Nebraska
Transportation
Center

MID-AMERICA
TRANSPORTATION CENTER

NDOR
Nebraska
Department of Roads

Report SPR-P1(14) M008

Final Report
26-1121-0016-001

Investigation of Rural/Suburban High-Speed Multilane Roundabouts

Aemal J. Khattak, Ph.D.
Associate Professor
Department of Civil Engineering and Nebraska Transportation Center
University of Nebraska-Lincoln

Eric Thompson, Ph.D.
Associate Professor and Director of the Bureau of Business Research
Department of Economics
University of Nebraska-Lincoln

Shanshan Zhao
Graduate Research Assistant
Department of Civil Engineering and Nebraska Transportation Center
University of Nebraska-Lincoln

2015

Nebraska Transportation Center
262 WHIT
2200 Vine Street
Lincoln, NE 68583-0851
(402) 472-1975

Investigation of Rural/Suburban High-Speed Multilane Roundabouts

Aemal J. Khattak, Ph.D.
Associate Professor
Department of Civil Engineering and Nebraska Transportation Center
University of Nebraska-Lincoln

Eric Thompson, Ph. D.
Associate Professor and Director of the Bureau of Business Research
Department of Economics
University of Nebraska-Lincoln

Shanshan Zhao
Graduate Research Assistant
Department of Civil Engineering and Nebraska Transportation Center
University of Nebraska-Lincoln

Report on Research Sponsored by

Nebraska Department of Roads

March 2014

Technical Report Documentation Page

1. Report No.
SPR-P1(14) M008

2. Government Accession No.

3. Recipient's Catalog No.

4. Title and Subtitle
Investigation of Rural/Suburban High-Speed Multilane Roundabouts

5. Report Date
November 2014

6. Performing Organization Code

7. Author(s)
Aemal J. Khattak, Eric Thompson, Shanshan Zhao

8. Performing Organization Report No.
26-1121-0016-001

9. Performing Organization Name and Address
Nebraska Transportation Center
2200 Vine St.
PO Box 830851
Lincoln, NE 68583-0851

10. Work Unit No. (TRAIS)

11. Contract or Grant No.

12. Sponsoring Agency Name and Address
Nebraska Department of Roads
1500 Nebraska 2
Lincoln, NE 68502

13. Type of Report and Period Covered
Research report July 2013-December 2014

14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This research was focused on two issues related to multilane roundabouts on high-speed highways (speed limit 45 mph or greater) in rural and suburban areas. The first was the tradeoff between converting a traditional stop-controlled or signalized intersection to a multilane roundabout while the second was the safety of newly constructed high-speed multilane roundabouts in rural and suburban areas. The research team reviewed information from diverse published documents and conducted a survey of state and local transportation agencies. Crash data on multilane rural roundabouts were not available for this research. Therefore, the research team relied on crash and other data for single lane roundabouts that were constructed to replace rural two-way stop-controlled intersections in Kansas. To gain further insights into the safety of rural multilane roundabouts, the research team focused on investigating the safety of urban multilane roundabouts from published sources.

Results of the survey indicated the need for proper design of roundabouts including signage and lighting and the potential for gaining benefits from public informational campaigns. Results of the Kansas data analysis of single lane roundabouts showed that overall all types of crashes were reduced after conversion of TWSC intersections to modern single lane roundabouts. Total crashes decreased by 58.13%; fatal crashes were reduced by 100% at all locations and non-fatal injury crashes were reduced with an overall reduction rate of 76.47%. Property-damage-only crashes were reduced by 35.49% as a whole, but two out of the four analyzed sites experienced increases in property-damage-only crashes after conversion to roundabouts. The annual value of the reduction in comprehensive crash costs from conversion of a two-way stop-controlled intersection on a rural, high-speed highway to a single lane modern roundabout was between $1.0 million and $1.6 million in 2014 dollars. A review of multilane roundabout conversions (mostly in urban areas) showed safety improvements compared to signalized and two-way stop-controlled intersections. Recommendations are presented in the report.

17. Key Words
Rural, suburban, roundabouts, safety, Nebraska

18. Distribution Statement

19. Security Classif. (of this report)
Unclassified

20. Security Classif. (of this page)
Unclassified

21. No. of Pages
90

22. Price

Table of Contents

List of Figures

List of Tables

Acknowledgements

The authors would like to acknowledge the Nebraska Department of Roads (NDOR) for funding the research. NDOR staff members Ryan Huff, Dan Waddle, Matt Neeman, Phil TenHulzen, Nathan Sorben, Jodi Gibson, and Anna Rea helped with various aspects of the research and provided valuable insights. The authors are thankful for the assistance received from Kansas DOT staff including Rex McCommon, Michael Guerrero, Theresa Havenstein, and Cheryl Lambrecht and from Dr. Gene Russell Sr. of Kansas State University.

Disclaimer

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the information presented herein. This document is disseminated under the sponsorship of Nebraska Department of Roads.

Abstract

This research was focused on two issues related to multilane roundabouts on high-speed highways (speed limit 45 mph or greater) in rural and suburban areas. The first was the tradeoff between converting a traditional stop-controlled or signalized intersection to a multilane roundabout while the second was the safety of newly constructed high-speed multilane roundabouts in rural and suburban areas. The research team reviewed information from diverse published documents and conducted a survey of state and local transportation agencies. Crash data on multilane rural roundabouts were not available for this research. Therefore, the research team relied on crash and other data for single lane roundabouts that were constructed to replace rural two-way stop-controlled intersections in Kansas. To gain further insights into the safety of rural multilane roundabouts, the research team focused on investigating the safety of urban multilane roundabouts from published sources.

Results of the survey indicated the need for proper design of roundabouts including signage and lighting and the potential for gaining benefits from public informational campaigns. Results of the Kansas data analysis of single lane roundabouts showed that overall all types of crashes were reduced after conversion of TWSC intersections to modern single lane roundabouts. Total crashes decreased by 58.13%; fatal crashes were reduced by 100% at all locations and non-fatal injury crashes were reduced with an overall reduction rate of 76.47%. Property-damage-only crashes were reduced by 35.49% as a whole, but two out of the four analyzed sites experienced increases in property-damage-only crashes after conversion to roundabouts. The annual value of the reduction in comprehensive crash costs from conversion of a two-way stop-controlled intersection on a rural, high-speed highway to a single lane modern roundabout was between $1.0 million and $1.6 million in 2014 dollars. A review of multilane roundabout conversions (mostly in urban areas) showed safety improvements compared to signalized and two-way stop-controlled intersections. Recommendations are presented in the report.

Chapter 1 Introduction

1.1 Objective

This research focused on investigating two issues related to multilane roundabouts on high-speed highways (speed limit 45 mph or greater) in rural and suburban areas. The first was the tradeoff between converting a traditional stop controlled or signalized intersection to a multilane roundabout on high-speed state highways, and the second was the safety of newly constructed high-speed multilane roundabouts in rural and suburban areas.

Many single lane roundabouts have been constructed in Nebraska with favorable safety results, and several multilane roundabouts on high-speed Nebraska state highways are planned for construction in the near future. However, there are questions about the safety performance of multilane roundabouts constructed on high-speed facilities. The NCHRP 672 report (Rodegerdts et al. 2010) notes that most multilane roundabouts experience increased safety benefits compared to conventional intersections; however some state transportation agencies experienced an increase in crashes immediately after converting a conventional intersection to a multilane roundabout. In these instances, the subject roundabout was followed by negative publicity and public opinion. A recent City of Lincoln experience with the newly constructed multilane roundabout at North 14th and Superior streets has also not been favorable due to a spate of crashes after completion of construction. Therefore, one of the aims in this research is to avoid safety issues that other agencies experienced with newly constructed roundabouts in Nebraska and thereby mitigate possible negative publicity and public opinion about multilane roundabouts.

Overall, this research is aimed at investigating the tradeoffs between traditional intersections and roundabouts on high-speed state highways located in rural and suburban areas, and exploring safety issues associated with multilane roundabouts on high-speed facilities located in rural and suburban areas. The following NDOR projects could potentially benefit from this research: Kearney East Bypass, 11th St. to 56th St.; Norfolk intersection of US-275 and N-35; and Norfolk intersection of 37th St. and US-275. These projects are planned for construction during the 2013-2015 period.

1.2 Previous Studies

Constructing roundabouts is considered one way to reduce vehicle collisions and improve the efficiency of intersections (Nebraska Department of Roads 2012). This literature review focuses on two aspects: the tradeoff of converting a traditional stop or signal controlled intersection into a roundabout, and the safety benefits or drawbacks of a roundabout. In fact, the two aspects are so closely related that research studying one aspect usually digs into the other as well. Research on high-speed multilane roundabouts constructed in rural or suburban areas was emphasized, however, research achievements on roundabout safety to date showed an obvious concentrate on single-lane roundabouts and urban roundabouts. The number of research papers on high-speed suburban or rural multilane roundabouts is relatively few.

This literature review focuses on the safety evaluation of roundabouts and benefits/costs of converting conventional intersections into roundabouts. Eight sections are included. They are the (1) general evaluation of roundabouts operational performances; (2)

benefits and costs of converting conventional intersections into roundabouts; (3) before/after safety studies on converting traditional intersections into roundabouts; (4) crash predicting models; (5) safety-related research on the high-speed/rural/suburban/multilane roundabouts; (6) design issues for rural high-speed multilane roundabouts; (7) safety of pedestrian and cyclists at roundabouts; and (8) some other significant safety studies on roundabouts.

1.2.1 General Evaluation of Roundabouts' Operational Performances

Generally, roundabouts increase capacity and reduce delays and crashes. The NCHRP Report 672 (Rodegerdts et al. 2010) provides several operational performance evaluation methods that may serve as sound comparison bases between roundabouts and stop- or signal-controlled intersections. Those methods include the HCM method, deterministic software, and simulation. Through the evaluations, the report concluded that a roundabout always provides a higher capacity and lower delays than an all-way stop control (AWSC) and generally produces lower delays than a signalized intersection under the same traffic volumes. Roundabouts are unlikely to offer lower overall delays than two-way stop control (TWSC) but can offer significant safety benefits over TWSC intersections. For intersections with heavy left turns from the major street or an intersection with major street traffic causing too much delay over minor street traffic, roundabouts may perform better than a TWSC intersection. Compared with a signal control, a roundabout within its capacity usually provides better operational performance in terms of stops, delay, vehicle queues, fuel consumption, safety, and pollution emissions. Russell et al. (2005) studied the operational performance of 11 roundabouts in Kansas and compared them with other conventional controlled intersections. This study concluded that the operational efficiency was significantly improved because there were statistically significant reductions in delay, queuing, and proportion of vehicles stopped at all the study sites after the installation of a modern roundabout.

1.2.2 Benefits/Costs of Converting Conventional Intersections to Roundabouts

The benefits-cost method is the most appropriate for evaluating the trade-off of public works, such as converting a signal- or stop-controlled intersection into a roundabout. This method needs to take into account the costs and benefits of public works. As for roundabouts, costs may include construction costs, engineering and design fees, land acquisition, and operation and maintenance costs. Benefits may be classified as safety benefits (reduced crash rates and severity), operational benefits (reduced delay and stops), and environmental benefits (fuel consumption and emissions) (Robinson and Rodegerdts 2000).

When comparing two alternatives, the basic premise of benefits-cost evaluation is to compare the incremental benefit between two alternatives to the incremental costs between the same alternatives (Rodegerdts et al. 2010). The equation is:

$$B/C_{B\rightarrow A} = (\text{Benefits}_B - \text{Benefits}_A)/(\text{Costs}_B - \text{Costs}_A)$$

In which, A and B are two alternatives.

While assessing one viable project, the benefit-cost ratio is a measure of return, or benefit, for each dollar expended. A viable project should have a benefit-cost ratio exceeding

1: the higher the ratio, the better the investment (Niederhauser, Collins, and Myers 1997). The equation is:

$$\frac{B}{C} = \frac{EUAB}{EUAC} = \frac{EUAB}{CRF * Construction\ Costs + Annual\ O\&M\ \mathrm{Costs}}$$

In which, O&M is Operation and Maintenance; EUAC is the equivalent uniform average cost, which equals the equivalent annual construction cost plus average O&M costs; EUAB is the equivalent uniform average benefits; CRF is capital recovery factor.

1.2.2.1 Benefits

(1) Safety Benefits

The safety benefits are the assumed savings to the public due to a reduction in crashes within the project area. To determine the safety benefits, the existing safety history in terms of crash rates and severity need to be checked. The number of future crash rates (after the construction of roundabouts) of each level of severity is to be forecasted. Safety benefits are estimated by multiplying the expected number of "after" crashes of each level of severity by the average cost of each crash. Table 1.1 shows the economic costs per crash based on different severity levels. Crash reductions from converting conventional intersections to roundabouts are discussed in section 1.2.3.

Table 1.1 Economic cost of crashes

Crash Severity	**Economic Cost Per Crash (2008 dollars)**
Fatality	$4,200,000
Class A (incapacitating injury)	$214,200
Class B (non-incapacitating evident injury)	$54,700
Class C (possible injury)	$26,000
Property Damage Only (per crash)	$2,400

Source: National Safety Council (Rodegerdts et al. 2010)

(2) Operational Benefits

The operational benefits can be quantified in terms of the overall reduction in person-hours of delay to the public. The calculation of annual person-hours of delay can be performed with varying levels of detail, depending on the availability of data (Rodegerdts et al. 2010). Roundabouts generally increase capacity and reduce delays and crashes. A roundabout always provides a higher capacity and lower delays than an AWSC, which generally produces lower delays than a signalized intersection, but is unlikely to offer lower overall delays than TWSC, as discussed in section 1.2.1.

Delay models were developed to estimate delay at roundabouts and compare it to delay of other conventional intersections. Queuing theory was used in research to develop the estimation model for single lane roundabout approaches (Flannery and Kharofeh 2000). Results were compared with field measures. For multilane roundabouts, Seiberlich's research presents a formulation for evaluating the capacity and delay of multilane roundabouts. The formulation uses the gap acceptance theory and evaluates entry lanes on a lane-by-lane basis (Seiberlich 2001). On the other hand, Signalized and Unsignalized Intersection Design and

Research Aid (SIDRA), which is able to evaluate all types of intersections including roundabouts, is often used to evaluate the performance of roundabouts with other intersections (Florida Department of Transportation 1995; Luttrell, Russell, and Rys 2000; Chung, Young, and Akcelik 1993). In Luttrell's research, the roundabout was found to operate statistically better than the comparable two-way stop intersections.

(3) Environmental Benefits

The environmental benefits are quantified in terms of reduced fuel consumption and improved air quality. One way to determine fuel consumption is to use the same procedure for estimating delay. The resulting estimate can then be converted to a cost by assuming an average cost of fuel, expressed in dollars per gallon (dollars per liter) (Rodegerdts et al. 2010).

Since roundabouts generally reduce delays and stops compared to other types of intersections, the environmental benefits of converting conventional intersections into roundabouts are obvious. Carbon emissions, for instance, can be expected to save $500 annually when replacing a signalized intersection with a roundabout (Bahar, Smahel, and Smiley 2009).

1.2.2.2 Costs

(1) Construction Costs

Construction costs of any intersection alternative should be calculated using normal preliminary engineering cost-estimating techniques. The costs include the costs of any necessary earthwork, paving, bridges and retaining walls, signing and striping, illumination, and signalization (Rodegerdts et al. 2010). The construction cost depends on several factors including the setting, that is, urban or rural, the complexity of the changes to the existing site, mostly on the approaches, and maintenance of traffic during construction (Kansas Department of Transportation 2003).

Constructing a roundabout may cost more or less than a traffic signal, depending on the amount of new pavement area and the extent of other roadway work required. Roundabouts may require more pavement area at the intersection compared to a traffic signal, but less on the approaches and exits. Compared to the two-way or all-way stop-controlled intersection, in most cases a roundabout is more expensive to construct. According to the National Cooperative Highway Research Program (NCHRP) Synthesis 264, the average construction cost of 14 U.S. roundabouts at that time was approximately $250,000 (Robinson and Rodegerdts 2000). Roundabout construction costs mentioned by previous research or publications are summarized in table 1.2.

