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# Quantifying safety and speed data for rural roundabouts with high-speed approaches

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**Quantifying safety and speed data for rural roundabouts with high-speed approaches**

by

Hillary Nicole Isebrands

A dissertation submitted to the graduate faculty  
in partial fulfillment of the requirements for the degree of  
**DOCTOR OF PHILOSOPHY**

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Ames, Iowa

2011

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## ABSTRACT

If transportation agencies are going to move Towards Zero Deaths on their roadways, it will be essential to address the thousands of fatal and injury crashes occurring at intersections. With nearly 3,000 fatalities at rural intersections annually, better intersection designs are critical. Roundabouts are a proven safety countermeasure, but until this point the safety data for rural roundabouts on high speed roadways has been limited. This research conducted an in depth safety and approach speed data analysis for rural roundabouts on high speed roadways and provides the first published planning level crash prediction model available for rural roundabouts.

Crash analysis results showed that rural roundabouts with high speed approaches significantly reduced total crashes by 62 to 68 % and injury crashes by 85 to 88 % at nineteen rural roundabouts. Moreover, the number of angle crashes, which tend to have a higher likelihood of causing injuries at high speeds, were reduced by 83%, also a statistically significant reduction. Approach speed data proved that drivers are able to slow down in advance of roundabouts on rural roadways and the mean speeds at 100 ft from the yield line were 2.5 mph lower than mean speeds at 100 ft from the stop bar at stop controlled approaches. Additionally, a comparison between roundabout approaches with and without rumble strips showed mean speeds 4.3 mph and 3.3 mph lower at 100 ft and 250 ft from the yield line, respectively, for the approaches with rumble strips; however, the variation in speeds increased with the introduction of rumble strips.

The results of this research support decision-making to invest in an intersection alternative that lowers speeds and significantly reduces the risk of injury crashes.

Roundabouts eradicate the risk of drivers running stop signs and red lights. Roundabouts save lives.



## CHAPTER 1. GENERAL INTRODUCTION

*“Although crashes, injuries, and fatalities at intersections are not entirely avoidable, much can be done to improve the current situation.” (1).*

### Introduction

A primary goal of transportation agencies is to reduce crashes and potential crashes attributable to highway system failures (2) as well as minimize the potential for human error and provide a forgiving intersection environment. Recent national and international initiatives such as *Toward Zero Deaths: A National Strategy on Highway Safety* and *Decade of Action* are data driven efforts focused on changing institutional and cultural attitudes towards highway safety (3). If the target of zero deaths is to be achieved, the fatal and injury crashes occurring on rural two-lane highways must be addressed and reduced. During 2009, 41% of all fatal motor vehicle crashes in the United States occurred on two-lane rural roads. Six percent of all these fatal crashes occurred at unsignalized intersections on rural two-lane roads (4).

Speed is often a contributing factor to intersection crashes (5), however, only a modest number of studies evaluate speeds at intersections and its' relationship to safety (6,7). Considering the causal factors – rural, intersection, speed, severe crashes – a solution must address each of these to be deemed successful. The modern roundabout, hereinafter referred to as roundabout, is one solution that can significantly reduce the fatal and injury crashes at intersections.

Three characteristics of roundabouts that contribute to their increased safety are reduced vehicular speeds (on all approaches), reduction in the number of conflict points and

the change in the types of crashes that occur. All traffic is forced to reduce their speeds through geometry and yield to circulating traffic upon entry. Roundabouts encourage slow and consistent speeds (15 to 25mph) for all traffic. Figure 1 shows the typical characteristics of a roundabout, including splitter islands on the approaches, entry deflection, and yield on entry.



**FIGURE 1. Typical roundabout features (8)**

The implementation of roundabouts has been successful in Europe and Australia in both the urban and rural environments for decades. The United Kingdom continues to replace many of its' traditional intersections with roundabouts and France builds approximately 1,000 new roundabouts per year (9). It is estimated that there may be as many as 2,500 roundabouts in the United States but still less than 40 are on rural high-speed roadways similar to those found in this research.

Even as roundabouts have gained momentum in the United States over the past 10 years, the comprehensive research is limited to a few studies. NCHRP Report 572 *Roundabouts in the United States (10)* reports a 35 % reduction in overall crashes and a 76 % reduction in injury crashes at 55 modern roundabouts. More specifically to rural roundabouts, the research is limited to nine roundabouts where the total crash reduction was found to be 71 % and the injury crash reduction was reported at 87 % (10).

Despite the promise of significant reductions in crashes at rural roundabouts, reluctance remains in constructing roundabouts on rural high speed roadways. The most common concern heard is that drivers will not be able to reduce their highway speeds (free-flow) from 45, 55 or 65 mph to navigate a roundabout at 15, 20, or 25 mph. Figure 2 shows a typical approach of a rural roundabout on a high-speed roadway.



**FIGURE 2. Rural roundabout approaches**

Although roundabouts may be a “new” intersection design in the United States, rural roadways have an abundance of geometry changes that drivers experience where they must reduce their speeds. For example, roadway segments with horizontal curves often are signed with “Curve Ahead” signs or “Chevrons” and supplemented with advisory speed plates. Additionally, we also have traffic signals, stop signs and flashing warning lights at rural

intersections that require a driver's attention and ability to slow the vehicle from high speeds to low speeds or even a complete stop. Therefore, drivers do slow their vehicles for the changing conditions ahead as long as they are provided with proper warning and guidance.

