28	0.255	0.328

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

The primary goal of this research study was to conduct a safety evaluation of roundabouts in Georgia, estimating the potential impact on crashes and crash severities. This research develops a methodology to perform the analysis consistent with the data challenges that are often inherent in these kinds of analyses.

An initial pool of 361 roundabouts was selected from two sources: (1) a circular intersection database developed in a previous study at GDOT, and (2) the GDOT 2015 RC-Link shapefile and attribute tables. Through the application of several selection filters (including construction year, design, and location), and consultations with GDOT staff, the researchers selected a final list of 27 roundabouts that were converted from prior conventional intersections. The reference sites were selected as conventional intersections with similar traffic (1000–20,000 AADT), physical characteristics (three and four legs), and driver population (reference sites were located in the same counties as the treatment sites) as the study roundabouts. A total of 49,960 three-leg intersections and 8510 four-leg intersections were used as reference sites. The research team checked the roadway information contained in the annual GDOT RC-Link databases to ensure that none of the reference sites had any kind of signal device, multi-lane approaches, missing traffic information within the analysis period, or more than one type of traffic control within the analysis period.

Crash information was obtained from the Georgia crash database from 2006 to 2016. There were about 3.42 million crashes in the database in that period. Several options for identifying the crashes related to the study's reference and treatment sites were explored by the research team.

These options included matching road names in the crash database and the annual RC-Link databases, and matching latitude and longitude information in the crash database and the RC-Link database. There were inconsistencies in the use of road names (i.e., primary names, alternate names, prefixes, suffixes, etc.) within the database, and the quality control efforts required to fully resolve these issues exceeded available resources. The researchers found that the latitude and longitude data were more suitable than road names for identifying crash locations, even considering the limitation of the latitude/longitude data. Ultimately, a minimum distance algorithm with a buffer distance of 250 feet for reference sites and 325 feet for the roundabouts was adopted.

Limitations regarding available data required some extensions of the HSM empirical Bayes predictive method. Consistent traffic volume data were available only for the 2010–2015 time period and, thus, traffic volume estimates for the 2006–2009 time period were imputed from the 2010–2015 trends. As a result, although overall results are reasonable, predicted crash frequencies for individual sites may be somewhat over- or underestimated. To minimize any potential bias in this approach, the parameters used within the SPFs developed in this study were allowed to be temporally dependent (similar to a full-Bayesian approach) rather than constants, as in the HSM predictive method. While somewhat more complex, the research team considered this approach important to this study to minimize the impacts of temporal trends and regression-to-the-mean issues.

The safety effectiveness of the roundabouts was estimated as CMFs. In calculating the CMFs, it was assumed that hazard ratio at each site (i.e., the impacts of other potential influences on crashes at the treatment sites) was constant other than the overall temporal trends (i.e., change in average crash rate with time) and changes in traffic volume at the sites that were considered explicitly.

5.1 Overall Effectiveness of Converting Conventional Intersections into Roundabouts in Georgia

The analysis results from the data available to this study show that:

- Conventional four-leg intersections with only single-lane approaches that are converted into roundabouts in Georgia experience approximately a 37 percent reduction in average crash frequency for all crashes and a 51 percent reduction in injury/fatal crashes.
- Conventional four-leg intersections, including both single-lane and multi-lane approaches, can collectively experience about 48 percent and 60 percent reductions in average crash frequency for all crashes and injury/fatal crashes, respectively, when converted to a modern roundabout.
- When analyzed as a group, three-leg and four-leg conventional intersections that are converted into roundabouts in Georgia can experience approximately a 56 percent reduction in average crash frequency for all crashes and about a 69 percent reduction in average injury/fatal crash frequency.

These estimated safety benefits range from 37 to 56 percent for all crashes and 51 to 69 percent for injury/fatal crashes. These estimates are comparable to estimates from published U.S. studies: a 9–72 percent and a 52–100 percent reduction in average crash frequencies for all crashes and injury/fatal crashes, respectively.

5.2 Recommendations

The primary challenges encountered in performing this safety evaluation of roundabouts in Georgia are the limitations of availability and quality of traffic data and crash data, and the significantly short history for the majority of roundabouts in Georgia, which affects the size and quality of available before-period and after-period data. Since these limitations will continue to decline as more roundabouts are constructed and others remain in service, these analyses should be reexamined at a later date, specifically as follows:

- Future research should be conducted when the number of "roundabout-years" for Georgia has significantly increased (e.g., 2× the conditions of this study). This larger dataset could allow for the development of CMFs specific to different characteristics of roundabouts and/or other crash severity levels.
- Ongoing efforts to improve the quality of crash location information in the Georgia crash database should continue. More consistent inclusion of road names in the annual RC-Link databases should also be examined.
- Future research can be enhanced by developing a system by which changes in RCLINK IDs for the same physical location could be tracked due to changes in route, jurisdiction, or other reasons.

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