Table 1.2 Roundabout (RAB) construction costs

State	Reference	Construction Year	Construction Costs ($)	Method*	Note
Kansas	(Church 2007)	2006	3.2 million	R	TWSC converted to a five-leg RAB
Kansas	(Church 2007)	2001	2.5 million	R	TWSC converted to five-leg RAB
Kansas	(Church 2007)	2006	2.4 million	R	Three leg braided intersection
Kansas	(Alisoglu 2010)	Unknown	735,855	E	Replacement of a dilapidated roundabout to a new one
Washington	(WSDOT)	2012	5,824,000	F	Two RABs
Washington	(WSDOT)	2012	4.9 million	F	A single-lane RAB
Washington	(WSDOT)	2013	7,763,000	F	Two single-lane RAB
Washington	(WSDOT)	2014	4.5 million	E	TWSC to RAB
Washington	(WSDOT)	2014	4,925,000	F	Two RABs

Maryland	(MD-SHA 2002)	1999	232,284	R	A single-lane RAB
Maryland	(MD-SHA 2002)	2000	520,613	R	TWSC to single-lane RAB
Maryland	(MD-SHA 2002)	2001	300,000	E	Single-lane RAB
Maryland	(MD-SHA 2002)	UN	300,000	E	Single-lane RAB
Maryland	(MD-SHA 2002)	2001	679,569	R	Single-lane RAB
Maryland	(MD-SHA 2002)	2000	687,434	R	Single-lane RAB
Maryland	(MD-SHA 2002)	1996	464,540	R	TWSC to Single-lane RAB
Maryland	(MD-SHA 2002)	1993	200,000	E	TWSC to Single-lane RAB
Maryland	(MD-SHA 2002)	1995	472,014	R	TWSC to Single-lane RAB
Maryland	(MD-SHA 2002)	1995	493,881	R	TWSC to Single-lane RAB
Maryland	(MD-SHA 2002)	2001	300,000	E	Single-lane RAB
Maryland	(MD-SHA 2002)	2001	300,000	E	Single-lane RAB
Maryland	(MD-SHA 2002)	1995	386,145	R	TWSC to single-lane rural RAB
Maryland	(MD-SHA 2002)	1998	500,678	R	Single-lane RAB
Maryland	(MD-SHA 2002)	1999	382,347	R	TWSC to Single-lane RAB
Michigan	(Biolchini 2013)	2013	2.3 million	E	Included is a $470,000 water main replacement project by the city of Ann Arbor
Alabama	(Anderson 2013)	2014	1.4 million	E	None
Louisiana	(Leblanc 2009)	Unknown	885,304	E	None
Ohio	(B & G ENG 2012)	Unknown	321,100	E	None
Ohio	(B & G ENG 2012)	Unknown	299,900	E	None
Ohio	(B & G ENG 2012)	Unknown	467,400	E	None
Multi States	NCHRP 264 (Jacquemart 1998)	N.A.	250,000	E	Ranges between $10,000 and $500,000, with an average total cost of $250,000, including construction, maintenance of traffic, design, and engineering
California	NCHRP 264	Unknown	400,000	R	None

	(Jacquemart 1998)				
Colorado	NCHRP 264 (Jacquemart 1998)	Unknown	2.8 million	R	This figure includes construction of both two RABs, the reconstruction of the freeway ramp termini and other roadways, drainage work, landscaping ($500,000), maintenance of traffic, and design and engineering costs ($375,000).

Note: *Costs were given based Real Cost (R), Funding (F) or Estimate (E)

On the other hand, the cost of maintaining traffic during construction tends to be relatively high when converting conventional intersections into roundabouts. The expense is due mainly to maintaining existing traffic flow through the intersection while rebuilding it in stages (Robinson and Rodegerdts 2000).

(2) Operation and Maintenance (O&M) Costs

Roundabouts usually have slightly higher illumination power and maintenance costs compared to signalized or sign-controlled intersections due to a larger number of illumination poles. Roundabouts have slightly higher signing and pavement marking maintenance costs due to a higher number of signs and pavement markings (Rodegerdts et al. 2010). Roundabouts can also have higher landscape maintenance costs, depending on the degree of landscaping provided on the central island, splitter islands, and perimeter (Robinson and Rodegerdts 2000).

Compared to signalized intersections, however, roundabouts do not have signal equipment that requires constant power, periodic light bulb and detection maintenance, and regular signal timing updates. Also, roundabouts do not need to worry about power failures during daytime. The service life of a roundabout is significantly longer, approximately 25 years, compared to 10 years for a typical signal (Robinson and Rodegerdts 2000). For signalized intersections, the annual power cost is around $3,000. Signal timing maintenance requires a specialized workforce and equipment. Traffic signals are often added to an agency's responsibility without a commensurate increase in budget. Signal retiming costs approximately $2,500 to $3,100 per signal and needs to be repeated every 8-9 years (Rodegerdts et al. 2010).

In general, O&M costs for roundabouts are higher than for other un-signalized intersections, but less than those for signalized intersections (Robinson and Rodegerdts 2000). Especially in the long-term, operational costs of roundabouts are reduced.

Proost and DeGeest (2006) examined a wide range of benefits from changing a crossing with traffic lights into a roundabout. They conclude that roundabouts are cost effective, and that a sensitivity analysis indicated the results were very robust for changes in accident, time, and infrastructure costs. A cost-benefit analysis was also used in this study.

1.2.3 Before-After Safety Studies of Converting Traditional Intersections to Roundabouts

1.2.3.1 International Experience

Thirty-eight roundabouts in Greater London, England, were studied during a nineteen-month before-after period (Lanani 1975), most of which were mini and small roundabouts located in built-up areas. The results showed a 39% reduction in vehicle accidents.

A more comprehensive safety research on eighty-four roundabouts in the United Kingdom (Maycock and Hall 1984) once acted as the basis of designing and constructing roundabouts in many countries. It developed the U.K. roundabout capacity model and the collision prediction model, which relates injury crashes to several geometric design parameters. All the roundabouts in the research were conventional (usually single-lane) or small-island roundabouts located in 30-40 mile/h and 50-70 mile/h speed limit zones.

Tudge studied 230 roundabouts and 60 controlled intersections in New South Wales, Australia, and the results showed a 50% overall reduction in accidents at roundabouts with a 63% reduction in fatal accidents, a 45% reduction in injury accidents, and a 40% reduction in damage-only accidents (Tudge 1990). Stuwe conducted a comparative study between roundabouts and other controlled intersections in Germany (Stuwe 1991). The results indicated that the total number of accidents at roundabouts seemed to be higher than at intersections, but the severity of these accidents was lower.

Another study was conducted in Victoria, Australia on seventy-three roundabouts (AUSTROADS 1993). A 74% reduction in the casualty accident rate was found after the installation of roundabouts. A 68% reduction was observed in pedestrian casualty accidents, even it was not so significant in the 90% confidence level.

A two-year before/after study conducted near Sydney, Australia (Adams 1995) assessed the crash frequency and severity after the installation of eleven traffic signals and thirteen roundabouts. Results showed a greater reduction in crash frequencies at the roundabouts than at the signal intersections (71% versus 35%).

A before and after comparison of 122 roundabout intersections in Belgium (Antoine 2005) indicated an average 42% decrease in injury crashes and 48% decrease in serious accidents. The reduction varied by environment: in urban, suburban, and open rural areas, the reductions rates were 15%, 46% and 50% respectively.

A summary of the above international experience is presented in table 1.3.

Table 1.3 International experience in before-after safety analysis

Country, City & Year	**Roundabouts Studied**	**Findings**
Greater London, UK, 1975	38 roundabouts, most are mini and small roundabouts	A 39% reduction in vehicle accidents
New South Wales, Australia, 1990	230 roundabouts and 60 controlled intersections	A 50% overall reduction in accidents at roundabouts with a 63% reduction in fatal accidents, a 45% reduction in injury accidents and a 40% reduction in damage-only accidents
Victoria, Australia, 1993	73 roundabouts	A 74% reduction in the casualty accident rate and a 68% reduction in pedestrian casualty accidents
Sydney, Australia, 1995	11 traffic signals and 13 roundabouts	A 71% reduction in crash frequencies at the roundabouts and a 35% at the signal intersections
Germany, 1991	2 single-lane and 8 multilane roundabouts	The total number of accidents at roundabouts seemed to be higher than at intersections, but the severity of these accidents was lower
Belgium, 2005	122 roundabouts	An average of 42% decrease in injury crashes and 48% decrease in serious accidents. The reduction varied by environment, in urban, suburban and open rural areas, the reductions rates were 15%, 46% and 50% respectively.

1.2.3.2 U.S. Experience

Thirteen roundabouts located in California, Florida, Maryland, and Nevada were analyzed in Flannery and Datta's research (Flannery and Datta 1996). Their before/after analysis was conducted through the crash data associated with six of the locations to determine if roundabouts are an effective alternative to stop and signalized intersections. The before/after time period was set at two years. Results showed that the reduction in the mean of crashes in the before and after periods was significant at a 99% level of confidence.

Taekratok compared the advantages and disadvantages of roundabouts, summarized safety implications, and discussed pedestrian and bicyclist considerations in the report for Oregon Department of Transportation (Taekratok 1998). Research before that time was reviewed.

A before-after study was completed by Insurance Institute for Highway Safety (IIHS) in places where traditional intersections including urban/rural single-lane stop controlled, urban multilane stop controlled, and urban signalized intersections were converted to roundabouts (Persaud et al. 2000). A highly significant 39% reduction for all crash severities combined for the twenty-four converted intersections was found. Reduction in injury collisions was 76% and reduction in fatal and incapacitating collisions was about 90%. Those figures are “consistent with numerous international studies” and considered as collision modification factors (CMF’s) for some crash prediction models.

An Empirical Bayes observational before-after study on crashes was conducted in the United States following the conversion of twenty-three intersections from stop sign and traffic signal control to modern roundabouts (Persaud et al. 2001). The twenty-three intersections included both single-lane and multilane designs in the urban sample. The rural sample consisted of only single-lane designs. The results indicated a significant 40% reduction in all crashes and an 80% reduction in injury crashes. The five rural single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes.

Maryland also conducted both a before/after study and a benefit/cost analysis for fifteen single-lane roundabouts (Maryland State Highway Administration 2002). The average annual crashes and crash severity were both found to decrease in the before-after study. The benefit/cost analysis indicated that for every dollar spent on these projects, there is a return of approximately eight dollars to be realized through crash reduction. Eight two-lane roundabouts were also studied. Only four of them have before records, and the comparison of the number of accidents and injuries before and after the installation of roundabouts found no particular trend.

The NCHRP Report 572, *Roundabouts in the United States* (Rodegerdts 2007), reported a before/after study that compared the performance of traditionally controlled intersections with roundabouts. It concluded that roundabouts improved both overall crash rates and injury crash rates in a wide range of settings (urban, suburban, and rural) and over previous forms of traffic control. Reductions were found when a stop or signal-controlled intersection was converted into a roundabout. All types of crashes were reduced by approximately 35.4% and injury crashes were reduced by 75.8%. The conversions from all-way stop control (AWSC) intersections were exceptions because the crash experience remained statistically unchanged. The research pointed out that single-lane roundabouts offered greater safety benefits than multilane roundabouts due to fewer points of conflict, and the safety performance of a multilane roundabout seemed sensitive to design details.

The NCHRP Report 672 (Rodegerdts et al. 2010) is still a main text on the safety evaluation of roundabout conversions. The before-after studies conducted by many researchers show similar results: roundabouts greatly reduce the number and the severity of crashes at intersections. Although specific values regarding crash reductions may be different because of variations in the way collisions are reported between different countries/places, the prevailing trends are quite obvious.

Table 1.4 U.S. experience in before-after safety analysis

City/Agency & Year	Roundabouts Studied	Findings
California, Florida, Maryland, and Nevada, 1998	6 single-lane urban roundabouts with speed lower than 45 mph that were converted from stop or signal controls	Significant reduction in crashes
Insurance Institute for Highway Safety (IIHS), 2000	24 single/ multilane rural/urban roundabouts that were converted from traditional controls	A highly significant 39% reduction for all crash severities. Reduction in injury collisions was 76% and reduction in fatal and incapacitating collisions was about 90%.
Multiple US cities, 2001	Conversion of 23 intersections from stop sign and traffic signal control to modern roundabouts, including both single-lane and multilane designs in the urban sample and only single-lane designs in the rural sample	A significant 40% reduction in all crashes and an 80% reduction in injury crashes. Of them, the five rural single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes.
Maryland, 2002	15 single-lane roundabouts	The benefit/cost analysis indicated that for every dollar spent on these projects there is a return of approximately eight dollars to be realized through crash reduction. Two-lane roundabouts in this study showed no certain trend in crash reduction rates.
Multiple US cities (NCHRP Report 572 & 672), 2007	55 roundabouts of all situations	All types of crashes are reduced approximately by 35.4% and injury crashes are reduced by 75.8%.

1.2.4 Crash Predicting Models

Besides a before/after study, another way to evaluate roundabouts' safety is to use crash predicting models. Two crash predicting models proposed by the NCHRP Report 572 and further discussed by the NCHRP Report 672 are the intersection-level crash prediction model and the approach-level crash prediction model. Prediction models are preferred over before/after studies in Report 572 because a comprehensive set of crash modification factors required by the latter is not always available.

According to Angelastro's review (2011), the majority of the research involving crash prediction at roundabouts has been conducted in Europe, Australia, and Sweden. Limited research on this aspect has been conducted in the United States. The majority of the research regarding American roundabouts consists of before and after crash analyses that establish the effectiveness of roundabouts in reducing crashes (Angelastro 2011). Angelastro studied the relationship between available driver sight distance and driver speeds and crash rates. The data contained twenty-six single-lane roundabouts in the United States. Vehicle speeds and crash rates were found to be related to driver sight distance through regression models. Additionally, the author developed a crash prediction model at roundabouts based on American roundabouts.

Chapter five of the FHWA's Roundabouts Informational Guide (Robinson and Rodegerdts 2000) also describes several roundabout safety models that may be applied to the United States, including the Maycock and Hall model developed based on data from UK roundabouts (Maycock and Hall 1984); FHWA's four leg roundabout crash prediction models for America; Arndt's model for Australia (Arndt and Troutbeck 1998); Brude and Larsson's Swedish model (Brude 2000); and Guichet's French model. These models can be used to predict the general number of accidents at roundabouts (Guichet 1997).

Arndt’s collision prediction model (Arndt and Troutbeck 1998) uses non-linear regression equations based on driver behaviors and other significant predictors of crashes to model different types of crashes, including single-vehicle, approach, entry-circulating, exit-circulating, sideswipe, and other. Driver behaviors in this research were reflected by the 85th percentile speeds on each geometric element and the location of vehicle paths through the roundabout.

Apart from the direct prediction models, collisions can also be predicted on the basis of collision modification factors (CMF’s) using the results of before/after studies of intersections converted to roundabouts (Weber 2007). Al-ghirbal developed a prediction model in the master thesis for severe accidents at roundabouts by utilizing the Artificial Neural Network technique (an artificial intelligence approach) to relate the available geometric traffic characteristics with the accident records (Al-Ghirbal 2005).

1.2.5 Safety-Related Research on the High-Speed/Rural/Suburban/Multilane Roundabouts

1.2.5.1 High-Speed/Rural/Suburban

(1) International Experience

A comprehensive study of 12,000 roundabouts throughout France was conducted in 1997 (Guichet 1997). There were very few accidents that occurred within the one year study period, totaling 1,339 accidents. Comparisons were made between the safety performance of rural traditional controlled intersections and roundabouts. Roundabouts were reported to have an averaged 38 fatal or serious injuries out of every 100 accidents, and traditional intersections had an average of 55 out of 100. Roundabouts were also found to be safer in urban areas than in rural areas.

Inadequate signing (location, appropriateness, size, and quantity), which may be relevant to rural environments, has been reported as the reason for high approaching speed and driver confusion at roundabouts in a review of fifty safety audit reports of roundabouts in New Zealand (Traffic Design Group of Lower Hutt 2000).

Another New Zealand research project investigated the design and operational guidelines required for the safe application of roundabouts in rural environments (Thomas and Nicholson 2003). Design issues including design speed, sight distance, roundabout layout, etc., were discussed. They indicated that a rural environment may induce a lower level of alertness, so rural roundabouts require supplementary measures on the approach to warn drivers so they can negotiate it safely.

Further research in New Zealand (Turner and Roozenburg 2006) revealed that roundabouts with approaching speeds higher than 44 mph had 35% more injury crashes than those with lower speeds. It is unclear if these roundabouts with high-speed approaches represented both rural and urban environments and both single-lane and multilane roundabouts.

A study on conversion to roundabouts in Belgium (Antoine 2005) showed an average 42% decrease in injury crashes and 48% decrease in serious crashes in all settings. Roundabouts in rural open country environments, which usually have high speed approaches, had a 50% crash reduction. Roundabouts in suburban locations had a crash reduction of 46%

and those in urban areas a reduction of 15%.

Steel et al. (Steel et al. 2007) addressed the suitability of installing roundabouts in Alberta's rural areas with respect to improving the overall safety performance.

(2) U.S. Experience

Flannery and Elefteriadou (Flannery and Elefteriadou 1999) addressed the safety performance of single roundabouts in the United States. They found that the overwhelming majority of the crashes that occurred at high speed rural roundabouts were caused by inadequate speed reduction alignment on the inbound approaches. About 45% of the single vehicle crashes at the studied roundabouts were "loss of control" crashes. It appeared that the vehicles were traveling at excessive speeds when approaching the roundabout.

Myers (1999) studied crashes at five rural roundabouts with high-speed approaches in Maryland by analyzing data gathered three years before and three years after the installation of the roundabouts. A before-after analysis showed that the average crash rate at these five intersections reduced by 59% and injury or serious crashes were reduced by 80%.

As mentioned earlier, Persaud et al. (2001) conducted an EB observational before-after study on crashes when twenty-three intersections were converted from stop sign and traffic signal control to modern roundabouts. Results indicated a 40% reduction in all crashes and an 80% reduction in injury crashes. Of all the intersections, the five rural single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes, which were both higher than the average of all settings.

The New York State Department of Transportation (NYSDOT) expanded the IIHS study to 33 roundabouts in 2003 by conducting surveys among 50 state DOTs as well as many local municipalities and consultants (Robinson et al. 2004). A before/after safety model was also built. The results showed the total collisions of all types were reduced by 47%, and injury collisions were reduced by 72% (Jacquemart 2004). The study also showed that multilane roundabouts are more prone to property damage only (PDO) collisions. However, multilane roundabouts were not shown to be more prone to injury collisions.