## **Dissertation Organization**

This dissertation is based on research conducted on roundabouts on high-speed roadways and is presented as a compilation of published and submitted papers in peer-reviewed transportation journals.

Chapter 1 - General Introduction provides a general introduction to the research topic, the organization of this dissertation, and the significance of and need for the research.

Chapter 2 – Literature Review documents the existing research and information relevant to roundabouts on high-speed roadways.

Chapter 3 – Data Collection describes the gathering of crash data and the data collection plan and methodology for speed data collected at rural roundabouts and two-way stop controlled intersections.

Chapter 4 - Crash Analysis of Roundabouts at High-speed Rural Intersections is a modified version of a published research paper (11) documenting the before and after crash data following the installation of roundabouts and the crash characteristics for rural roundabouts on high speed roadways.

Chapter 5 – A Statistics Analysis and Development of a Crash Prediction Model for Roundabouts on High-speed Rural takes an in depth look at the statistical significance of the before and after crash data and provides the first crash prediction model specifically for rural roundabouts on high speed roadways.

Chapter 6 – Approach Speed Effects at Rural High-Speed Intersections: Roundabouts vs. Two-way Stop Control provides a comparative analysis of the approach speeds for roundabouts (without rumble strips) and the stop controlled approaches of two-way stop controlled intersections and for roundabouts with and without approach rumble strips. The variation in approach speeds was also documented and discussed.

Chapter 7 – General Conclusions provides a discussion of the research results, its potential impacts, limitations, and recommendations for future research.

Appendices are also provided for materials that are relevant to the main text but not included in the chapters.

## **Need for Research**

Conquering the problem of intersection fatalities and injuries continues to be a focus of national, state and local agencies. Thus far it has been difficult to find countermeasures that significantly reduce the number of severe crashes at rural intersections. One feasible alternative that has consistently gained recognition as a safety alternative to traditional intersection design in the past decade is the roundabout; however, consideration of roundabouts on two-lane high-speed (40+ mph) rural highways has not been realized to the extent that urban and suburban roundabouts have in the United States. Research is needed to document the existence of rural roundabouts on high-speed roadways and substantiate the safety benefits and their significance in reducing fatal and injury crashes at vulnerable rural two-lane roadway intersections. Furthermore, data is needed to provide hesitant agencies and doubtful citizens that drivers do slow down for roundabouts on rural high-speed roadways.

## **Research Objectives**

Roundabouts on rural high speed roadways have the ability to improve the overall safety of intersections and dramatically reduce the number of serious injury and fatal crashes. The objectives of this research were to:

First, quantify and document the safety benefits of rural roundabouts with high-speed approaches (40+ mph on at least one approach). As this research began, the transportation research industry and practitioners were seeking research that provided results that were ready for implementation.

Second, provide statistical significance to substantiate the safety benefits and present the first crash prediction model for rural roundabout on high speed roadways.

Third, perform a comparative evaluation of the difference in the average approach speed between roundabouts and two-way stop control intersections, neither with rumble strips, and between roundabouts with and without rumble strips.

Fourth, determine if mean speed and speed variation on roundabout approaches is an viable crash surrogate for intersection safety.

Finally, consider the crash data, more specifically, the types of crashes, contributing factors to the crashes and severity of crashes amongst the intersections and determine if a relationship between approach speed characteristics and crash data could be established.

## **Expected Benefits and Research Contributions**

Research included in this dissertation is some of the first documented and quantified safety research on rural roundabouts on high-speed roadways in the United States. The research contained in this dissertation provides a number of unique contributions to the body

of knowledge on research related to modern roundabouts and is being sought after by researchers and practitioners alike. The rural roundabout dataset is the only one of its kind in the United States and in fact, researchers and practitioners from numerous transportation agencies in the United States (i.e. California, North Carolina, Texas, Montana, Tribal Nations) as well as Canada and Australia have used this rural roundabout research to spearhead and gain government support for rural roundabout implementation on high-speed roadways.

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## CHAPTER 2. LITERATURE REVIEW

The literature review presented in this chapter supplements the literature within each individual paper chapter (Chapters 4, 5 and 6). In some cases the literature cited below provides additional information about the study and in other cases it serves as background information for this research. Within the literature below, the terms collision, accident and crash can all be used interchangeably.

### **Intersections on High Speed Roadways**

Eck and Sabra (1) studied signalized intersections on high-speed roadways in West Virginia. Conditions that were problematic at rural intersections included speed, left turning traffic, left turning drivers' misjudgment of speed of oncoming traffic, and high volume left-turning without left-turn phasing. Countermeasures for rear-end crashes, right angle crashes, red light violations, speeding and truck issues were placement of detectors with adjusting the yellow, activated Red Signal Ahead signs, Prepare to Stop When Flashing signs, and Flashing Signal Ahead signs.

Agent (2) conducted a study of sixty-five intersections on rural high-speed roadways in Kentucky identifying types of traffic control (stop signs, intersection beacon, and signal control), types of accidents, contributing factors and making recommendations for countermeasures at such locations. Forty-seven of the intersections were signalized, sixteen were stop controlled supplemented with an intersection beacon and a majority of the intersections had turn lanes. The accident rates were similar for all traffic control devices, 1.1 to 1.2 accidents per million vehicles.

For intersections that were converted from stop control to stop control with a beacon (eleven), two intersections showed a statistically significant increase in crashes/year and two showed a statistically significant decrease in crashes/year. Similarly, conversions from stop control to signal control (sixteen) showed four intersections with a statistically significant increase in crashes/year and three showed a statistically significant decrease in crashes/year. Lastly, conversions from stop control with beacon to signal control (twenty) showed three intersections with a statistically significant increase in crashes/year and six showed a statistically significant decrease in crashes/year. The results were not consistent, especially for the signalized intersections.

Despite the inconsistency in the results additional data were reported about the types of crashes that did occur. The stop controlled and stop controlled with the beacon intersections had higher percentages of angle crashes than the statewide average, 71%, 68% and 54% respectively. The signalized intersection showed that angle, rear end and opposing left-turns each accounted for approximately 30% of the total number of crashes. The injury crashes accounted for 37%, 40% and 34% of the total crashes for stop controlled, stop controlled with beacon and signal control, respectively. The statewide average for all intersections was lower, at 24%, indicating that intersections in these environments are at higher risk for injury crashes.

Accident report comments indicated the most common events leading up to the accident were after stopping at the minor road the driver did not see the approaching vehicle (when sight distance was okay), the minor road vehicle did not stop, not enough time to stop when the signal turned red, disregard for traffic signal.

Recommendations included upgrading the signalized intersections to include a left-turn phase, modification to the change interval, all red intervals added to all signalized intersections, addition of a left turn lane, adding additional warning signs or modifying existing signs and finally that advance intersection warning is critical for drivers.

Stackhouse and Cassidy (3) performed a study of warning flashers at rural high speed roadway intersections in Minnesota. The results did not support the effectiveness of flashing lights on intersection safety based on driver opinion survey, analysis of accident data, and a field study. The authors concluded that adding warning flashers may not increase the safety of the intersection.

Preston and Storm (4) found that right angle crashes were the most predominant type of crash at rural thru-stop controlled intersections in Minnesota and that these crashes were producing 62% of the series injury crashes and 71% of the fatalities. Fifty-seven percent of the right angle crashes occurred when the vehicle stopped pulled out in front of the vehicle with the right of way and another 26% of the crashes involved vehicles that ran the stop sign, these crashes were more severe. The field review indicated that more, brighter and larger stop signs and warning signs (i.e. use of large stop ahead sign) appear to reduce the number of running the stop sign crashes. Intersections with lighting and Stop Ahead pavement marking also had less crashes. A systematic approach of these potential mitigation strategies was recommended.

Sarchet (5) conducted a study on the crash history of signalized intersections in Colorado. The data showed found that accidents increased at 75% of the 112 locations that were converted to signals. Injury accidents increased at 63% of the intersections. Rural intersections included in this data set also showed a 63% increase in injury accidents.

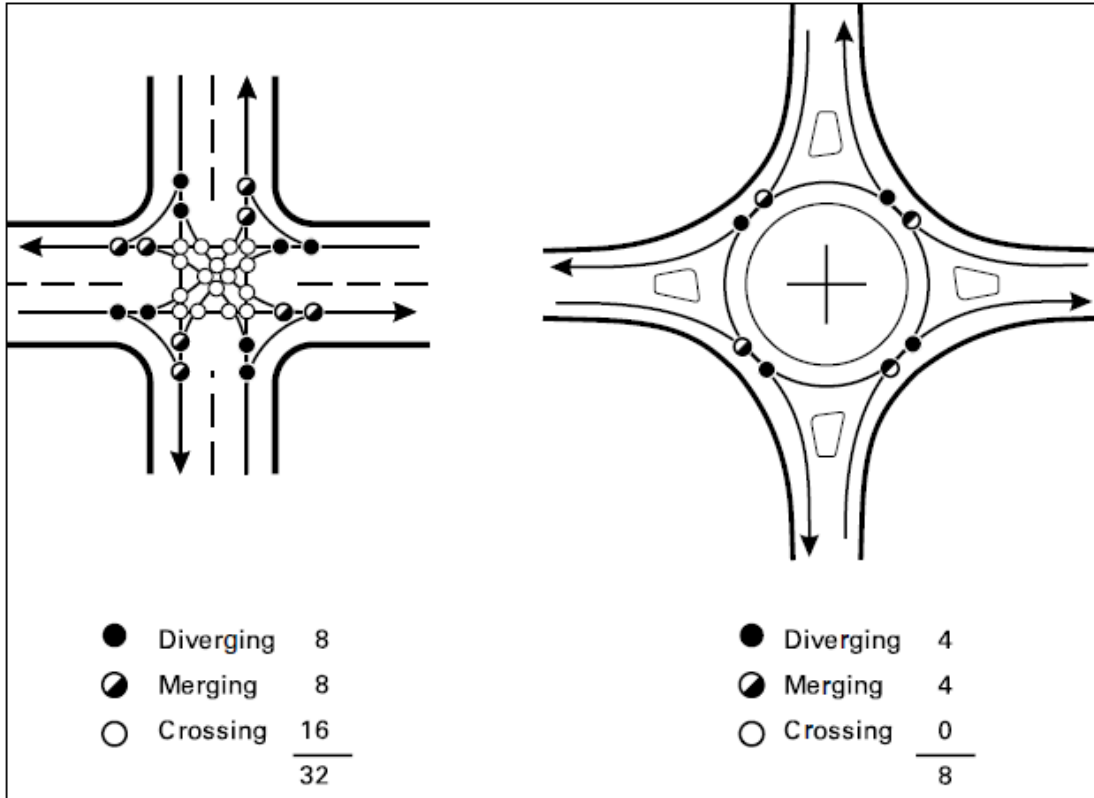
As a part of the NCHRP Report 613, *Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections* (6), three speed reduction treatments were evaluated in a before and after study. Dynamic warning signs, transverse pavement markings and transverse rumble strips each showed a reduction in the approach speeds however only the first two treatments indicated safety improvements.