As speed may be crucial to rural roundabout safety, eleven single-lane roundabouts in potentially high-speed environments were selected from several U.S. states to study the relationship between roundabout geometric design elements and driving speeds (Johnson and Flannery 2005).

Richie and Lenters (2005) compared the performance of roundabouts and traffic signals with high-speed approaches (45+ mph). They reported that roundabouts out-perform their signalized counterparts by nearly a 50% reduction in injury and fatal crashes; one specific site demonstrated an 80% reduction in expected crashes after conversion to roundabouts.

Also as mentioned earlier, Rodegerdts (2007) conducted an EB before-after study comparing the performance of traditionally controlled intersections with roundabouts. The study concluded that roundabouts reduced both overall crash rates and injury crash rates in a wide range of settings, including urban, suburban, and rural. All types of crashes were reduced by approximately 35.4% and injury crashes were reduced by 75.8%. For the nine rural roundabouts studied in the report, all of which were converted from TWSC intersections, the total crash reduction was 71.5 % and injury crashes were reduced by 87.3 %. For the 24 suburban roundabouts converted from signalized or TWSC intersections, the total crash reduction and injury crashes reduction were about 42% and 68%, respectively.

In Maryland, crash reports of 149 crashes at twenty-nine single-lane roundabouts and 134 crashes at nine double-lane roundabouts were reviewed (Mandavilli et al. 2009). Several of the roundabouts in the study were rural roundabouts on high-speed roadways; about three quarters of all reported collisions were at roundabout entrances and a high approach speed was an important factor in crashes.

When considering factors affecting safety at roundabouts, another concern besides high vehicle speed is the difference in speeds between entering and circulating traffic, and between circulating and exiting traffic. Either a very large or very small difference between the speed of the entering traffic and the speed of the circulating traffic creates potential for a crash (Angelastro 2011).

Isebrands (2012) conducted a study on rural roundabouts with high-speed approches. A before-after crash analysis using a negative binomail regression model and a before-after EB estimation were both conducted and showed consistent results. The negative binomial regression showed that total crashes were reduced by 63% and injury crashes by 88% at nineteen rural roundabouts with high speed approaches. The before-after EB estimation showed reductions of 67% in total crashes and 87% in injury crashes.

An evaluation of 24 roundabouts was conducted in Wisconsin (Qin et al. 2013). The EB before-after analysis showed an overall reduction of 9.2% in total crashes in all locations and a 52% reduction of fatal and injury crashes. Eight of the 24 roundabouts were identified as rural; these roundabouts experienced reductions of 45% in total crashes and 56% in fatal and injury crashes. The study included 11 roundabouts with posted speed limits of 45 mph or greater. These roundabouts experienced reductions of 34% in total crashes and 49% in fatal and injury crashes.

Although almost all of the roundabout guidance indicated significant benefits of roundabouts at rural high-speed locations, the application of this type of roundabout is one of the slowest to emerge in the United States. The Maryland State Highway Administration constructed their first roundabouts in the mid-1990s, several of which were rural applications, followed by the Kansas Department of Transportation in 2001, and the Washington State Department of Transportation in 2004. To date, the Wisconsin Department of Transportation has constructed the most rural roundabouts starting from 2005 (Isebrands 2011). As the number of modern roundabouts grows rapidly in the United States, new data is more available for U.S.-specific research.

1.2.5.2 Multilane

(1) International Experience

Hagring et al. constructed a multilane roundabout capacity model based on a two-lane roundabout in Copenhagen, Denmark (Hagring et al. 2003). The primary objective was to evaluate the need for more complex capacity models than currently exist in order to properly represent driver gap-acceptance behavior at multilane roundabouts.

Yin and Qiu (2011) compared the operation performance of a two-lane roundabout at the intersection of two rural arterial highways in Alberta, Canada based on the analysis results from two different types of software. One is a macroscopic traffic analysis software (SIDRA) and the other is a microscopic simulation package (VISSIM). The results showed that there was no significant difference for the delays predicted by the two types of software at medium-to-high traffic flow rates and at all left-turn proportion levels. Queue length predicted by VISSIM was longer than those predicted by SIDRA. Good correlation existed between predicted delays and queue length. They also mentioned roundabout capacity could be estimated by a delay curve obtained from the method presented in their study.

Taylor (2012) evaluated the capacity of two-lane signalized roundabouts under saturated conditions in Australia. A signalized roundabout using the standard phasing technique is a viable option for replacing an existing un-signalized roundabout that is failing to cater for capacities, especially in cases where the intersection has a high percentage of right turn movements, pedestrian flows, and is located in an urban environment.

(2) U.S. Experience

NCHRP 3-65 (Rodegerdts 2004) and the final report of NCHRP Report 572 (Rodegerdts 2007) provided a before/after analysis for multilane roundabouts. They found that conversion from a signalized intersection to a multilane roundabout (four sites, suburban settings) yielded a 67% reduction in all crashes. Only two crashes involved injury in the 98 crashes reported in the after period. Conversion from a two-way stop to a multilane roundabout (11 sites, urban/suburban settings) yielded an 18% reduction in all crashes and a 72% reduction in injury crashes. Of the 272 crashes in the after period, 13 involved injuries

(Weber 2007).

Lee’s research project examined the performance of two multilane roundabouts in Anchorage, which were the first multilane roundabouts constructed in Alaska in 2004 (Lee 2010). Results showed that extended queues observed at the roundabouts were due to unbalanced flow patterns that caused high circulating flow in front of one roundabout. The high circulating flow resulted in low-capacity, high-delay queue values.

Xiao Qin et al. conducted a roundabout crash research based on Wisconsin roundabouts (Qin et al. 2011). They evaluated roundabouts’ performance in varying situations by analyzing crash trends and patterns. They also developed crash prediction models, which would help in quantifying roundabout safety, especially when selecting which locations to be converted to roundabouts. Forty-one roundabouts with varied configurations, layouts, design features, previous traffic control, and traffic volumes were selected as the research sample. Eighteen of them were single-lane roundabouts and twenty-three were multilane roundabouts.

Multilane roundabouts have some of the same safety performance characteristics as single-lane roundabouts. However, multilane roundabouts introduce additional conflicts due to the presence of additional entry lanes and the accompanying need to provide wider circulatory and exit roadways. Crash frequencies increase with the number of circulating lanes (Rodegerdts et al. 2010). Although the number of conflicts increases at multilane roundabouts when compared to single-lane roundabouts, the overall severity (and often number) of conflicts is typically less than other intersection alternatives (Rodegerdts et al. 2010).

Table 1.5 is a summary of the high-speed rural/suburban roundabouts or multilane roundabouts discussed in this subsection (1.2.5).

Table 1.5 Safety research on high-speed/rural/suburban or multilane roundabouts

International Experience	Roundabouts	Major Findings
France (Guichet 1997)	Rural	Roundabouts have less severe injuries than that of traditional intersections. Roundabouts were also found to be safer in urban areas than in rural areas.
New Zealand (Traffic Design Group of Lower Hutt 2000)	Rural	Inadequate signing in rural area may be a reason for high approaching speed and driver confusion.
New Zealand (Thomas and Nicholson 2003)	Rural	Lower level of alertness in rural roundabouts requires supplementary measures on the approach to warn drivers in advance.
New Zealand (Turner & Roozenburg 2006)	High-speed (45mph+)	High-speed roundabouts have more injury crashes than those with lower speeds.
Belgium (Antoine 2005)	Including rural, suburban	An average of 42% decrease in injury crashes and 48% decrease in serious crashes in all settings. Rural, suburban and urban roundabouts had a 50%, 46% and 15% crash reductions, respectively.
Albert (Steel et al. 2007)	Rural	Roundabouts improve the overall safety performance.
Denmark (Hagring et al. 2003)	Multilane	Developed a multilane roundabout capacity model that reflected driver gap-acceptance behaviors
Alberta, Canada (Yin and Qiu 2011)	Two-lane, rural	Compared the operational performance analysis results of two different software packages.
Australia (Taylor 2012)	Two lane, signalized	A signalized roundabout using the standard phasing technique is a viable option in replacing an existing un-signalized roundabout.
U.S. Experience	**Roundabouts**	**Major Findings**
Multiple states (Flannery and Elefteriadou 1999)	Rural, single-lane, high-speed	Inadequate speed reduction might be an important reason for crashes at high-speed rural roundabouts.
Maryland (Myers 1999)	Rural, high-speed	Total accidents were reduced by 59% and injury accidents were reduced by 80%.
Multiple states (Persaud et al. 2001)	Including rural	The five rural single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes.
Multiple states (Eisenman et al. 2004)	Including multilane	Total collisions were reduced by 47%, and injury collisions were reduced by 72%. Multilane roundabouts are more prone to property damage only (PDO) collisions.
Multiple states (Johnson and Flannery 2005)	Rural, high-speed, single-lane	Simple linear regression equations were developed to estimate the differential in speeds.
Multiple states (Richie	High-speed	Roundabouts out-performing their signalized

and Lenters 2005)	(45mph+)	counterparts by nearly a 50% reduction in injury and fatal crashes.
Multiple states (Rodegerdts 2007)	Including rural	The included 9 rural roundabouts that were converted from TWSC intersections had a total crash reduction of 71.5 % and injury crash reduction of 87.3 %. The included 24 suburban roundabouts that were converted from signalized or TWSC intersections had a total crash reduction of 42% and an injury crashes reduction of 68%.
Maryland (Mandavilli et al. 2009)	Single-lane and multilane, some are in rural	High approach speeds were pointed out as an important driver crash factor.
Multiple states (Isebrands 2009)	High-speed (40+ mph), rural	Total crashes were significantly reduced by 62% - 68% and injury crashes by 85% - 88%. Angle crashes were reduced by 83%.
Wisconsin (Qin et al. 2011)	Including rural and high-speed (45+)	Eight of the 24 roundabouts were identified as rural; they experienced reductions of 45% in total and 56% in fatal and injury crashes. A total of 11 roundabouts had posted speed limit of 45 mph or greater. These roundabouts experienced reductions of 34% in total and 49% in fatal and injury crashes.
NCHRP Report (Rodegerdts 2004, 2007)	Multilane, urban/suburban	67% reduction in all crashes after converting from a signalized intersection to a multilane roundabouts (4 sites, suburban); conversion from a two-way stop to a multilane roundabout (11 sites, urban/suburban) yielded an 18% reduction in all crashes and a 72% reduction in injury crashes.
Alaska (Lee 2010)	multilane	Unbalanced flow patterns cause high circulating flow which results in low-capacity, high-delay queue values.
Wisconsin (Qin et al. 2011)	Including multilane	A total of 23 roundabouts were multilane.
Multiple states (Rodegerdts et al. 2010)	Including multilane	Crash frequencies increase with the number of circulating lanes. But the overall severity (and often number) of conflicts is typically less than other intersection alternatives.

1.2.6 Design Issues for Rural High-Speed Multilane Roundabouts

1.2.6.1 Design Speed

Several studies have investigated the controlling speed through the roundabout. The guideline as a desirable maximum entry speed for multilane roundabouts is 25 to 30 mph (Rodegerdts et al. 2010). Since the 85th percentile speed in rural areas is much higher than the desirable maximum entry speed, the negotiating speed of roundabouts should be carefully taken into consideration (Singh et al. 2011) (Thomas and Nicholson 2003). The speed of vehicles negotiating roundabouts is dependent upon the geometry of the facility. The entry path radius should not be significantly greater than the circulatory radius in order to maintain an appropriate speed reduction rate when dealing with the secondary curve (Thomas and Nicholson 2003).

1.2.6.2 Sight Distance

In rural areas, the speed of the vehicle is normally high, so providing safe sight distance is crucial. The sight distance of the roundabout depends on the approach speed and negotiating speed (Turner et al. 2009). One study investigated driver sight distance as an independent variable to predict passenger vehicle speed and vehicle crash rates at 26 single-lane roundabouts. Three regression models indicated that driver sight distance is a statistically significant predictor of approach speed, negotiating speed, and the difference between approach and negotiating speed (Angelastro 2011). The research showed that vehicle speeds and crash rates at modern roundabouts in the United States are related to driver sight distance. Meanwhile, sight distances provided must be equal to all approaches in the roundabout. If one approach leg has better sight distance than the others, it allows vehicles on that leg to approach the roundabout at much faster speeds than vehicles at the other entries (Thomas and Nicholson 2003).

The approach to the roundabout should be aligned so that the driver has a good view of the splitter island, the central island, and preferably, the circulating roadway. There are two types of sight distance: stopping sight distance and gap acceptance sight distance. Adequate approach stopping sight distance should be provided to the yield line (Rodegerdts et al. 2010). In terms of gap acceptance sight distance, there are two geometric aspects: sight distance external to the inscribed circle for other vehicles approaching the roundabout in the roadway to the left, and sight distance within the inscribed circle for vehicles already in the circulating roadway (Florida Department of Transportation 1995). Figures 1 and 2 below represent both stopping and gap acceptance sight distance.

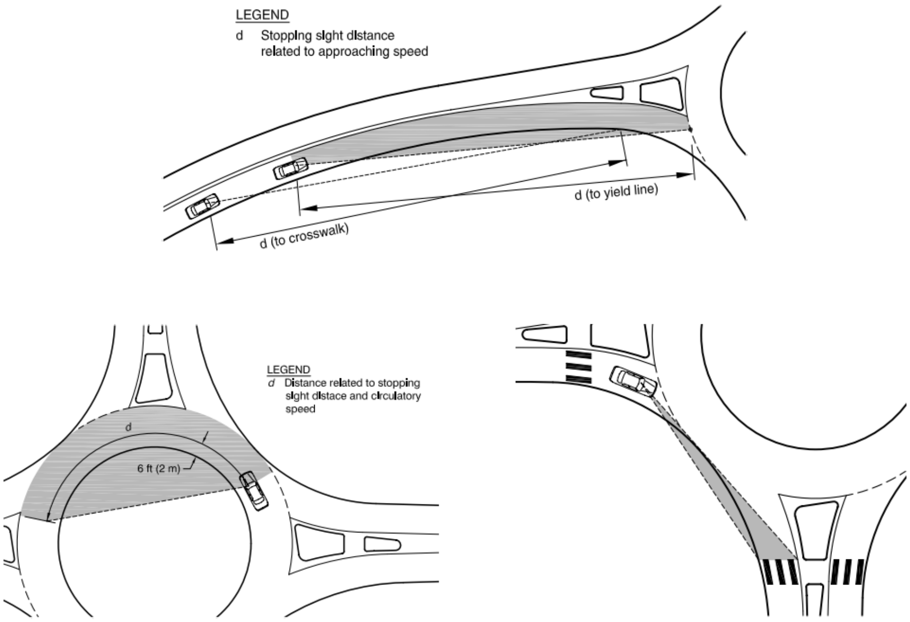

Figure 1.1 Stopping sight distance (Source: Technical Summary of Roundabouts FHWA)

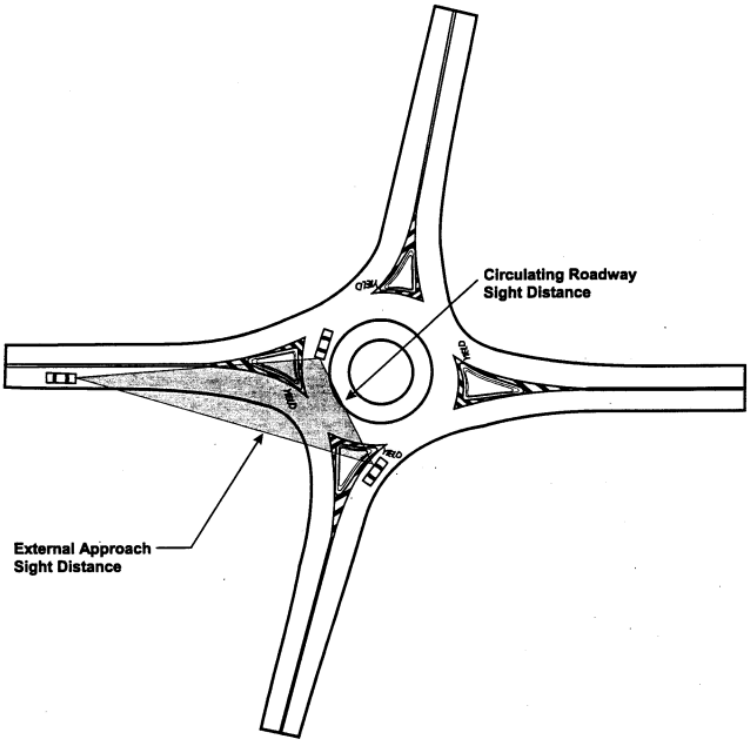

Figure 1.2 Gap acceptance sight distance (Source: Florida Roundabout Guide 1995)

1.2.6.3 Roundabout Layout

A well-designed geometric layout enables safety optimization in roundabouts. There are several issues that refer to the roundabout layout.

(1) Entry Path Deflection

First, it is crucial to provide proper deflection on each approach, and adequate deflection to control traffic speed through the roundabout should be emphasized (Bramwell 1986; Montella 2007; Davis et al. 2003). In order to slow vehicles down before they meet the circulating traffic stream, sufficient deflection is required. If the entry path is obviously too tangential, the arriving vehicles tend to be too fast right before merging with the circulatory traffic stream. On the other hand, if the entry path curvature is too tight as with perpendicular or sharply curved entries, there is a rise in single vehicle crashes (LENTERS 2004). Figures below show the examples of a roundabout having too much deflection (fig. 1.3) and insufficient deflection (fig. 1.4). When it comes to the size of the central island, the bigger central island can ensure that drivers cannot take a straight line through the roundabout when the deflection angle is too small (LENTERS 2004). However, several studies have found that the larger the traffic island, the higher the accident rate becomes (Elvik 2003).