## **Roundabouts**

Well designed roundabouts create safer intersection environment for all users (7,8,9). Roundabout change how a driver approaches the intersection and how they navigate through the intersection. The reasons roundabouts create a safer intersection are three-fold:

1. All vehicles are travelling, on average, 15 to 25mph, through the intersection;
2. The number of vehicle-vehicle conflict points are one-quarter that of a traditional four approach intersection, as shown in Figure 1, therefore reducing the probability of a crash; and
3. The types of crashes that occur have changed from high speed, right-angle (left turns) crashes and are replaced with lower speed sideswipe crashes and rear end crashes.

The international and now national roundabout safety research verifies the effectiveness of reducing injury crashes in all driving environments. A sampling of the roundabout safety research follows.



**FIGURE 1. Vehicle-vehicle conflict points (Source: 2000 FHWA Guide, Exhibit 2-3) (7)**

Accident research on thirty-eight roundabouts, predominantly mini- and small-roundabouts, in the Greater London, England area conducted by Lalani (10) found a 39% reduction in vehicle accidents. The number of rear-end and single-vehicle crash types remained virtually unchanged after the roundabouts were implemented but cross-road and right-turning (US left turning) crash types were eliminated entirely. The average before and after periods for this study were only 19 months which may not take into account regression to the mean. However, the elimination of the two types of conflicts (cross-road and right-turning) that have the greatest potential to cause the most injury is a significant finding. The number of cross-road crash types dropped from 108 in the before condition to zero in the

after condition and right-turning (US left-turning) crash types dropped from 42 to zero in the after condition.

*Accidents at 4-arm Roundabouts (11)*, provides an in depth safety study of eighty-four roundabouts in the United Kingdom. Crash frequencies ranged from 2.36 to 4.38 crashes/year at the roundabouts with approximately 16 % of those crashes being injury crashes. Furthermore, at eleven roundabouts on high speed roadways, the crash history indicated only four fatal and injury crashes per 100 million vehicles. Figure 2 shows a photo of a rural roundabout in the United Kingdom. This comprehensive safety research on roundabouts was monumental, in that many countries used these results, as the basis for designing and constructing roundabouts. (Note: by comparison, the AASHTO Highway Safety Manual (12) reports that fatal and injury crashes account for nearly 41% of all crashes at traditional intersections on rural two-lane roadways.)



**FIGURE 2. Rural roundabout in the United Kingdom (driving on left hand side)**

A study was conducted near Sydney, Australia to assess the accident frequency and severity of crashes after the installation traffic signals (11 sites) and roundabouts (13 sites) over a two-year before and after period (13). The results indicated significant reductions in accident frequency for traffic signals and roundabouts; however the performance of the roundabouts showed a much higher reduction, 71% versus 35%. Accident severity was evident at the roundabout intersections but not at the 95% significance level. The study showed that seven fatalities occurred at the signalized locations in the after period and one fatal accident was reported at the roundabout intersections. Signals and roundabouts both reduced accident frequency but not to the same degree.

Although roundabout construction began in the United States in the mid- 1990's, it wasn't until 1997 and 1998 that roundabout safety data emerged in the literature in the United States. In an article in TR News, (14) made reference to the limited number of roundabouts in the United States that disallowed extensive safety analysis to be performed but noted that similarities in accident prediction models from the United Kingdom and United States for conventional intersections may allow the United States to conclude that roundabouts have the potential to reduce crashes as they do in the United Kingdom.

In NCHRP Synthesis of Highway Practice 264: *Modern Roundabout Practice in the United States*, Jacquemart (15) noted that roundabouts promote an environment for the driver to have a "higher level of responsibility" and a reduced "level of frustration" while driving. Additionally, he reported that European studies indicate that the safety benefits are greatest for single-lane roundabouts in rural conditions.

A review of 50 safety audit reports of roundabouts resulted in a summary of key issues at roundabouts in New Zealand (16). Inadequate signing (location, appropriateness,

size and quantity) was noted as the most common problem by safety auditors. The signing problems may have contributed to poor driver guidance, high approach speeds and poor driver recognition of intersection control. Poor signing, inadequate or inappropriately located, (relating to rural environments) can lead to confusion for unfamiliar drivers seeking a particular location and affect the ability of the driver to anticipate the intersection. The authors suggest providing larger warning signs on high speed approaches and/or increasing the number of signs (i.e. one on each side of the road) and installing large advance directional signs.

Furthermore, the New Zealand study found that lack of recognition of the central island may cause loss of control, rear end, or failure to yield crashes. Raising the central island to improve its visibility, chevron signs in the central island, lighting and proper design of the splitter island are all suggestions to alleviate the problems. Inadequate deflection on approach to roundabouts can lead to a failure to yield to circulating vehicles, rear end collisions and loss of control accidents. Some solutions suggested are moving the center island, increasing the diameter, modifying the approach geometry, and increasing the deflection by realignment of the curbs and splitter island.

The Swedish Road Administration commissioned a study on accident and injury risks at roundabouts (17). The study performed a speed analysis in 536 roundabouts, a safety (of motorists) analysis of 182 roundabouts and safety of cyclists and pedestrians in 72 roundabouts. Nineteen percent of the accidents at roundabouts (over 563 accident years) were injury accidents – no fatalities – and 85% of those had only slight injuries. Still, the study found that the number of accidents was directly proportional to the posted speed (within the roundabout) and the number of injured had a quadratic relationship with posted



speed (within the roundabout). Recommended speeds (i.e. advisory speeds) are not posted in Sweden. A new prediction model was presented to estimate predicted accident rate. The explanatory variables included number of intersection legs, posted speed and number of circulating lanes. The model showed a reduction (14%) in accidents at roundabouts with three legs versus four legs, and increase (88%) in accidents when the posted speed is 70 km/hr and an increase (20%) in accidents if there are two circulating lanes.

Persaud et al. (18) conducted an empirical Bayes observational before-after study on twenty-three intersections in the United States. The results indicated a 40% reduction in all crashes and an 80% reduction in injury crashes. Five rural, single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes. These crash reductions were consistent with international findings.

A case study example, where roundabouts were considered was documented by Rosales et al. (19). An alternative analysis for two intersections along a corridor in Washington County, OR, where there was a high number of crashes over a five-year period. The intersection alternative needed to improve safety (i.e. reduce crashes), provide room for large trucks and agricultural equipment and minimize the environmental impacts (wetlands, farm land). Two roundabout and two traditional intersection alternatives were analyzed. A project advisory committee was established to recommend the best alternative based the criteria above. Roundabout alternatives were chosen for both intersections based on safety and the ability of the roundabout to improve intersection operations and provide priority given to major traffic movement.

Thomas and Nicholson (20) discuss many of the design features of rural roundabouts in New Zealand that maintain their level of safety. 1.) Geometric design should allow for

only 30mph (50kph) circulating speeds in rural environments and minimize the relative speeds between vehicles, as many rural roundabouts can potentially have a higher number of large trucks. 2.) Low absolute speeds for all drivers allowing them to react to potential crashes. 3.) Adequate deflection to keep speeds low and conflicting speeds consistent. 4.) Appropriate approach, entering and intersection sight distances. 5.) Avoid inducing curvature (reverse curves) on the approaches 6.) Splitter islands should be at least 60m in length but desirable to have it the length of the deceleration distance on the approach to the roundabout. 7.) Lighting is required but the lighting configuration should not be misleading. 8.) Installation of transverse pavement markings to induce speed reduction on the approaches, where necessary. 9.) Driver education. The study also indicates an 86 to 100% reduction in injury crashes at two rural roundabouts over a 4.5 year and 3 year period, respectively, after the roundabout was constructed

Another early case study for roundabout implementation was when Washington State Department of Transportation (WSDOT) considered a roundabout as an intersection alternative for a high-speed, rural intersection in King County (21). WSDOT designers compared crash rates for rural roundabouts in the United Kingdom verses signalized intersections on high speed roadways in King County. The predicted injury crash comparison indicated that the roundabout would outperform the existing intersection control and a signalized intersection, as shown in Table 1. A roundabout was constructed in 2004 and the number of injury crashes dropped from 3.75 per year to 2 per year.

**TABLE 1. Injury Accident Statistics – Roundabouts vs. Signals (21)**

Category	Injury Accidents per 100 Million Vehicles					
	Fatal	Serious	Slight	Total	Number of Sites	Average Daily Traffic
Roundabouts 50–70 mph <sup>1</sup>	0.19	3.8	24.7	28.7	11	27,800
Signals 45-55 mph <sup>2</sup>	0.56	11.8	39.2	51.5	8	20,400
Novelty Hill Road, Existing <sup>2</sup>	0.0	29.9	62.3	92.2	1	13,700
Projected Roundabout <sup>3</sup>	0.13	2.54	16.52	19.19		

<sup>1</sup> LR1120 “Accidents at 4-arm Roundabouts”

<sup>2</sup> WSDOT Accident Records and WSDOT Traffic Counts

<sup>3</sup> Projections from RODEL Ltd.

Johnson and Flannery (22) evaluated speeds at eleven roundabouts in high-speed environments in order to develop models to estimate how design may affect safety and operations. (Five of these locations were considered actual rural roundabouts based on this current study.) The speeds collected were within 250 ft of the yield line. The findings showed that the approach half-width, effective flare length and posted speed limit are all statistically significantly correlated to mean and 85<sup>th</sup> percentile approach speeds. Furthermore, inscribed circle diameter, posted speed limit, effective flare length and approach half width are statistically significant estimators of approach and entry speed differentials.

A before and after roundabout comparison of 122 intersections in Belgium by Antoine (23) showed a 42% decrease in injury crashes and 48% decrease in series accidents. The reduction varied by environment, 15%, 46% and 50% reduction in urban, suburban and open country, respectively. A reduction of 15% of crashes was observed at all other

intersection types. Traffic signals in the open country (rural environment) showed a crash frequency that was twice as high as roundabouts. In 56% of the crashes a vehicle was turning left. The researchers state that traffic signals should be avoided in the open country. Obstacle (or fixed object) collisions were the most common (59%) for the open country (rural) environment. The central island, splitter island and lighting posts were the most common objects hit. These crashes were attributed to poor decisions made on the approaches and high approach speeds. Roundabouts provide a safe intersection in open country.

Turner and Roozenburg (24) suggest that the evolution of roundabout design standards has provided better roundabout designs in recent years, however that infers that there are many roundabouts in operation that have fundamental deficiencies which invoke several safety concerns, such as inadequate deflection. Roundabouts have a particularly good safety record in high-speed environments compared to traditional intersection traffic control in New Zealand. It is thought that there is a relationship between accidents, speed, traffic volume and sight distance. The authors found that roundabouts with approach speeds higher than 70km/h (44 mph) had 35% more reported injury crashes than roundabouts with approach speeds less than 70 km/h. It is unclear if these roundabouts with high-speed approaches represented both rural and urban environments and both single-lane and multi-lane roundabouts. The authors suggest that roundabout design standards that encourage reducing both entering and circulating speeds would be beneficial.