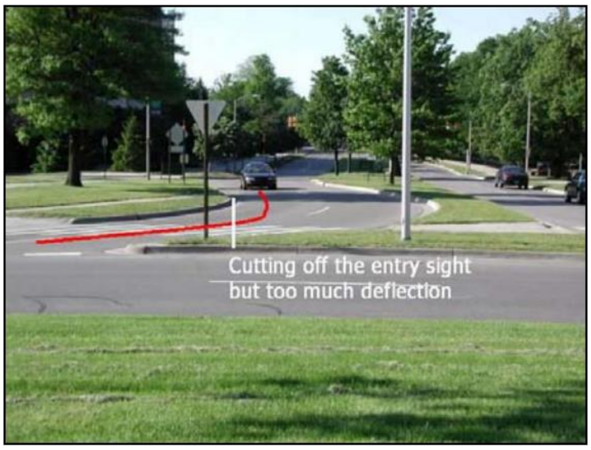

Figure 1.3 Over-deflected entry

Figure 1.4 Insufficient entry path (Source: Safety Auditing Roundabouts 2004)

(2) Entry width

Entry width is a dominant factor in both the capacity and safety of a roundabout. The widening of entries leads to an increased capacity (Highway Capacity Manual 2010), but also an increase in accidents since wider entry width exposes pedestrians to traffic for a longer duration (LENTERS 2004). There are two options when additional entry capacity is needed (Rodegerdts et al. 2010). One is adding a full lane upstream of the roundabout and maintaining parallel lanes through the entry geometry, while the other is widening the approach gradually (flaring) through the entry geometry. Figures 1.5 and 1.6 below show the two options.

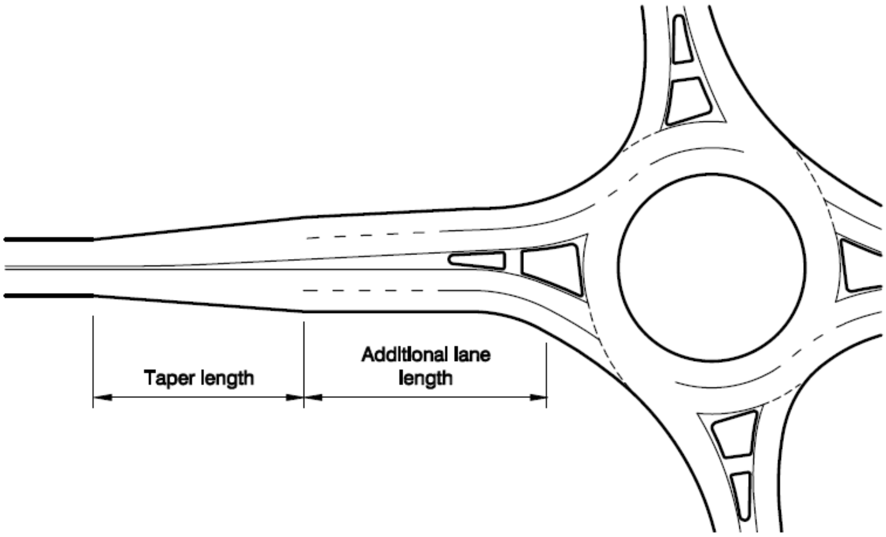

Figure 1.5 Approaches widening by adding a full lane (Source: Roundabouts Informational Guide 2000)

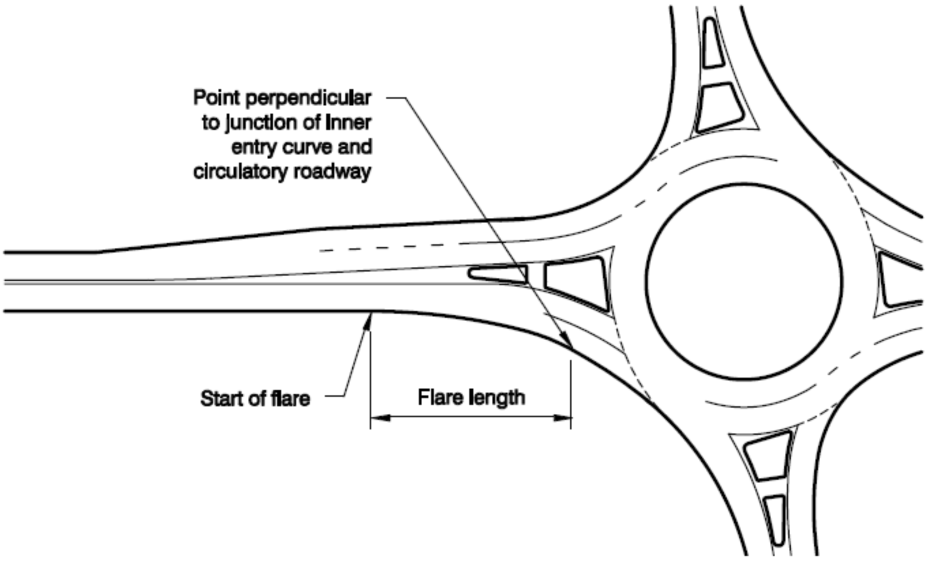

Figure 1.6 Approaches widening by entry flaring (Source: Roundabouts Informational Guide 2000)

(3) Vehicular Path Overlap

Path overlap occurs when the natural paths of vehicles in adjacent lanes overlap or cross one another. It occurs most commonly at entries, where the geometry of the right-hand lane tends to lead vehicles into the left-hand circulatory lane (Kansas Department of Transportation 2003). Figure 1.7 below shows vehicular path overlap, and the preferred design technique to avoid the problem for multilane entries is illustrated in figure 1.8. The design consists of a small-radius entry curve set back from the edge of the circulatory roadway. A short section of tangent is provided between the entry curve and the circulatory roadway to ensure vehicles are directed into the proper circulatory lane at the entrance line (Kansas Department of Transportation 2003).

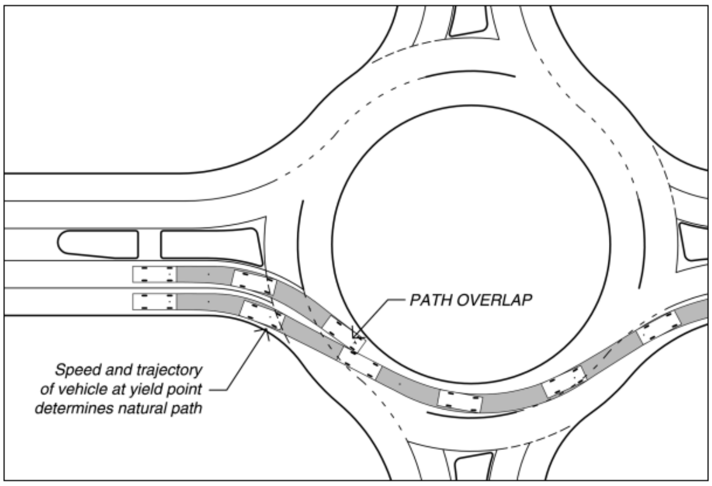

Figure 1.7 Vehicle path overlap (Source: Technical Summary of Roundabouts FHWA)

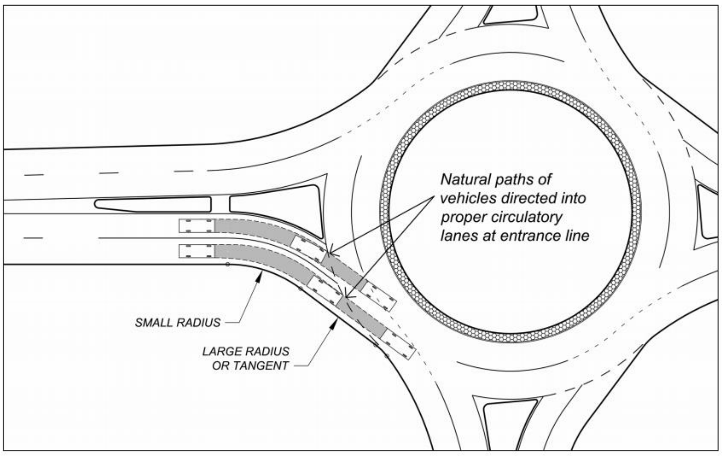

Figure 1.8 Design technique to avoid path overlap at entry (Source: Technical Summary of Roundabouts FHWA)

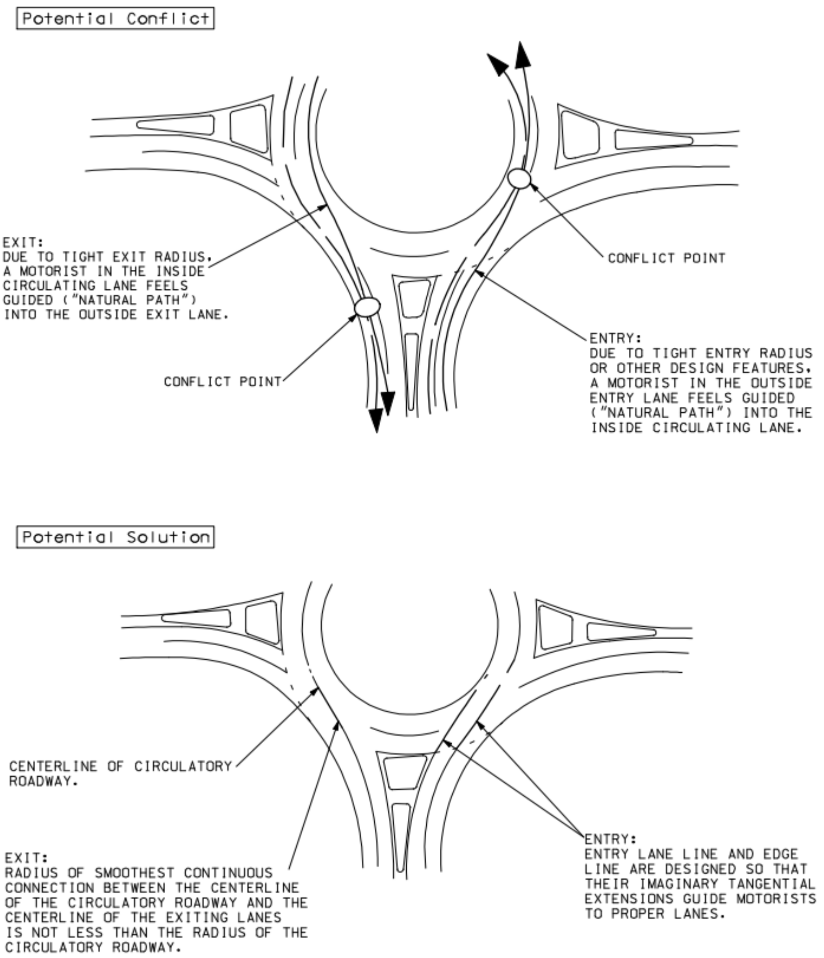

Figure 1.9 Vehicle path overlap at two-lane roundabouts (Source: Technical Summary of Roundabouts FHWA)

(4) Recognition of Central Island and Splitter Island

The results of an unclear or ambiguous central island or splitter island result in control crashes of drivers who are unfamiliar with negotiating roundabouts (LENTERS 2004). Maintaining the largest splitter island possible and using vertical curb face is necessary to aid in deflecting traffic on the approach to a roundabout entry, as well as providing an adequate refuge for pedestrians. Also, curb, gutter, or splitter islands help drivers negotiate the roundabout safely by providing good deflection and speed adjustment at the entry. In multilane roundabouts, usage of splitter islands could be more emphasized because path overlap may happen (City of Colorado Springs 2005)

(5) Signs and Markings

Inappropriate or poorly designed signs and markings cause drivers to have guidance or navigational mistakes while negotiating roundabouts (Lord et al. 2007). Such driving mistakes usually do not cause serious crashes, but those errors can direct drivers in a wrong way in a multilane roundabout where frequent circulatory lane changes exist (Kinzel 2003). Traffic signs and road markings should be an essential element of the design procedures for roundabouts because lane designation may be closely related to entry and exit design and splitter layout (LENTERS 2004).

1.2.6.4 Other Design Issues

(1) Road Markings

Yellow bar markings on the approach to roundabouts is one option to make the vehicle wary and slow down before negotiating the roundabout (Kinzel 2003). These markings may be particularly suitable on rural roundabout approaches where background visual stimuli are lacking (LENTERS 2004).

(2) Lighting

Illuminating the roundabout should be given considerable attention since positive contrast lighting and vertical luminance is essential for pedestrian and signage visibility (LENTERS 2004). There are several findings (Lutkevich et al. 2004): (a) in the roundabout area, lighting should be provided at all roundabouts, including those in rural locations; (b) approach lighting is important for providing good visibility throughout the roundabout; and (c) a minimum level of vertical illumination at pedestrian crosswalks is recommended. However, in rural conditions, illumination is recommended but not mandatory. If the roundabout is without light, it should be well signed and marked so that it can be correctly perceived day and night (American Association of State Highway and Transportation Officials [AASHTO] 1985). In general, the use of reflective pavement markers and retro-reflective signs should be used when lighting cannot be installed in a cost-effective manner (Robinson and Rodegerdts 2000).

1.2.7 Safety of Pedestrians and Cyclists at Roundabouts

Roundabouts have their own advantages and disadvantages over pedestrians and cyclists when compared to conventional intersections. International and U.S. research about pedestrians and cyclists safety at roundabouts is reviewed.

1.2.7.1 International Experience

A study in the Netherlands in 1993 examined collision experiences at 181 intersections converted to roundabouts. Pedestrian collisions dropped 73% and pedestrian casualties dropped 89%. A Swedish study concluded that single-lane roundabouts are very safe for pedestrians, at about a 78% reduction in injuries, and that multilane roundabouts are about as safe as other intersections (Weber 2007).

Cyclists at roundabouts have about the same number of conflicts as drivers or pedestrians since they have the option to travel as a vehicle or pedestrian. However, because cyclists usually ride on the right side, they may face additional conflicts due to overlapping paths with motor vehicles when travelling through or exiting a roundabout as a vehicle, which is a typical case at multilane roundabouts. As to bicyclist safety at roundabouts in North America, there is even less research than that pedestrian safety. A study conducted in western France at 1,238 signalized intersections and 179 roundabouts found that in proportion to the total number of crashes, two-wheeled vehicles were involved in crashes more often at roundabouts (+16%), but were involved in injury crashes more often at signalized intersections (+77%). A study in Sweden at 72 locations concluded that at single-lane roundabouts bicyclists were involved in 20% fewer injury collisions than at other intersections. However, at multilane roundabouts they were twice as likely to be involved in light injury crashes. Studies in the Netherlands showed that roundabouts decreased bicyclist injuries by 44% to 73%. Separate bicycle paths were found to be the safest, while a bicycle lane within the circulatory road was found to be the least safe (Weber 2007).

In Sweden, nearly 1,000 roundabouts are in operation. Three separate national research studies were conducted to determine the safety of roundabouts, including a speed analysis study in 536 roundabouts, a safety study of cyclists and pedestrians in 72 roundabouts, and a motorist safety study in 182 roundabouts. Roundabouts are found to have provided equal or better pedestrian safety than their conventional intersection counterparts. Multilane roundabouts have more cyclist accidents (six times) than single lane roundabouts, although this was likely due to the volume difference. They also found that central island diameters greater than 10 meters were safer than those smaller than 10 meters (Brude 2000).

Daniels et al. (Daniels et al. 2008) conducted a roundabout study on bicyclists in Flanders-Belgium. They included both single- and multilane roundabouts in their sample. The before/after study reveals that roundabouts increased injury collisions involving bicyclists by 27% and severe injury collisions by up to 46%. In 2009, they launched another study to determine if bicycle facilities within roundabouts have any effect on bicyclist safety. They unexpectedly found that roundabouts with cycle lanes increased bicycle injury collisions significantly (as opposed to roundabouts with separate cycle paths, grade separated paths, or no bicycle facilities) and suggested that a clear distinction should be made between roundabouts with cycle lanes and those with other types of facilities.

1.2.7.2 USA Experience

Baranowski and Waddell (Baranowski and Waddell 1997) discussed pedestrian and vehicle crashes and design practices at roundabouts in Australia, France, Great Britain, and the USA. A significant reduction in pedestrian accidents was found after roundabouts were installed. Two newly constructed roundabouts in the USA at that time that used alternate design methods to reduce travel speeds were compared, both of which were two-lane roundabouts. One alternative, the tight-exit design, was analyzed, and results showed it has little benefit for pedestrians by reducing speed, and in some cases may endanger them by limiting sight-distance for drivers.

The IIHS study (Persaud et al. 2000) shows that none of the U.S. multilane roundabouts under their study have had a single pedestrian crash after the installation, even though there were two crashes during the before period at these sites.

As indicated in the FHWA guide (Robinson and Rodegerdts 2000), the risk of pedestrian-vehicle crashes increase if there are multiple lanes of exiting or entering traffic as opposed to a single lane. Bicyclists may conflict with vehicles in the same way as pedestrians if cyclists are using bike lanes or sidewalks, and may go through the same conflicts with vehicles if cyclists choose to ride on the roadway.

A study conducted in 2002 in Park City, Vail, West Vail, and Avon, Colorado, showed two pedestrian crashes prior to the roundabouts operating with over 164 million vehicle movements, compared to one pedestrian crash with roundabouts experiencing over 282 million vehicle movements (Weber 2007).

Furtado studied the accommodation of vulnerable road users in roundabout design (Furtado 2004). The author mentioned that given a properly designed roundabout facility, the vehicular and pedestrian safety at roundabouts is almost always improved when compared to conventional intersections. Cyclist safety is somewhat mixed. Due to the elimination of conflict points at roundabouts and the lower speed differentials compared to conventional intersections, accident severity for all users is often significantly reduced when collisions occur, although frequency may increase.

Arnold et al. (Arnold et al. 2010) examined the safety and demand issues for pedestrians and bicyclists at multilane roundabouts. Literature reviews, case studies, in-field counts and surveys, focus groups, and video analyses were conducted. Bicyclists and pedestrians did not show an actual preference for using traditional intersections, but 25% of bicyclists and 14% of pedestrians surveyed stated that they would change their route to avoid multilane roundabouts. According to self-reports, bicyclists were more likely than pedestrians to report feeling uncomfortable traveling through the multilane roundabout. When having a choice, pedestrians equally prefer signalized intersections and roundabouts, but bicyclists prefer signalized intersections and not roundabouts. Observational studies also found that pedestrians are more likely to hesitate at multilane roundabouts than at other types of intersections (Harkey and Carter 1982) and pedestrians experience longer waiting times and more risky crossings at multilane roundabouts (Ashmead et al. 2005).

1.2.8 Some Other Significant Safety Studies on Roundabouts

The FHWA roundabout informational guide identifies that the several features that have the most crash problems are inadequate entry deflection, long straight sections of circulatory roadway, and sharp turns into exits (Robinson and Rodegerdts 2000). A number of safety studies have been conducted to evaluate the performance of U.S. roundabouts since the publication of the FHWA Roundabout Guide.

Chapter 5 of the Kansas Roundabout Guide discusses roundabout safety (Kansas Department of Transportation 2003). Typical crash patterns at roundabouts are identified based on data collected from countries outside of the United States and then transferred to the United States. Failure to yield at entry, a single-vehicle running off the circulatory roadway, single vehicle loss of control at entry, and rear-end at entry are the top four types of crashes in all countries researched.

The ITE Transportation Safety Council developed an informational report that identified safety benefits of modern roundabouts, as well as specific design practices and features that enhance safety at roundabouts (Isebrands and Retting 2008). It provides a synthesis of available research, including international experience. It also includes a summary of available information regarding geometric design features, traffic control devices, and lighting and landscaping elements to further enhance safety at roundabouts.

In 2006, Ourston Roundabouts Canada completed a “Synthesis of North American Roundabout Practice” for TAC. Chapter 5 of this synthesis (Weber 2007) presents the results of roundabout safety. The reason that roundabouts have a high potential for safety was explained. Many studies undertaken in North America and other countries were studied to evaluate the effects of roundabouts on the safety of motorists, pedestrians, and bicyclists. A web-based survey was conducted, aiming to find measures that maximize safety potential. These measures may vary depending on whether the roundabouts are single-lane or multilane and whether there are any high-speed approaches.

Chapter 2 Survey of State and Local Transportation Agencies

2. 1 Objective

A telephone survey was conducted with the objective of collecting information from various state and local transportation agencies across the US regarding safety issues experienced with roundabouts including measures for mitigation of those issues. However, before the survey, a review of news media on the Internet was undertaken to identify public concerns with roundabouts and remedial measures undertaken by transportation agencies.

2.2 Identification of Potential Issues from News Media

The research team searched news articles on the Internet and found 51 news articles related to public concerns on roundabouts across the states. While the news articles were written from a variety of perspectives, the major public concerns were as follows:

(1) Driver confusion about newly constructed roundabout,

(2) Drivers lack of knowledge of roundabout negotiation rules,

(3) Small size and narrow lanes for some of the roundabouts,

(4) Unclear signage at or in proximity of roundabouts,

(5) Difficulty for large vehicles to negotiate roundabouts,

(6) Lack of advance warning signs regarding roundabout presence,

(7) Limited access to nearby businesses during roundabout construction,

(8) Cost concerns regarding roundabouts in comparison to signalized intersections,

(9) Confusion amongst drivers between modern roundabouts and old traffic circles,

(10) Pedestrian and bicyclist safety at roundabouts, and

(11) Complaints about multilane roundabouts.

From the review of the news articles a few general characteristics of “problematic” roundabouts emerged. These included:

(1) Design flaws, including curves that were too subtle, allowing drivers to travel through at a fairly high speed,

(2) Confusing signage, and

(3) Dark or poorly marked roundabouts.

Mitigation strategies mentioned in these news articles included roundabout realignment, reconstruction, or modifications; installation of more flags and signage; and more education for the users and alterations to landscape for improved visibility.

2.3 Survey Process

A sampling frame was established that included baseline contacts for various transportation agencies. The baseline contacts served as points of “first contact” with an agency. The nature and objectives of the survey were explained to these first contacts and they were asked if they were the most appropriate person in that agency to provide response to the telephone survey; if not, they were asked to provide the contact information for the most relevant person that could be interviewed. Telephonic and/or email contact with respondents to the survey began on July 11th, 2014 and ended August 29th, 2014; most of the respondents were traffic engineers who provided responses on behalf of their respective agencies. In some instances respondents were contacted through email when telephone messages were not returned or when email was the only contact information. Email reminders were sent after approximately one week following the initial email in cases where no response was received.

Appendix A presents the survey questionnaire. Upon completion of the survey, the respondent’s phone number was recorded in an Excel spreadsheet along with his/her responses. A total of 25 surveys with different state and local agencies were successfully completed.

2.4 Survey Outcomes

Figure 2.1 shows the states in which a transportation agency was surveyed. Twelve out of the 25 responding agencies acknowledged experiencing safety issues after roundabouts were constructed. In total, 20 roundabouts were mentioned by these 12 responding agencies.

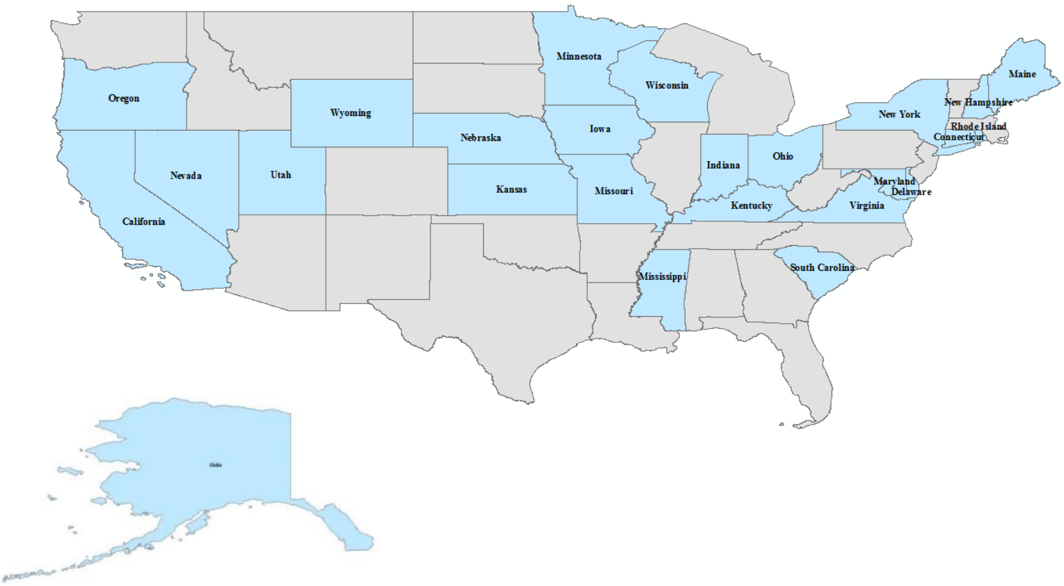

Figure 2.1 Map of States from Where a Transportation Agency Responded

The 12 agencies that reported safety issues were Alaska DOT and Public Facilities; Public Works Department, City of Davis, California; Indiana DOT; Washington County, Kentucky; Minnesota DOT; Mississippi DOT; Nebraska Department of Roads; New Hampshire DOT; New York DOT; Franklin County, Ohio; Virginia DOT; and Wisconsin DOT. Major safety issues mentioned by these agencies included:

(1) Drivers not familiar or confused with navigation,

(2) Drivers driving too fast,

(3) Undersized roundabouts,

(4) Drivers' rough adjustment period after conversion,

(5) Increase in sideswipe and rear-ending crashes,

(6) Sudden speed changes before roundabouts,

(7) Drivers "missing" roundabouts alignment,

(8) High navigating speed due to poor design (e.g., lack of enough deflection),

(9) Driver exiting from the wrong lane at multilane roundabouts and causing sideswipe accidents,

(10) Crashes due to drivers missing the roundabout turn,

(11) Maps and GPS did not update timely after construction changes were made, and

(12) Heavy traffic, close proximity to railroads, too many different signs in very urban areas confusing drivers, and location in a high density student housing area.

Main public concerns or media publicity that were encountered included the following:

(1) New roundabouts were confusing/unfamiliar; motorists tried to avoid roundabouts,

(2) Significant resistance to roundabouts in the beginning,

(3) Concerns from older drivers,

(4) Drivers did not yield to the vehicles in the circle,

(5) Increased crashes,

(6) Request for additional signs and markings,

(7) Bicyclists' concerns of changing travel lanes,

(8) Concerns for pedestrian safety,

(9) Difficulty in negotiating multilane roundabouts,

(10) Noise due to rumble strips installed on roundabout approaches, and

(11) Effectiveness of the inside apron.

Countermeasures mentioned by the responding agencies mainly focused on the following aspects, the results of which were said to be effective in terms of helping drivers navigate roundabouts, lowering crashes, and reducing public complaints related to roundabouts.

(1) Speed control by adding speed bumps on roundabout approach entrances and exits including striping; addition of transverse rumble strips; use of adequate deflection angles on approaches to reduce vehicle speeds,

(2) Installation of "Yield to Traffic in Circle" signs and yield triangle markings on all roundabout approaches,

(3) Improved pavement markings and signage to help with roundabout navigation,

(4) Use of law enforcement to ensure appropriate navigation of roundabouts,

(5) Reduction in the number of roundabout lanes to reduce driver confusion at multilane roundabouts and addition of median fencing to separate opposing traffic flows,

(6) Inclusion of pedestrian-related signage for improving pedestrian safety at roundabouts,

(7) In-depth study and safety analysis to isolate design flaws and redesign of roundabouts,

(8) Use of larger signs; stripes; reflective paint on curbs; improvements in roundabout lighting; public campaigns to help drivers understand roundabout negotiation rules; giving drivers time to get familiar with roundabouts,

(9) Avoidance of roundabouts in proximity of highway-rail grade crossings, and

(10) Peer review of roundabout design.

The surveyed agencies also provided valuable experiences in dealing with single-lane and multilane roundabouts. Surveyed agencies were mostly pleased with the operation and safety performance of single-lane roundabouts. Single-lane roundabouts were deemed much less challenging than multilane roundabouts. However, some responding agencies were concerned with increased rear-end crashes, speeding, and less space for larger vehicles at single-lane roundabouts. For multilane roundabouts, adequate design was deemed more challenging; however many of the surveyed agencies did not have adequate experience with multilane roundabouts. The City of Davis, CA, indicated that it avoided multilane roundabouts due to safety concerns for bicyclists. Howard County, MD, indicated avoidance of multilane roundabouts unless absolutely necessary. Virginia DOT indicated its preference to start with single-lane roundabouts and the subsequent addition of lanes, if necessary. Indiana DOT mentioned the need to train snow plow drivers on the use of roundabouts. New York DOT underscored the need for ensuring pedestrian safety at multilane roundabouts while Wisconsin DOT showed its concern regarding a higher likelihood of crashes. Recommendations to prevent negative publicity included the following:

(1) Public education via media outreach campaigns,

(2) Information dissemination of roundabout benefits regarding increased capacity and fewer/less severe crashes, lower roundabout retrofit/construction and maintenance costs,

(3) Use of roundabout case studies for public education, and

(4) Encouragement of drivers to try driving through roundabouts and give drivers time to adapt.

Chapter 3 Safety of Rural Roundabouts

The research team collected historical crash data from Kansas and conducted a safety analysis to investigate the safety benefits of converting two-way stop controlled intersections with high-speed approaches to modern roundabouts in rural areas.

3.1 Study Objective

Construction of modern roundabouts is becoming common in the United States. Their use in the United States began in the 1990s and has been increasingly popular since then (Rodegerdts 2007). Construction of roundabouts is one way to reduce vehicle collisions and improve the efficiency of intersections (Nebraska Department of Roads 2012). Numerous studies in the United States have shown that roundabouts are effective in urban environments, but published literature is relatively sparse on the safety performance of roundabouts constructed on high-speed (45-65 mph) roads in rural and suburban areas.

A concern with roundabouts constructed on high-speed rural roadways is the speed differential of vehicles traveling on the roundabout approaches and roundabout entries. Roundabouts on high-speed roadways are not “high-speed roundabouts” (Isebrands and Hallmark 2012). With a well-designed roundabout, drivers are allowed to navigate at a reduced speed (15 to 30 mph) inside the roundabout (Isebrands and Hallmark 2012, Persaud et al. 2001, Rodegerdts 2010). Inadequate signing, absence of nighttime lighting, and possible lower levels of drivers’ alertness in rural environments may be some of the reasons causing high approach speeds and driver confusion at the roundabouts (Thomas and Nicholson 2003; Appleton and Clark 1998). Therefore, the research question addressed in this chapter is: “Are roundabouts on rural high-speed roadways safer than traditionally controlled intersections?" Specifically, due to limited data, this chapter investigates the safety of roundabouts that were converted from two-way stop control (TWSC) intersections.

Therefore, the objective of this chapter is to statistically quantify the changes in reported crashes before and after conversion of rural TWSC intersections with high-speed approaches to roundabouts. To answer the above questions, crash records on several TWSC intersections that were subsequently converted to roundabouts were collected from Kansas Department of Transportation (KDOT). A before-after analysis using the Empirical Bayes (EB) method, as given in the Highway Safety Manual (AASHTO 2010a), is utilized.

3.2 Previous Studies

Several studies have shown that roundabouts reduce crash frequencies as well as severities compared to their traditional traffic control counterparts (Rodegerdts 2007; Persaud et al. 2001; Rodegerdts 2010; Flannery and Datta 1996; Lanani 1975; Cunningham 2007; Maycock and Hall 1984; Persaud et al. 2000; Tudge 1990). Most of the roundabouts studied were in urban settings. Studies specially pertaining to rural roundabouts with high-speed approaches are relatively sparse. The few studies on rural roundabouts with high-speed approaches in the U.S. were summarized in the previous section (1.2.5).

The reviewed literature showed that roundabouts are mostly safer than stop-controlled or signalized intersections in terms of total crash frequencies, especially injury crash frequencies. Roundabouts converted from stop-controlled or signalized intersections with high-speed approaches in rural and suburban areas had greater crash reductions than roundabouts in low-speed urban settings. With a significant reduction in crash frequency and severities, substantial safety benefits of the conversion can be expected. However, more research work is still needed before we draw the conclusion that roundabouts are the most appropriate and cost-effective control for intersections with high-speed approaches in rural settings. This study therefore explores the safety performance and its corresponding economic values of roundabouts with high-speed approaches in rural settings, using data obtained from Kansas. The studied roundabouts were all TWSC intersections before conversion.

3.3 Modeling Background

The EB before-after analysis method uses safety performance functions (SPFs) to estimate what the expected average crash frequency would have been at a location where a safety improvement treatment was implemented, had the treatment not been implemented. It then compares the actual observed crashes after treatment application to the expected average if the treatment had not been applied to determine the treatment's safety effectiveness (AASHTO 2010a).

The fluctuation of crashes over time at a location makes it difficult to determine whether the crash frequency changes are due to a safety treatment or are due to natural fluctuation. When a site experiences high (low) crash frequency in a certain period, it is statistically probable that it will experience a comparatively low (high) crash frequency in the following period of similar duration. This phenomenon is known as regression-to-the-mean (RTM). Compared to a simple before-after analysis, EB results are adjusted by changes in traffic volumes and corrected for potential biases from the RTM effect. The EB method is used in the Highway Safety Manual (AASHTO 2010a); the procedures are described as follows.

The predicted average crash frequency for a year, $N_{predicted}$, is expressed as per intersection per year.

$$N_{predicted} = N_{spfx} \times (CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}) \times C_x \quad (2.1)$$

where N_{spfx} = predicted average crash frequency determined for base condition of the SPF developed for site type x,

CMF_{yx} = crash modification factors specific to SPF for site type x, and

C_x = calibration factor to adjust SPF for local conditions for site type x.