The first comprehensive safety study in the United States was published in 2007 as NCHRP Report 572 Roundabouts in the United States (8). Overall, a 35 % reduction in total crashes was realized at 55 roundabouts and a 76 % reduction in injury crashes. The nine rural locations showed a 72 % reduction in total crashes and an 87 % reduction in injury crashes.

Table 2 shows a copy of the results from this research. Furthermore, this research also provides the first United States based safety prediction models for roundabouts as shown in Table 3. These models do distinguish between number of approach legs and number of circulating lanes; it does not distinguish between environments, urban, suburban or rural.

**TABLE 2. Before and After Safety Analysis Results from NCHRP Report 572, Table 28 (8)**

Control Before	Sites	Setting	Lanes	Crashes recorded in after period		EB estimate of crashes expected without roundabouts		Index of Effectiveness $\theta$ (standard error) & Point Estimate of the Percentage Reduction in Crashes	
				All	Injury	All	Injury	All	Injury
All Sites	55	All	All	726	72	1122.0	296.1	0.646 (0.034) 35.4%	0.242 (0.032) 75.8%
Signalized	9	All	All	215	16	410.0	70.0	0.522 (0.049) 47.8%	0.223 (0.060) 77.7%
	4	Suburban	2	98	2	292.2	Too few	0.333 (0.044) 66.7%	Too few to estimate
	5	Urban	All	117	14	117.8	34.6	0.986 (0.120) 1.4%	0.399 (0.116) 60.1%
All-Way Stop	10	All	All	93	17	89.2	12.6	1.033 (0.146) -3.3%	1.282 (0.406) -28.2%
Two-Way Stop	36	All	All	418	39	747.6	213.2	0.558 (0.038) 44.2%	0.182 (0.032) 81.8%
	9	Rural	1	71	16	247.7	124.7	0.285 (0.040) 71.5%	0.127 (0.034) 87.3%
	17	Urban	All	102	6	142.7	31.6	0.710 (0.090) 29.0%	0.188 (0.079) 81.2%
	12		1	58	5	93.7	22.5	0.612 (0.101) 39.8%	0.217 (0.100) 80.3%
	5		2	44	1	48.9	Too few	0.884 (0.174) 11.6%	Too few to estimate
	10	Suburban	All	245	17	357.2	57.0	0.682 (0.067) 31.8%	0.290 (0.083) 71.0%
	4		1	17	5	77.1	21.8	0.218 (0.057) 78.2%	0.224 (0.104) 77.6%
	6		2	228	12	280.1	35.2	0.807 (0.091) 19.3%	0.320 (0.116) 68.0%
	27	Urban/ Suburban	All	347	23	499.9	88.6	0.692 (0.055) 30.8%	0.256 (0.060) 74.4%
	16		1	75	10	162.8	44.3	0.437 (0.060) 56.3%	0.223 (0.074) 77.7%
	11		2	272	13	329.0	44.3	0.821 (0.082) 17.9%	0.282 (0.093) 71.8%

**TABLE 3. Safety Prediction Model for Total and Injury Crashes at Roundabouts from NCHRP Report 572, Tables 19 (top) and 20 (bottom) (8)**

Number of Circulating Lanes	Safety Performance Functions [Validity Ranges]		
	3 legs	4 legs	5 legs
1	$0.0011(\text{AADT})^{0.7490}$ [4,000 to 31,000 AADT]	$0.0023(\text{AADT})^{0.7490}$ [4,000 to 37,000 AADT]	$0.0049(\text{AADT})^{0.7490}$ [4,000 to 18,000 AADT]
2	$0.0018(\text{AADT})^{0.7490}$ [3,000 to 20,000 AADT]	$0.0038(\text{AADT})^{0.7490}$ [2,000 to 35,000 AADT]	$0.0073(\text{AADT})^{0.7490}$ [2,000 to 52,000 AADT]
3 or 4	Not In Dataset	$0.0126(\text{AADT})^{0.7490}$ [25,000 to 59,000 AADT]	Not In Dataset
Dispersion factor, $k=0.8986$			

Number of Circulating Lanes	Safety Performance Functions [Validity Ranges]		
	3 legs	4 legs	5 legs
1 or 2	$0.0008(\text{AADT})^{0.5923}$ [3,000 to 31,000 AADT]	$0.0013(\text{AADT})^{0.5923}$ [2,000 to 37,000 AADT]	$0.0029(\text{AADT})^{0.5923}$ [2,000 to 52,000 AADT]
3 or 4	Not In Dataset	$0.0119(\text{AADT})^{0.5923}$ [25,000 to 59,000 AADT]	Not In Dataset
Dispersion factor, $k=0.9459$			

Mandavilli et al. (25) studied twenty-nine single-lane roundabouts and nine two-lane roundabouts in Maryland that were constructed from 1993 to 2005. Run-off-road, rear end, entering-circulating and sideswipe crashes accounted for 97% of the 149 total crashes. Of those, 50% were single vehicle run-off-road and “unsafe” speeds were reported at 50% of those crashes. 42% of these crashes occurred on the entrance approach. Rear end crashes accounted for 34% of the crashes and entering-circulating (i.e. failure to yield) crashes for 13%. Field observations suggest that speed related issues may have resulted from lack of advanced signing, insufficient street lighting, wide approach lane widths, lack of conspicuous central island landscaping, and short splitter island lengths. The authors suggest several low costs solutions to encourage speed reduction prior to the roundabout, some include enhanced

landscaping, reflective signs on the central island, extension of the splitter island, and enhanced street lighting.

Kennedy (26) summarizes the international safety experience of roundabouts in eight countries. The crash frequency ranged from 0.05 to 8.71 crashes per year for all intersection environments and traffic volumes. In the United Kingdom, a 2005 study of 1,162 roundabouts found that only 7% of the crashes resulted with a fatal or serious injury, down from 16% reported in 1984 by Maycock and Hall.

## **Roundabout Guidance**

Until recently the available roundabout design and guidance has primarily relied on international experience. The United Kingdom Department of Transport published *Geometric Design of Roundabouts*, in 1993 (27), followed by the *State of the Art Review: The Design of Roundabouts* in 1995 (28). These documents were the basis of roundabout design guidelines published by the Federal Highway Administration in 2000 (7), known as *Roundabouts: An Informational Guide* or the FHWA Guide.

In the years that immediately followed the publication of the 2000 FHWA Guide (7), it is estimated that between 1,000 and 1,500 roundabouts were constructed in the United States. With each of these roundabouts, more experience was gained and best practices for roundabout design quickly materialized. The research project, *NCHRP 3-65 Roundabouts in the United States* was already underway documenting these best practices, collecting safety and operational data and refining the design guidance for roundabouts in the United States. Other design guidance became known during this time that helped shape applications and designs in the United States, such as the Wisconsin Department of Transportation - Facilities

Development Manual (29), Kansas Department of Transportation Roundabout Guide (30) and Australia's Department of Main Roads Road Planning and Design Manual (31). This research and publications paved the way for the update to the 2000 FHWA Guide, which was published as NCHRP Report 672 *Roundabouts: An Informational Guide, Second Edition* (9).

Interestingly, all of the guidance mentioned above, indicated significant benefits of roundabouts on rural high speed locations, yet this application is one of the slowest to emerge in the United States. Exceptions to this slow start were the Maryland State Highway Administration, who constructed some of their first roundabouts in the mid 1990's and several of them were rural applications and followed by the Kansas Department of Transportation in 2001 and Washington State Department of Transportation in 2004. To date the Wisconsin Department of Transportation, has constructed the most rural roundabouts, almost all of them being constructed after 2005.



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### CHAPTER 3. DATA COLLECTION

This research was conducted with limited funding and resources. In addition to the limited funding for this project, at the time of data collection, less than thirty roundabouts in the United States and Canada could be identified as candidate intersections for this research. Both safety records and speed data would be collected for this research.

The definition of rural can be inconsistent and it is an important component of this research. The United States Department of Agriculture has multiple definitions for a non-metro area with the most rural category defined as “completely rural or less than 2,500 urban population, not adjacent to a metro area” (1). The photos in Figure 1 show examples of the rural environment in the context of the intersections included in this research. Rural roundabouts can vary considerably due to roadway and land use considerations and may account for some variation in safety experience.



**FIGURE 1. Examples of rurality (Photo credit: Kansas DOT - left)**

It was understood that the number of intersections would not be as robust as desired but considering this was the first research on rural roundabouts on high speed roadways in North America the effort was deemed to be necessary and appropriate. Also knowing that in

the future this data would be supplemented with new data and rural roundabouts on high-speed roadway with continue to be evaluated for their safety effectiveness.

Data collection efforts were consistent with similar research at high speed rural intersections (2,3,4,5) with the appropriate modifications made specifically for this research.

Additional details about the data collection are included in Chapters 4, 5, and 6.

## **Safety and Intersection Data**

Twenty-nine roundabouts in thirteen jurisdictions were originally considered for this research effort. A list of these intersections can be found in Appendix A. A site visit was conducted at nineteen of the intersections and the remainders were evaluated for consistency with aerial imagery. Several locations were immediately dismissed because they were new intersections (i.e. there was no intersection before) and no before data was available for the safety evaluation. Other intersections were removed because it was determined that they did not meet the rural environment definition.

Originally, seventeen roundabout intersections were selected for the safety evaluation (These results are presented in Chapter 4 of this dissertation). Subsequently, three additional intersections were added to the list but only nineteen qualified intersections for the statistical analyses and crash prediction model, as presented in Chapter 5 of this dissertation.