The expected average crash frequency for the before treatment period is expressed as per intersection summed for the entire before period.

$$N_{expected,B} = w_{i,B} N_{predicted,B} + (1 - w_{i,B}) N_{observed,B} \quad (2.2)$$

where, the weight for each site *i* is determined as:

$$w_{i,B} = \frac{1}{1 + k \sum_{Before\ years} N_{predicted}} \quad (2.3)$$

$N_{expected,B}$ = expected average crash frequency at site *i* for the entire before treatment period,

$N_{observed,B}$ = observed crash frequency at site *i* for the entire before treatment period, and

k = over-dispersion parameter for the applicable SPF.

The predicted average crash frequency for each site *i* during each year of the after treatment period can be calculated in the same way. The adjustment factor, r_i, which accounts for the difference between the before and after treatment periods in duration and traffic volume at each site *i* is:

$$r_i = \frac{\sum_{After\ years} N_{predicted,A}}{\sum_{Before\ years} N_{predicted,B}} \tag{2.4}$$

The expected average crash frequency for each site *i* over the entire after period in the absence of the treatment is:

$$N_{expected,A} = N_{expected,B} \times r_i \tag{2.5}$$

The estimate of the safety effectiveness of the treatment at site *i* can be expressed in the form of an odds ratio,

$$OR_i = \frac{N_{observed,A}}{N_{expected,A}} \tag{2.6}$$

The percentage crash change at site *i* is:

$$P_i = 100 \times (1 - OR_i) \tag{2.7}$$

The overall effectiveness of the treatment for all sites combined, in the form of an odds ratio, is expressed as:

$$OR' = \frac{\sum_{All\ sites} N_{observed,A}}{\sum_{All\ sites} N_{expected,A}} \tag{2.8}$$

The odds ratio above is potentially biased. An unbiased estimate of the overall effectiveness is:

$$OR = \frac{OR'}{1+\frac{Var(\sum_{All\ sites} N_{expected,A})}{(\sum_{All\ sites} N_{expected,A})^2}} \tag{2.9}$$

In which, $Var\left(\sum_{All\ sites} N_{expected,A}\right) = \sum_{All\ sites}[(r_i)^2 \times N_{expected,B} \times \left(1 - w_{i,B}\right)]$.

3.4 EB Before-After Crash Analysis

3.4.1 Crash and Traffic Data

Crash data on four rural high-speed (45-65 mph) intersections with two-way stop control that were converted to roundabouts were obtained from the Kansas Department of Transportation (KDOT). The period when two-way stop control was in effect was referred to as the “before” time period (i.e., before conversion to roundabouts), while the roundabout period was termed as the “after” period; conversion to roundabout was the safety treatment in each case. Crashes reported during the conversion year were excluded to remove any construction effects. Information for fatal, injury, and property-damage-only (PDO) crashes for each year in the before and after periods was utilized in the analysis. Table 3.1 presents the locations of the four roundabouts, the crash counts in the two time periods, and annual average daily traffic (AADT) before and after roundabout conversion.

Table 3.1 Information on the four intersections/roundabouts

			Before Period					After Period				
Intersecting Roads	**Conversion Year**	**Number of Legs**	**Years**	**Total Crashes**	**Fatal and Injury Crashes**	**AADTmaj**	**AADTmin**	**Years**	**Total Crashes**	**Fatal and Injury Crashes**	**AADTmaj**	**AADTmin**
US-400 & K-47	2009	4	2004-2008	21	13	4116	3004	2010-2012	9	4	3673	2250
US-400/US-69A & K-66	2008	4	2003-2006	19	10	6818	4940	2009-2012	3	0	6730	4923
E. Jct. of US-77 & US-166	2009	4	2004-2008	21	11	5036	4192	2010-2012	3	1	5493	4157
US-50 & US-77	2006	5	2001-2004	20	14	3545	2190	2007-2010	9	2	3370	2028

The AADT information was collected from the KDOT historical state traffic flow map. In some instances AADT on the corresponding major road legs were different, in which case, the larger of the two values was recorded as the AADT for the major road (AADTmaj), consistent with the guidance in the Highway Safety Manual (AASHTO 2010a). The AADT on the minor roads (AADTmin) were determined in a similar manner. Traffic volumes did not change significantly after conversion of the TWSC intersections to roundabouts except for the US-400 & K-47 intersection. Traffic volumes for the four sites ranged from 2,000 to 7,000 vehicles/day. Annual average crash rates before conversion covered from 4.2 to 5.0 accidents/year.

While the characteristics of these four TWSCs that were converted to roundabouts may not be represent all TWSC intersections in the U.S. with respect to traffic volumes and number of crashes, they should be representative of TWSCs that have comparable crash histories and traffic volumes.

3.4.2 EB Before-After Analysis

Table 3.2 presents the results of the EB before-after analysis for total, fatal, non-fatal injury, and property-damage-only (PDO) crashes reported at each site. The odds ratios (column 5) were calculated by dividing the observed number of crashes by expected number of crashes; a value smaller than 1.00 indicates that a particular location experienced fewer crashes after conversion to roundabouts. Percentage reductions (column 6) represent crash reduction rates, and larger values represent greater crash reductions. The intersection at US-400 & K-47 experienced an increase in total crashes after conversion, a 100% decrease in fatal crashes, and a slight decrease in injury crashes. The other three locations had a percentage reduction ranging from 45% to 84% for total crashes, 100% for fatal crashes, and from 80% to 100% for injury crashes. The results for the PDO crashes, however, were mixed as two locations experienced an increase in such crashes.

Table 3.2 Empirical Bayes analysis of all crashes

Intersecting Roads	**Observed Total Crashes (Before)**	**Observed Total Crashes (After)**	**Expected Total Crashes (After)**	**Odds Ratio (Observed/ Expected)**	**Percentage Reduction % [100*(1-Odds Ratio)]**
Total Crashes					
US-400 & K-47	21.00	9.00	8.03	1.12	-12.10
US-400/US-69A & K-66	19.00	3.00	19.34	0.16	84.48
E. Jct. of US-77 & US-166	21.00	3.00	13.64	0.22	78.01
US-50 & US-77	20.00	9.00	16.31	0.55	44.81
Fatal Crashes					
US-400 & K-47	3.00	0.00	0.36	0.00	100.00
US-400/US-69A & K-66	0.00	0.00	0.41	0.00	100.00
E. Jct. of US-77 & US-166	0.00	0.00	0.40	0.00	100.00
US-50 & US-77	3.00	0.00	0.43	0.00	100.00
Non-Fatal Injury Crashes					
US-400 & K-47	10.00	4.00	4.26	0.94	6.15
US-400/US-69A & K-66	10.00	0.00	9.31	0.00	100.00
E. Jct. of US-77 & US-166	11.00	1.00	6.57	0.15	84.78
US-50 & US-77	11.00	2.00	9.60	0.21	79.17
Property-Damage-Only (PDO) Crashes					
US-400 & K-47	8.00	5.00	3.60	1.39	-38.99
US-400/US-69A & K-66	9.00	3.00	10.02	0.31	68.85
E. Jct. of US-77 & US-166	10.00	2.00	10.84	0.29	70.69
US-50 & US-77	6.00	7.00	6.82	1.11	-11.04

Table 3.3 presents the results of aggregated analysis of all four locations, i.e., crashes at all locations in each time period were pooled for the analysis. The overall effectiveness of the treatment (conversion to roundabouts) for all sites combined can be expressed in the form of an odds ratio (column 5). This odds ratio is potentially biased, but an unbiased estimate of the overall effectiveness is presented in column 6. Overall, all types of crashes were reduced after conversion to roundabouts. Total crashes were reduced by 58.13%, fatal crashes were reduced by 100%, and injury crashes were reduced by 76.47%, while property-damage-only crashes were reduced by 35.49%. The results are mostly consistent with studies reported in the literature.

Table 3.3 Empirical Bayes before-after analysis for all locations (aggregated)

Crash Type	**Observed Crashes (After)**	**Expected Crashes (After)**	**Percentage Change %**	**Odds Ratio**	**Unbiased Odds Ratio**
Total	24.00	57.31	58.13	0.42	0.41
Fatal	0.00	1.22	100.00	0.00	0.00
Injury	7.00	29.74	76.47	0.24	0.23
Property-damage-only	17.00	26.35	35.49	0.65	0.63

The following assumptions were made in the EB analysis:

1) The TWSC intersections did not have any significant skew.

2) Except for the US-400 & K-47 intersection, the remaining three intersections had no left-turn lanes and no lighting during the before time period (the US-400 & K-47 intersection showed a left-turn lane on each major approach as well as lighting before conversion on Google Map Street View, imagery

captured in November 2007).

3) All intersections were assumed to have no right-turn lanes and the local calibration factors (Cs) were assumed equal to 1.0.

3.4.3 Before-After Analysis of Fatalities and Injuries in Crashes

Table 3.4 presents the before-after analysis of fatality and injury rates at the four locations. Fatality and injury rates (on a per-year base) in all four locations were reduced after conversions to roundabouts. Fatality rates were reduced by 100% while injury rates were reduced by at least 60%. The analysis showed that severe crashes significantly decreased after the TWSC intersections were converted to roundabouts.

Table 3.4 Before-after analysis of death and injury rates (per year)

Location	**Death Rate (Before)**	**Injury Rate (Before)**	**Death Rate (After)**	**Injury Rate (After)**	**Death Rate Change %**	**Injury Rate Change %**
US-400 & K-47	0.60	5.80	0.00	2.33	-100.00	-59.77
US-400/US-69A & K-66	0.00	4.75	0.00	0.00	-	-100.00
E. Jct. of US-77 & US-166	0.00	5.00	0.00	0.33	-	-93.33
US-50 & US-77	1.00	7.00	0.00	0.50	-100.00	-92.86
All Sites	0.39	5.61	0.00	0.71	-100.00	-87.27

3.5 Conclusion and Discussion

Modern roundabouts provide an alternative to stop-controlled or signalized intersections, and conversions of existing intersections to roundabouts continue across the U.S. While the safety benefits of converting traditionally controlled intersections to modern roundabouts in urban settings have been well-documented, conversions of TWSC intersections on rural, high-speed roadways to modern roundabouts have not been explored to the same extent. This chapter focused on the assessment of four rural high-speed approach TWSC intersections that were converted to roundabouts in Kansas. The evaluation procedures utilized were from the Highway Safety Manual (AASHTO 2010a).

Results of the analysis showed that overall, all types of crashes were reduced after conversion of TWSC intersections to roundabouts. Total crashes decreased by 58.13%, fatal crashes were reduced by 100% at all locations, and non-fatal injury crashes were reduced with an overall reduction rate of 76.47%. Property-damage-only crashes were reduced by 35.49% as a whole, but two out of the four sites experienced increases in property-damage-only crashes after conversion to roundabouts. Based on a before-after analysis, fatality and injury rates were found to decrease at all four sites. In conclusion, the answer to the question “Are roundabouts on rural high-speed roadways safer than TWSC intersections?” is affirmative, and conversion of TWSC rural high-speed intersections to roundabouts provided similar safety benefits to their urban counterparts. The conclusions are consistent with previous studies on rural high-speed roundabouts.

Chapter 4 Economic Analysis

To investigate the tradeoffs between converting a traditional stop controlled or signalized intersection to a roundabout on high-speed highways, this chapter uses the data collected from KDOT and answers the question, "What economic benefits can be expected from the conversion from TWSC intersections to roundabouts in terms of safety improvement?" Therefore, this chapter quantitatively evaluates the economic values of the changes in reported crashes before and after conversion of rural TWSC intersections with high-speed approaches to roundabouts. An economic evaluation is conducted based on the results of the previous safety analysis.

4.1 Economic Analysis Method

Economic benefits can be expected from conversions of intersections to roundabouts. The main safety benefits of converting a TWSC intersection to a roundabout are the assumed savings to the public due to a reduction in crashes in the before-after periods within the project area. Non-safety related benefits may include reductions in motorist delays, fuel consumption, and vehicle emissions. Safety benefit estimation requires crash history before and after conversion to a roundabout. The EB before-after analysis can be used to eliminate the effects of regression-to-the-mean and changes in traffic volumes during the before-after periods.

As reviewed earlier, roundabouts basically reduce crashes compared to stop-controlled or signalized intersections. Table 4.1 presents an estimate of average economic costs on a per accident basis for each severity level for the year 2000 available from the

American Association of State Highway and Transportation Officials (AASHTO 2010b).

Table 4.1 Average comprehensive cost of motor-vehicle crashes by injury severity, 2000

Severity	**Economic Cost Per Accident (2000 Dollars)**
Fatal	\$3,753,200
Non-Fatal Injury	\$138,100
Property Damage Only	\$3,900
All Injury	\$202,300

Source: AASHTO 2010b

Safety benefits are then estimated by multiplying the change in number of crashes of each severity level by the average costs of each crash (Rodegerdts 2010). The results of this economic evaluation are shown in the following section.

4.2 Economic Evaluation by Safety Benefit

An important and a major component of the economic analysis is the avoided cost of crashes. Analysis in tables 3.2 through 3.5 revealed a significant decline in crashes after conversion of the TWSC intersections on rural, high-speed roads to roundabouts at the four sites as a group. In particular, the number of crashes in the years after roundabout completion was well below expected crashes, based on crash rates in the periods before conversions to roundabouts. The decline was particularly pronounced among injury crashes, suggesting that the conversion to roundabouts was reducing both the number and severity of crashes. Such a change would generate significant economic value in terms of safety benefits. These benefits are estimated in table 4.2.

Table 4.2 Value of avoided comprehensive crash costs over 3-4 years

Crash Type	**Observed Crashes (After)**	**Expected Crashes (After)**	**Reduction in Crashes**	**Comprehensive Crash Cost 2014**	**Crash Costs Avoided**
All Crashes	24.00	57.31	33.31	-	-
Fatal	0.00	1.22	1.22	$10,480,100	$12,785,700
Injury (Non-Fatal)	7.00	29.74	22.74	$385,600	$8,769,000
Property-damage-only	17.00	26.35	9.35	$10,900	$101,800
Total (4 intersections over 3-4 years)					$21,656,500

Table 4.2 also reports crash cost estimates for fatal, non-fatal injury, and PDO crashes. Estimates are for 2014, which were based on values from 2000 reported in the AASHTO (AASHTO 2010b), and updated from 2000 to 2014 based on the change in the value of a statistical life reported for 2000 (Blincoe et al. 2000) and 2014 (Rogoff and Thomson 2013). There has been a sharp increase in the measured value of a statistical life from $3.4 million in 2000 to $9.4 million in 2014. This change partly reflects inflation and changes in real wages, but also reflects an updated methodology.

The total value of the estimated 33.3 avoided crashes was $21.7 million. The value is large because the conversion to a roundabout helped reduce the severity as well as the number of crashes. For example, more than half of this amount, $12.8 million, resulted from avoiding 1.2 fatal crashes. Approximately 33.3 avoided crashes were avoided at the four roundabouts over a three- or four-year post roundabout construction period. The annual value of reduced crashes at a single intersection would be one-fourteenth as much, or $1.6 million. This result, however, depends to a significant degree on avoided fatal crashes at the roundabout. Six fatal crashes were reported at the TWSC intersections in the years before they were converted to roundabouts, but none were reported afterwards. Given the small number of intersections and fatal crashes involved and comprehensive crash costs in excess of $10 million for each fatal crash, it is natural to wonder how much chance influenced the results. In particular, severe crashes may have occurred both before and after installation of the roundabout, but none were fatal after the roundabout was in use. This may reflect the relative safety of roundabouts, but also may simply reflect chance. To address the latter possibility, table 4.2 was revised by summing the fatal and non-fatal injury crashes to create a category for all injury crashes (fatal and non-fatal). The higher comprehensive crash cost in 2014 ($567,700) for all injury crashes was utilized; table 4.3 shows the results.

Table 4.3 Value of avoided comprehensive crash costs over 3-4 years with fatal and non-fatal injury crashes combined

Crash Type	Observed Crashes (After)	Expected Crashes (After)	Reduction in Crashes	Comprehensive Crash Cost 2014	Crash Costs Avoided
All Crashes	24.00	57.31	33.31	-	-
Injury (Fatal and Non-Fatal)	7.00	30.96	23.96	$567,700	$13,601,500
Property-damage-only	17.00	26.35	9.35	$10,900	$101,800
Total (4 intersections over 3-4 years)					$13,703,400

The total estimated value from the 33.3 avoided crashes was $13.7 million. This translated into avoided crash costs of $1.0 million per year at each intersection. Therefore, the estimate of the annual reduction in comprehensive crash costs from conversion of TWSC intersections to roundabouts on rural high-speed roads was between $1.0 million and $1.6 million in 2014 dollars. Assuming a 20-year lifespan for a roundabout, the estimated monetary benefits due to avoided crashes were between 20.0 million and 32.0 million.

Safety benefits are the primary type of benefit resulting from the installation of roundabouts. New traffic patterns resulting from a roundabout, however, also may influence other aspects of road use, including driver travel time and operating costs. In the current study, these other types of potential road user benefits were analyzed based on research studying roundabouts that had been installed over the past thirteen years. These studies examined the change in time spent idling at an intersection before the installation of a roundabout, when the intersection was a two-way stop, and after the roundabout was complete. Two studies were from Kansas (Russell et al 2005; Luttrell et al 2000) and one was from Maryland (Kennedy and Taylor 2005). Results varied by study, with two studies showing a small increase in time spent at the intersection and one showing a modest decline in time spent at the intersection. Average results across the three studies indicated that vehicles on average would spend an additional 0.8 seconds at the intersection after it was converted to a roundabout. Average AADT at the three intersections was approximately 8,200. This additional time at the intersection also would lead to additional fuel costs. Additional fuel costs, in turn would lead to additional environmental costs from pollution.

The additional time from 0.8 seconds per vehicle would lead to an additional 1.85 hours of travel time per day at the intersection. This time was valued at $10.72 per hour, which is half the average hourly private sector wage rate in Kansas of $21.45 per hour. The U.S. Department of Transportation recommends utilizing half of the wage when evaluating leisure time and wage rates for Kansas were taken from the Bureau of Labor Statistics of the United States Department of Commerce. The conservative approach assumes single occupancy during a leisure trip. This wage rate implies time costs of $20 per day after the installation of the roundabout or additional costs of $7,200 per year.

Additional time spent at the intersection implies additional gasoline usage. In particular, there is additional gas usage from idling while waiting to enter and pass through an intersection. Based on estimates in AASHTO (2010), 0.055 gallons of gasoline are utilized per minute of idling across classes of automobiles and trucks. This implies use of 6.1 gallons per day and $19 additional dollars per day in operations costs due to additional gasoline use and an average price for gasoline and diesel just above $3.00 per gallon. This yields an estimate of $6,900 in additional spending on gasoline per year after conversion to a roundabout. The additional fuel use also would lead to just over $1 per day in additional environmental costs assuming there is 20 pounds of carbon emitted per gallon of gasoline (Office of Transportation and Air Quality 2005) and a social cost of carbon of $21 per pound. This daily cost implies an annual cost of around $450. Combining time costs, vehicle operation costs and pollution costs, the increase in costs is $14,500 per year after the conversation of a two way stop intersection to a roundabout assuming AADT of 8,200.

These additional costs should be subtracted from the estimated $1.141 million in annual savings due to a reduction in accident costs after the installation of the roundabout. The net savings from all road user benefits would be an estimated $1,127 million per year. This amount of annual savings should be compared to the cost of installing a roundabout.

The present value of these annual savings can be calculated to compare to the construction costs. The present value is calculated over a 20-year period utilizing a 7% real interest rate. These are conservative values in terms of utilizing a relatively short project life and a high real interest rate. The higher rate is appropriate, given uncertainty about the benefits from any particular roundabout installation. Under these conditions, the present value of annual net road user benefits would be $11.94 million from the installation of the roundabout.

These benefits should be compared to the cost of roundabout construction. Costs were estimated based on the real (actual costs measured after project completion) costs of converting a two-way stop intersection into a roundabout. Costs estimates were available for three Kansas projects (Church 2007), including an intersection of US-50 and US-77 (during 2006), an intersection of K-68 and Old Kansas City Road (during 2001), and an intersection of the North Junction of US-59 and US-161 (during 2006). The average construction costs for the three projects, after adjusting for an increase in the cost of construction materials in the producer price index, was $3.61 million in 2013 dollars. These costs can be compared with the present value of road user benefits of $11.94 million to calculate an estimated benefit cost ratio for the project. The benefit cost ratio from projects to replace two-way stop intersections with a roundabout under AADT of around 8,200 was 3.3.

4.3 Conclusion and Discussion

This chapter focused on the economic assessment of four rural high-speed approach TWSC intersections that were converted to roundabouts in Kansas. The evaluation procedures utilized were from the Highway Safety Manual (AASHTO 2010a).

Results of the analysis showed that the estimated safety benefits were significant in monetary terms. As in our case, the annual value of the reduction in comprehensive crash costs from conversion of a TWSC intersection on a rural, high-speed roadway to a modern roundabout was between $1.0 million and $1.6 million in 2014 dollars. After taking additional operational costs and construction costs into consideration, the benefit cost ratio from projects to replace two-way stop intersections with a roundabout under AADT of around 8,200 was 3.3. Although it is too early to generalize this conclusion to all TWSC intersections, it should be reasonable for analysts and decision makers to expect parallel monetary benefits from converting rural high-speed approach TWSC intersections with similar traffic conditions and crash histories to modern roundabouts.

Although the above two chapters accomplished the objectives of evaluating the safety benefits of rural roundabouts with high-speed approaches, the analysis is limited to the four intersections. The four sites may not be representative of all TWSC intersections in the U.S. with respect to traffic volumes and number of crashes. However, they should be representative of TWSC intersections with similar crash and traffic histories, design features, and driving behaviors. Studies based on larger datasets that include more qualified rural high-speed intersections are needed in the future to further confirm the safety performance of such roundabouts. On the other hand, for the safety benefit evaluation, the analysis relies on the average severity of non-fatal injury crashes that was utilized in AASHTO (2010b). A more precise estimate of safety benefits could consider the specific severity of non-fatal injury crashes reported at roundabouts and stop-controlled or signalized intersections. The severity might be expected to differ, particularly in light of the lesser severity of crashes in roundabouts observed in table 3.3

Chapter 5 Safety of Multilane Roundabouts

5.1 Data Collection

Due to the non-availability of crash and other relevant data on rural multilane roundabouts for this research, the research team extended the topic to urban multilane roundabouts by extracting data from published research results (Bill et al. 2011; Eisenman et al. 2004; Bhagwant N. Persaud et al. 2001; Maryland State Highway Administration 2002) and synthesized them in this report (table 5.1).

Table 5.1 Before-after crashes for urban multilane roundabouts

State	County	Months Before	Months After	Control type before*	Before		After	
					Total	Injury	Total	Injury
WI	Wood	36	36	MRSC	17	8	20	0
WI	Brown	36	36	SGC	9	1	43	3
WI	Milwaukee	36	36	AWSC	1	0	13	2
WI	Racine	36	36	MRSC	28	9	20	2
WI	Dane	36	36	SGC	14	1	11	0
WI	Dane	36	36	AWSC	20	12	39	7
WI	Dane	36	36	AWSC	13	5	8	1
WI	Dane	36	36	AWSC	9	4	2	0
CO	Avon	22	19	SGC	44	4	44	1
CO	Avon	22	19	SGC	25	2	13	0
CO	Avon	22	19	SGC	48	4	18	0
CO	Avon	22	19	MRSC	12	0	3	0
CO	Avon	22	19	MRSC	11	0	17	1
CO	Vail	36	47	MRSC	16	5	14	2
CO	Vail	36	47	MRSC	42	5	61	0
CO	Vail	36	21	MRSC	18	1	8	1
CO	Vail	36	21	MRSC	23	2	15	0
MD	Baltimore	36	24	MRSC	5	2	0	0
MD	Prince George's	36	12	UN	1	0	9	1
MD	Anne Arundel	60	36	UN	30	13	9	1
MD	Baltimore	60	60	SGC	34	21	77	14

*Traffic control types before the intersections were converted to roundabouts: MRSC- Minor Road Stop Control; AWSC- All-Way Stop Control; SGC- Signal Control; UN –Unknown.

5.2 Multilane Roundabout Crash Summary by State

A summary of crash frequencies for each involved state mentioned above is presented in table 5.2, and a simple before-after crash rate analysis was carried out. Table 5.3 shows the annual crash rates and changes before and after conversion. Notice this simple before-after analysis did not reflect the changes in traffic volumes before and after a roundabout is constructed; a more sophisticated model (e.g., an EB model that takes into account the changes of traffic conditions) may reveal different results.

Table 5.2 Summary of crashes for each state

States	Months Before	Months After	Before		After	
			Total	Injury	Total	Injury
WI (8 sites)	288	288	111	40	156	15
CO (9 sites)	254	231	239	23	193	5
MD (4 sites)	192	132	70	36	95	16
Total (21 sites)	734	651	420	99	444	36

Table 5.3 Changes in crash rates in before and after periods

States	Total Crash Rates (crashes/year)			Injury Crash Rates (crashes/year)		
	Before	After	Change	Before	After	Change
WI (8 sites)	4.6	6.5	1.9	1.7	0.6	-1.0
CO (9 sites)	11.3	10.0	-1.3	1.1	0.3	-0.8
MD (4 sites)	4.4	8.6	4.3	2.3	1.5	-0.8
Average (21 sites)	6.9	8.2	1.3	1.6	0.7	-1.0

From tables 5.2 and 5.3, it appears that when converted to multilane roundabouts, the urban intersections experienced a greater number of total crashes but fewer injury crashes overall. In Colorado, both total crashes and injury crashes were reduced after the construction of multilane roundabouts. Wisconsin and Maryland, based on the simple before-after crash rate comparisons above, experienced a slight increase in total crashes after construction of multilane roundabouts but injury crash rates decreased significantly.

Three out of the four studies cited above also applied the EB method to predict crashes in the after period, assuming no roundabout was constructed. The results were extracted from those reports and are summarized in table 5.4 (the sample size was 18).

Table 5.4 Crash reports with EB estimates

State	County	Months Before	Months After	Control type before	Total		Injury	
					Observed After	EB-After	Observed After	EB-After
WI	Wood	36	36	MRSC	20	12.7	0	5.3
WI	Brown	36	36	SGC	43	18.9	3	5.8
WI	Milwaukee	36	36	AWSC	13	3.3	2	1.4
WI	Racine	36	36	MRSC	20	17.6	2	3.9
WI	Dane	36	36	SGC	11	11.8	0	2.1
WI	Dane	36	36	AWSC	39	27.3	7	9.6
WI	Dane	36	36	AWSC	8	17.2	1	6.8
WI	Dane	36	36	AWSC	2	8.4	0	2.9
CO	Avon	22	19	SGC	44	49.8	1	5.4
CO	Avon	22	19	SGC	13	30.1	0	2.3
CO	Avon	22	19	SGC	18	52.1	0	5.3
CO	Avon	22	19	MRSC	3	19.9	0	0
CO	Avon	22	19	MRSC	17	12.2	1	0
CO	Vail	36	47	MRSC	14	19.1	2	4.6
CO	Vail	36	47	MRSC	61	50.9	0	5.7
CO	Vail	36	21	MRSC	8	9.8	1	1.1
CO	Vail	36	21	MRSC	15	11.8	0	1.3
MD	Baltimore	36	24	MRSC	0	4.3	0	1.6

Table 5.5 presents a comparison of observed crashes and EB predicted crashes in the

after period by state. Wisconsin still experienced an increase in total crashes, but Colorado and Maryland experienced reductions in total crashes. Injury crashes reported in all three states experienced significant reductions.

Table 5.5 Summary of observed and EB predicted crashes by states

State	Months Before	Months After	Total Crash			Injury Crash		
			Observed After	EB-After	Reduction (%)	Observed After	EB-After	Reduction (%)
WI (8 sites)	288	288	156	117.2	33.1	15	37.8	-60.3
CO (9 sites)	254	231	193	255.7	-24.5	5	25.7	-80.5
MD (1 site)	36	24	0	4.3	-100.0	0	1.6	-100.0
Total	578	543	349	377.2	-7.5	20	65.1	-69.3

5.3 Crash Summary by Control Type

Table 5.6 shows the comparisons of observed crash frequencies and predicted crash frequencies by EB model.

Table 5.6 Observed and EB predicted crashes by traffic control types before conversion

Control Type Before Conversion	Total Crash			Injury Crash		
	Observed After	EB-After	Reduction (%)	Observed After	EB-After	Reduction (%)
MRSC (9 sites)	158	158.3	-0.2	6	23.5	-74.5
AWSC (4 sites)	62	56	10.3	10	21	-51.7
SGC (5 sites)	129	162.7	-20.7	4	20.9	-80.9
total (18 sites)	349	377.2	-7.5	20	65.1	-69.3

Table 5.6 shows that multilane roundabouts improved safety overall by significantly decreasing injury crashes regardless of the type of traffic control they had before the

conversion. As to the total crashes, the conversion to roundabouts was most effective when the before traffic control type was signal control, followed by stop control on the minor road approaches (e.g., one way stop control for three-leg intersections and two-way-stop control of four-leg intersections). Compared to all-way-stop control, multilane roundabouts experienced more crashes.

In conclusion, multilane roundabouts in urban settings seem to be safer than traditional traffic controls, especially considering the severity of crashes. The safety benefit is mostly evident when the previous intersection was signal controlled or minor-road-stop controlled. Although total crashes seemed to increase for all-way-stop control, the increase was minimal compared to the decrease of severe crashes. Therefore, conversion to multilane roundabouts shows potential with regard to safety improvement.

5.4 Rural/Suburban Multilane Roundabouts

In the Wisconsin report (Bill et al. 2011), the researchers included several multilane roundabouts in rural settings. The crash information for those roundabouts was extracted from the report and is summarized in table 5.7.

Table 5.7 Rural/suburban multilane roundabouts in Wisconsin report

Intersection	Months Before	Months After	Setting	Control type before	Total Crashes		Injury Crashes	
					Before	After	Before	After
STH 42 & I 43 RAMPS (West)	36	36	Rural	SGC	9.5	12.5	2	4.5
STH 42 & I 43 RAMPS (East)	36	36	Rural	SGC	15.5	15.5	2	3.5
STH 42 & VANGUARD Wal-Mart Entrance	36	36	Rural	SGC	2	8	1	0
Elkhorn Rd (Bus 12)/Bluff Rd/Clay St	36	36	Suburb	NC/Y*	3	3	1	0
Total	-	-	-	-	30	39	6	8

*NC/Y – No control or yield

The Wisconsin report provided EB analysis results taking into consideration traffic and other changes between the before and after periods. The expected crash frequencies were compared with the actual observed crash frequencies, as shown in table 5.8. It can be seen that all four sites experienced significant reductions in injury crashes after multilane roundabouts were constructed. All but one site also experienced significant reductions in total crashes. Therefore, evidence suggests that the safety benefits of rural multilane roundabouts are even more significant than that of their urban counterparts.

Table 5.8 Compared the EB model results with observed crash frequencies

Intersection	Total Crashes			Injury Crashes		
	Expected Crashes (EB)-After	Observed-Expected	Reduction (%)	Expected Injury Crashes (EB)-After	Observed-Expected	Reduction (%)
STH 42 & I 43 RAMPS (West)	25.7	-13.2	-51.4	8.9	-4.4	-49.4
STH 42 & I 43 RAMPS (East)	25.8	-10.3	-39.9	7.0	-3.5	-50.0
STH 42 & VANGUARD Wal-Mart Entrance	12.1	-4.1	-33.9	7.9	-7.9	-100.0
Elkhorn Rd (Bus 12)/Bluff Rd/Clay St	2.8	0.2	7.1	1.1	-1.1	-100.0
Total	66.4	-27.4	-41.3	24.9	-16.9	-67.9

Chapter 6 Conclusions and Recommendations

This report focused on two aspects related to high-speed multilane roundabouts in rural or suburban settings; the first was the tradeoff of converting two-way stop-controlled intersections to roundabouts, and the second was the safety of newly constructed roundabouts.

Several research methods were implemented, including literature search, a survey of state and local transportation agencies, statistical analysis, and economic analysis. Results of the survey indicated the need for proper design of roundabouts including signage and lighting and the possibility of benefits that may be gained from public informational campaigns illustrating roundabout benefits. The use of peer review of roundabout design employed by some agencies holds promise in designing appropriate roundabouts that meet the needs of the traveling public.

Due to limited information on high-speed rural multilane roundabouts, two parts of the research focused on rural single-lane roundabouts and urban multilane roundabouts. Results revealed that high-speed rural single roundabouts provided similar safety benefits to their urban counterparts. The finding is consistent with previous studies on rural high-speed roundabouts. Through the sample collected from Kansas, this study found that by converting two-way-stop controls to high-speed rural single-lane roundabouts, total crashes decreased by 58.13%, fatal crashes reduced by 100% at all locations, and non-fatal injury crashes reduced with an overall reduction rate of 76.47%. Property-damage-only crashes were reduced by 35.49% as a whole. The reduction in crashes also yielded a monetary benefit of between $1.0

million and $1.6 million in 2014 dollars. While taking into consideration the added operational costs and initial construction costs, the benefit cost ratio from projects to convert two-way stop intersections to a roundabout under AADT of around 8,200 was 3.3. As far as multilane roundabouts were concerned, this study found that multilane roundabouts in urban settings seem to be safer than traditional traffic controls, especially considering the severity of crashes. The safety benefits are mostly evident when the previous intersection was signal controlled or minor road stop-controlled. Conversion from traditional controlled intersections to multilane roundabouts showed significant potential with regard to safety. Also, the safety benefits of rural multilane roundabouts were justified and their safety benefits seemed to be even more significant than that of the urban multilane roundabouts.

In conclusion, roundabouts constructed on high-speed rural or suburban highways appear to have significant benefits compared to two-way stop-controlled intersections and are recommended for construction with appropriate design, where feasible

References

Adams, P. 1995. “Traffic Signals and Roundabouts: Are They Really Safer?” *Road and Transport Research*.

Al-Ghirbal, AS. 2005. “Prediction of Severe Traffic Accident Rates at Roundabouts Using Artificial Neural Networks.” King Saud University. http://repository.ksu.edu.sa/jspui/handle/123456789/8721.

Alisoglu, S. 2010. “Roundabouts V.s. Signalized Intersections: A Comprehensive Analysis.” *Kansas Government Journal*: 212–213. http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Roundabouts+vs+Signalized+Intersections+A+Comprehensive+Analysis#0.

American Association of State Highway and Transportation Officials (AASHTO). 1985. *An Information Guide for Roadway Lighting*. Washington, D.C.

AASHTO, 2010. *User and Non-User Benefit Analysis for Highways*. (September).

Anderson, Marc D. 2013. “Traffic Roundabout Construction to Begin next Year in Daphne; Similar Proposal on Table in Fairhope.” http://blog.al.com/live/2013/06/traffic_roundabout_constructio.html.

Angelastro, Michael. 2011. “The Influence of Driver Sight Distance on Crash Rates and Driver Speed at Modern Roundabouts In the United States.” Rutgers, The State University of New Jersey. http://mss3.libraries.rutgers.edu/dlr/showfed.php?pid=rutgers-lib:35915.

Antoine, Diduer. 2005. “The Safety of Roundabouts and Traffic Lights in Belgium.” *Transportation Research Circular 2005* E-C083.

Arndt, Owen K., and Rod J. Troutbeck. 1998. “Relationship between Roundabout Geometry and Accident Rates.” *International Symposium on Highway Geometric Design Practices*.

Arnold, Lindsay S, Aimee Flannery, Lauren Ledbetter, Tierra Bills, Michael G Jones, David R Ragland, and Laura Spautz. 2010. “Identifying Factors That Determine Bicyclist and Pedestrian-Involved Collision Rates and Bicyclist and Pedestrian Demand at Multilane Roundabouts.”

Ashmead, D., D. Guth, R. Wall, R. Long, and P. Ponchillia. 2005. “Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout.” *Journal of Transportation Engineering*.

AUSTROADS. 1993. “Guide to Traffic Engineering Practice, Part 6: Roundabouts.” In *Guide to Traffic Engineering Practice*.

Bahar, Geni, Thomas Smahel, and Alison Smiley. 2009. “Study of the Environmental, Economic, Safety and Social Benefits of Roundabouts.”

Baranowski, Bill, and Edmund Waddell. 1997. “Alternate Design Methods for Pedestrian Safety at Roundabout Entries and Exits: Crash Studies and Design Practices in Australia, France, Great Britain and the USA”: 1–12.

Bill, Andrea, Xiao Qin, Madhav Chitturi, and David A.Noyce. 2011. “Comprehensive Evaluation of Wisconsin Roundabouts Volume 2 : Traffic Safety” 2 (September).

Biolchini, Amy. 2013. “$2.3M Roundabout Construction at State and Ellsworth to Start in June.” http://www.annarbor.com/news/new-23m-roundabout-construction-at-state-and-ellsworth-to-start-in-june/.

Bramwell, F. 1986. “20 Years of Roundabout Construction in Buckinghamshire.” *Highway Engineer* 29.

Brown and Gay Engineers, Inc. 2012. “Modern Roundabout Feasibility Study” (December).

Brude, Ulf. 2000. “What Roundabout Design Provides the Highest Possible Safety?” *Nordic Road and Transport Research* (2): 17–21. http://trid.trb.org/view.aspx?id=620080.

Chung, E, W Young, and R Akcelik. 1993. “Comparison of Roundabout Capacity and Delay Estimates from Analytical and Simulation Models.” *Proceedings-Australian Road Research Board*. MoDOT State Traffic and Safety Conference. http://forums.sidrasolutions.com/Cms_Data/Contents/SIDRA/Folders/Resources/Articles/Articles/~contents/VA22KKCGDCRYG4FA/ChungYoungAkcelik_1992_16thARRBConf.pdf.

Church, David. 2007. “Kansas - High Speed Approach Roundabouts Rural Roundabouts.” In *MoDOT State Traffic and Safety Conference*. http://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=1&ved=0CB8QFjAA&url=http%3A%2F%2Fwww.modot.org%2Ftsc%2F2007documents%2FHighSpeedApproachRoundaboutsKS.ppt&ei=5HXJU--pJMS3yATFiIGADQ&usg=AFQjCNGQWdKP8tUwKNwK56BYRdFHunHuPQ&sig2=iX0A51U5yNTFqe7AA9CL7A&bvm=bv.71198958,d.aWw&cad=rja.

City of Colorado Springs. 2005. “Roundabout Design Standards - A Section of the Traffic Engineering Policy and Design Standards.”

Daniels, Stijn, E Nuyts, and G Wets. 2008. “The Effects of Roundabouts on Traffic Safety for Bicyclists: An Observational Study.” *Accident Analysis and Prevention*: 1–28. http://www.sciencedirect.com/science/article/pii/S0001457507001352.

Davis, G. W., V. W. Inman, T. Shafer, and B. J. Katz. 2003. “A Simulation Study of Path and Speed through Double-Lane Roundabouts.” *In Proceedings of the Second International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design*.

“Designing and Operating Safer Roundabouts.” 2004. In *ITE Toolbox on Intersection Safety*.

Eisenman, Stacy, Jessica Josselyn, George List, Bhagwant Persaud, Craig Lyon, Bruce Robinson, Miranda Blogg, Eric Waltman, and Rod Troutbeck. 2004. “Operational And Safety Performance of Modern Roundabouts and Other Intersection Types”: 1–55.

Elvik, R. 2003. “Effects on Road Safety of Converting Intersections to Roundabouts: Review of Evidence from Non-US Studies.” *Transportation Research Record: Journal of the Transportation Research Board* 1847.

Flannery, A, and L Elefteriadou. 1999. “A Review of Roundabout Safety Performance in the United States.” *Proceedings of the 69th Annual Meeting of the Institute of Transportation Engineers*.

Flannery, Aimee, and Tapan K. Datta. 1996. “Modern Roundabouts and Traffic Crash Experience in United States.” *Transportation Research Record: Journal of the Transportation Research Board* 1553 (1): 103–109.

Flannery, Aimee, Jeffrey P. Kharoufeh, Natarajan Gautam, and Lily Elefteriadou. 2000. “Estimating Delay at Roundabouts.” *Institute of Transportation Engineers* (703): 1–23. http://trid.trb.org/view.aspx?id=677455.

Florida Department of Transportation. 1995. “Florida Roundabout Guide.” http://scholar.google.com/scholar?hl=en&btnG=Search&q=intitle:Florida+Roundabout+Guide#3.

Furtado, G. 2004. “Accommodating Vulnerable Road Users in Roundabout Design.” *TAC Annual Conference*.

Guichet, B. 1997. “Roundabouts in France: Development, Safety, Design, and Capacity.” *Third International Symposium on Intersections Without Traffic Signals*.

Hagring, Ola, Nagui M. Rouphail, and Henning A. Sørensen. 2003. “Comparison of Capacity Models for Two-Lane Roundabouts.” *Transportation Research Record: Journal of the Transportation Research Board*.

Harkey, David L., and Daniel L. Carter. 1982. “Observational Analysis of Pedestrian, Bicyclist, and Motorist Behaviors at Roundabouts in the United States.” *Transportation Research Record: Journal of the Transportation Research Board*.

Isebrands, Hillary. 2011. “Quantifying Safety and Speed Data for Rural Roundabouts with High-Speed Approaches.” Iowa State University. http://lib.dr.iastate.edu/cgi/viewcontent.cgi?article=1429&context=etd.

Isebrands, Hillary N., and Richard Retting. 2008. *Enhancing Intersection Safety through Roundabouts*. Institute of Transportation Engineers.

Jacquemart, G. 1998. *Modern Roundabout Practice in the United States*. http://trid.trb.org/view.aspx?id=487395.

Johnson, William, and Aimee Flannery. 2005. “Estimating Speeds at High Speed Rural Roundabouts.” *3rd International Symposium on Highway Geometric Design*.

Kansas Department of Transportation. 2003. *Kansas Roundabout Guide*.

Kennedy, D., Taylor, K., 2005. Estimating roundabout performance using delay and conflict opportunity crash prediction. *National Roundabout Conference* 1–13.

Kinzel, C. S. 2003. “Signing and Pavement-Marking Strategies for Multilane Roundabouts: An Informal Investigation.” *2nd Urban Street Symposium: Uptown, Downtown, or Small Town: Designing Urban Streets That Work.*

Lanani, N. 1975. “Roundabout: Impacts on Accidents.” *Greater London Intelligence Quarterly* 32.

Leblanc, Mike. 2009. “Lafayette MPO Roundabouts.”

Lee, Ming. 2010. “Performance Analysis of the Dowling Multilane Roundabouts in Anchorage, Alaska.” http://ine.uaf.edu/autc/files/2012/09/RR08.08.Final-Report-Dowling-Multilane-Roundabout-July-11-2010.pdf.

Lenters, Mark S. 2004. “Safety Auditing Roundabouts.” *In 2004 Annual Conference and Exhibition of the Transportation Association of Canada-Transportation Innovation-Accelerating the Pace*. http://www.tac-atc.ca/english/resourcecentre/readingroom/conference/conf2004/docs/s12/lenters.pdf.

Lord, D., I. van Schalkwyk, S. Chrysler, and L. Staplin. 2007. “A Strategy to Reduce Older Driver Injuries at Intersections Using More Accommodating Roundabout Design Practices.” *Accident Analysis and Prevention* 39.

Lutkevich, Paul, Parsons Brinckerhoff Quade, and Patrick Hasson. 2004. “An Examination and Recommendation for Current Practices in Roundabout Lighting.”

Luttrell, G, ER Russell, and Margaret Rys. 2000. “A Comparison of a Roundabout to Two-Way Stop Controlled Intersections with Low and High Traffic Volumes.” *Institute of Transportation Engineers*. http://trid.trb.org/view.aspx?id=677445.

Maryland State Highway Administration. 2002. “Maryland’s Roundabout Accident Experience and Economic Evaluation.” Maryland.

Maycock, G., and R. D. Hall. 1984. *Accidents at 4-Arm Roundabouts. Transportation Research Record: Journal of the Transportation Research Board*. Transport and Road Research Laboratory.

Montella, A. 2007. “Roundabout In-Service Safety Reviews: Safety Assessment Procedure.” *Transportation Research Record: Journal of the Transportation Research Board* 2109.

Myers, EJ. 1999. “Accident Reduction with Roundabouts.” *Transportation Frontiers for the Next Millennium: 69th Annual Meeting of the Institute of Transportation Engineers*. http://trid.trb.org/view.aspx?id=507545.

Nebraska Department of Roads. 2012. “Intersections, Driveways and Channelization.” In *Roay Design Manual*, 4–54. Nebraska Department of Roads.

Niederhauser, Michael E, Brian A Collins, and Edward J Myers. 1997. “The Use of Roundabouts: Comparison with Alternate Design Solution.” *Transportation Engineers 67th Annual Meeting*.

Office of Transportation and Air Quality, 2005. "Average Carbon Dioxide Emissions Resulting from Gasoline and Diesel Fuel," *Emission Facts*, EPA420-F-05-001 (February).

Persaud, B N, R A Retting, and P E Garder. 2000. *Crash Reductions Following Installation of Roundabouts in the United States*. Arlington, USA: Insurance Institute for Highway Safety.

Persaud, Bhagwant N., Richard A. Retting, Per E. Garder, and Dominique Lord. 2001. “Observational before-after Study of the Safety Effect of US Roundabout Conversions Using the Empirical Bayes Method.” *Transportation Research Record* 1751: 1–10.

Proost, Stef, and Gerrit De Geest. 2006. “Economic Analysis of Traffic Safety: Theory and Applications.”

Qin, Xiao, Ghazan Khan, Andrea Bill, and David Noyce. 2011. “Comprehensive Safety Evaluation of Roundabouts in Wisconsin.” *Journal of Transportation Safety and Security* 3 (4) (December): 289–303. doi:10.1080/19439962.2011.624290. http://www.tandfonline.com/doi/abs/10.1080/19439962.2011.624290.

Richie, Scott, and Mark Lenters. 2005. “High Speed Approaches at Roundabouts.” *Transportation Research Circular*. http://trid.trb.org/view.aspx?id=775164.

Robinson, BW, and L Rodegerdts. 2000. “Roundabouts: An Informational Guide.” http://trid.trb.org/view.aspx?id=654119.

Rodegerdts, Lee. 2004. “NCHRP 3-65: Applying Roundabouts in the United States” (July 2004).

Rodegerdts, Lee, Justin Bansen, Christopher Tiesler, Julia Knudsen, Edward Myers, Mark Johnson, Michael Moule, et al. 2010. *Roundabouts: An Informational Guide. Transportation Research Board National Research*. National Cooperative Highway Research Program.

Rodegerdts, Lee, Miranda Blogg, Elizabeth Wemple, Edward Myers, Michael Kyte, Michael Dixon, George List, et al. 2007. *Roundabouts in the United States*. *Transportation Research Board*. Vol. 572. National Cooperative Highway Research Program.

Russell, E, S Mandavilli, and MJ Rys. 2005. "Operational Performance of Kansas Roundabouts: Phase II" (May). ftp://parentpower.mt.gov/research/LIBRARY/K-TRAN-KSU-02-4.PDF.

Seiberlich, Erik Lawrence. 2001. "A Formulation to Evaluate Capacity and Delay of Multilane Roundabouts in the United States for Implementation into a Travel Forecasting Model." The University of Wisconsin-Milwaukee. https://www3.uwm.edu/cuts/its/seiber.pdf.

Singh, D, M Zaman, and L White. 2011. "Modeling of 85th Percentile Speed for Rural Highways for Enhanced Traffic Safety" (405): 1996. http://www.okladot.state.ok.us/hqdiv/p-r-div/spr-rip/library/reports/rad_spr2-i2211-fy2010-rpt-final-zaman.pdf.

Steel, Paul H. A., Robyn V. McGregor, and Mike Damberger. 2007. "The Application of Roundabouts to Improve the Safety Performance on Alberta Rural Highways." *Annual Conference and Exhibition of the Transportation Association of Canada: Transportation-An Economic Enabler (Les Transports: Un Levier Economique)*.

Stuwe, Birgit. 1991. "Capacity and Safety of Roundabouts-German Results." *Intersections without Traffic Signals II. Proceedings of An Intersectional Workshop*.

Taekratok, Thaweesak. 1998. "Modern Roundabouts for Oregon" (June). http://library.state.or.us/repository/2010/201007291227244/index.pdf.

Taylor, Jarrod Lee. 2012. "Evaluation of the Capacity of Signalised Two Lane Roundabouts." University of Southern Queensland.

Thomas, Grant, and Alan Nicholson. 2003. "Rural Roundabouts and Their Application in New Zealand." *Institution of Professional Engineers New Zealand (IPENZ) Transportation Group. Technical Conference Papers*.

Traffic Design Group of Lower Hutt. 2000. "The Ins and Outs of Roundabouts."

Tudge, RT. 1990. "Accidents at Roundabouts in New South Wales." *Australian Road Research Board (ARRB) Conference, 15th, 1990, Darwin, Northern Territory* 15 (5).

Turner, S, and A Roozenburg. 2006. "Roundabout Safety: Influence of Speed, Visibility and Design." *Institution of Professional Engineers New Zealand (IPENZ) Transportation Conference, 2006, Queenstown, New Zealand*.

Turner, SA, AP Roozenburg, and AW Smith. 2009. "Roundabout Crash Prediction Models June 2009" (June). http://www.bikeweek.org.nz/resources/research/reports/386/docs/386.pdf.

Weber, Philip. 2007. "Roundabout Safety Experience." In *Synthesis of North American Roundabout Practice*.

WSDOT. “Washington’s Roundabouts.” http://www.wsdot.wa.gov/Safety/roundabouts/washingtons.htm.

Yin, Derek, and Tony Z. Qiu. 2011. “Comparison of Macroscopic and Microscopic Simulation Models in Modern Roundabout Analysis.” *Transportation Research Record: Journal of the Transportation Research Board*.

Appendix A. Survey of State/Local Transportation Agencies

Interview Question List

Part 1. Are there any roundabouts in your state/city that experienced safety issues after they were constructed?

If there is any, please help us finish Part 2, Part3, Part 4 and Part 5. Thank you!

If there is none, please help us finish Part 6. Thank you!

Part 2 Basic Information. Please provide some basic information for these roundabouts (that experienced safety issues).

Roundabout No.	CITY	COUNTY	INTERSECTION LOCATION	PREVIOUS INTERSECTION CONTROL	SETTINGS 1.RURAL 2.URBAN 3.SUBURBAN	# OF APPROACHES	# OF LANES IN EACH APPROACH	# OF CIRCULATORY LANES	APPROACH SPEED LIMIT (mi/h)	Note
1										
2										

(Please add attachments if there are more)

Part 3 Safety Issues.

Roundabout No.	Q1. What safety issues did the roundabouts have?	Q2. What were the main public concerns or media publicity towards the roundabouts, if any?
1		
2		

(Please add attachments if there are more)

Part 4 Countermeasures.

Roundabout No.	Q3. What countermeasures have been taken to solve the problems?	Q4. What were the results of these countermeasures?
1		
2		

(Please add attachments if there are more)

Part 5 Experience and suggestions.

Q5. What is your agency's experience dealing with the safety of single-lane roundabouts?	
Q6. What is your agency's experience dealing with the safety of multilane roundabouts?	
Q7. What design, management or control elements does your agency pay attention to when constructing new roundabouts?	
Q8. What would your agency suggest do to prevent crash increase after the roundabout construction?	
Q9. What would your agency suggest do to prevent negative publicity after the roundabout construction?	

Part 6 Experience and suggestions.

Q10. What does your agency believe makes your roundabout successful in your state/city?	
Q11. What design, management or control elements does your agency pay attention to when constructing new roundabouts?	
Q12. What would your agency suggest do to prevent crash increase after the roundabout construction?	
Q13. What would your agency suggest do to prevent negative publicity after the roundabout construction?	