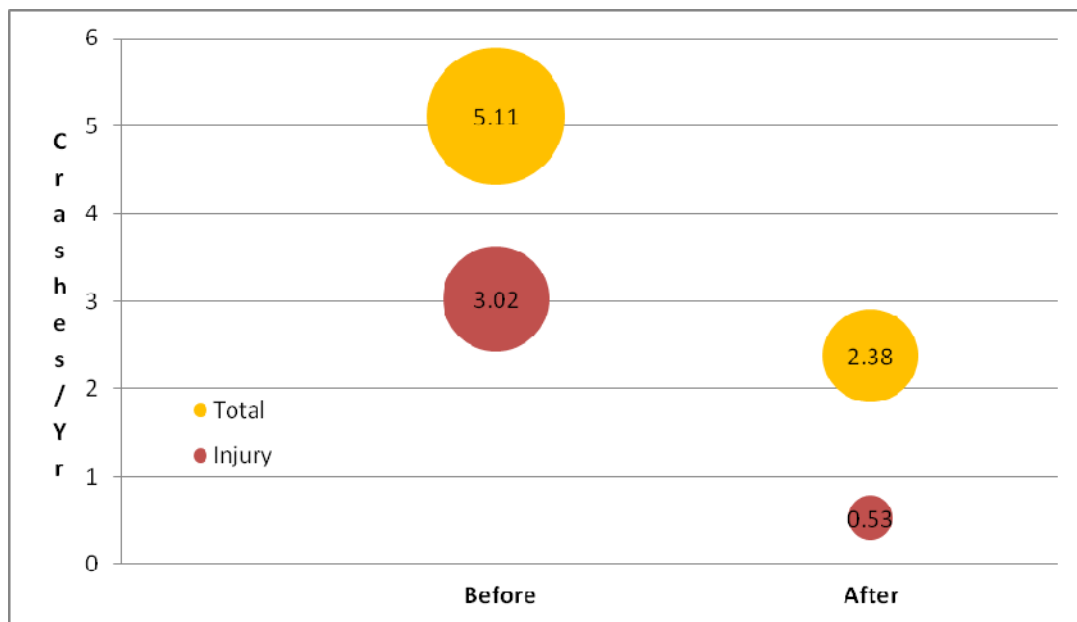
Ultimately, this research evaluated crash data from eight different transportation agencies.

The intersection locations and selected before and after aerial images are included in Appendices' B and C. Crash data reporting practices and availability from state to state and jurisdiction to jurisdiction was very improbable. Crash reports, crash data summaries, crash

diagrams, and historic traffic volume data were requested from each of the agencies in order to evaluate the safety data at the intersections, before and after roundabout implementation.

As is commonly known in the safety profession, the reporting of crashes is not consistent (i.e. not every jurisdiction uses KABCO) and injury crash reporting is subjective to the officers' judgment at the scene of the crash. Whenever possible, the crash data summaries were supplemented with the crash reports to provide a better understanding of the crash and circumstances that lead to the crash.

The data set provided crash records of 511 total crashes before and 212 total crashes after the installation of the roundabouts. Figure 2 shows the crashes per year before and after for total and injury crashes. Ninety-eight data years were available during the before and after periods, however both the before and after years varied. More importantly, the data set included 299 injury crashes before (12 fatal) and 44 injury crashes after (0 fatal).



**FIGURE 2. Crashes per year before and after the installation of roundabouts**

Interesting findings after reviewing the crash data were the limitations of the crash reporting documents in terms of accurately representing the types of crashes that occur at roundabouts. Some crashes at the roundabout were coded angle crashes when they would have been better represented at sideswipe crashes based on the sketch and anecdotal information on the crash report. Additionally, the fixed object crashes also stood out as and required more information. The crash reports indicated that many of the fixed object crashes were when vehicles became disabled or stuck after hitting the curb on the center island of the roundabout. This highlights the importance of having good crash reporting documents and appropriate training for officers to ensure accurate crash records.

Anecdotal information about the intersections and construction plans were also obtained for reference and use during the speed study. Example plan sheets are in Appendix G. Advanced traffic control signing and rumble strip locations were also needed and then confirmed in the field.

## **Speed Data**

Speed data collection was considered for all of the roundabouts selected as part of the safety analysis, as discussed above, and two-way stop controlled intersections that were similar to the before condition of the roundabouts sites and crash data was available. The research team would need to have the cooperation of the owning agency to collect data within the right of way and be in close proximity to Iowa to reduce expenses and travel costs. In the end, this resulted in the selection of four rural roundabouts one each outside New Prague, Minnesota and Paola, Florence and Garnett, Kansas as well as two rural two-way

stop controlled intersections in Story County and Polk County, Iowa. Table 1 lists the intersection locations and characteristics.

**TABLE 1. Speed Data Collection Sites**

State	Nearest City/Town	County	Intersection	Type	Legs	Posted Approach Speed Limit (Max)	Average Daily Entering Volume Before
Kansas	Florence	Marion	US 50/US 77	Roundabout	5	65 mph	4,848
Kansas	Garnett	Anderson	US 169/ K- 59	Roundabout	3	65 mph	5,086
Minnesota	New Prague	Scott	TH 13/CR 2	Roundabout	4	55 mph	6,700
Kansas	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane	Roundabout	5	65 mph	6,260
Iowa	Ames	Story	County Road R-38 and County Road E-36	TWSC	4	55 mph	2,620
Iowa	Alleman	Polk	State Highway 87 and County Road F22	TWSC	4	55 mph	3,663

It was desirable to collect speed profiles on the approaches to the intersections in at least three locations, 100 ft, 250 ft and 500 ft in advance of the intersection and if possible also at two additional locations of 1,500 ft and 2,500 ft, as needed. The equipment considered for the collection of speed data were radar guns, Autoscope®, and TRAX® road tube data collectors. Each of these data collection equipment were available for this research; however the road tubes provided the most flexibility and efficient data collection for this number of locations on each approach with only one to two data collectors on hand.

A total of twelve road tube data recorders were available for use which dictated the number of approaches and number of locations where data could be collected at each intersection. For a statistically valid analysis of the speed data it was desirable to have at least 100 speed records at each road tube location for each approach, knowing that data could only be collected over a four to eight hour period with set up and tear down times needing to be removed from the data set.

Prior to finalizing the data collection layout and protocol a trial run was scheduled at the closest roundabout location, rural New Prague, MN. It was during this trail data collection effort that it was realized that six hours would be the maximum number of hours of

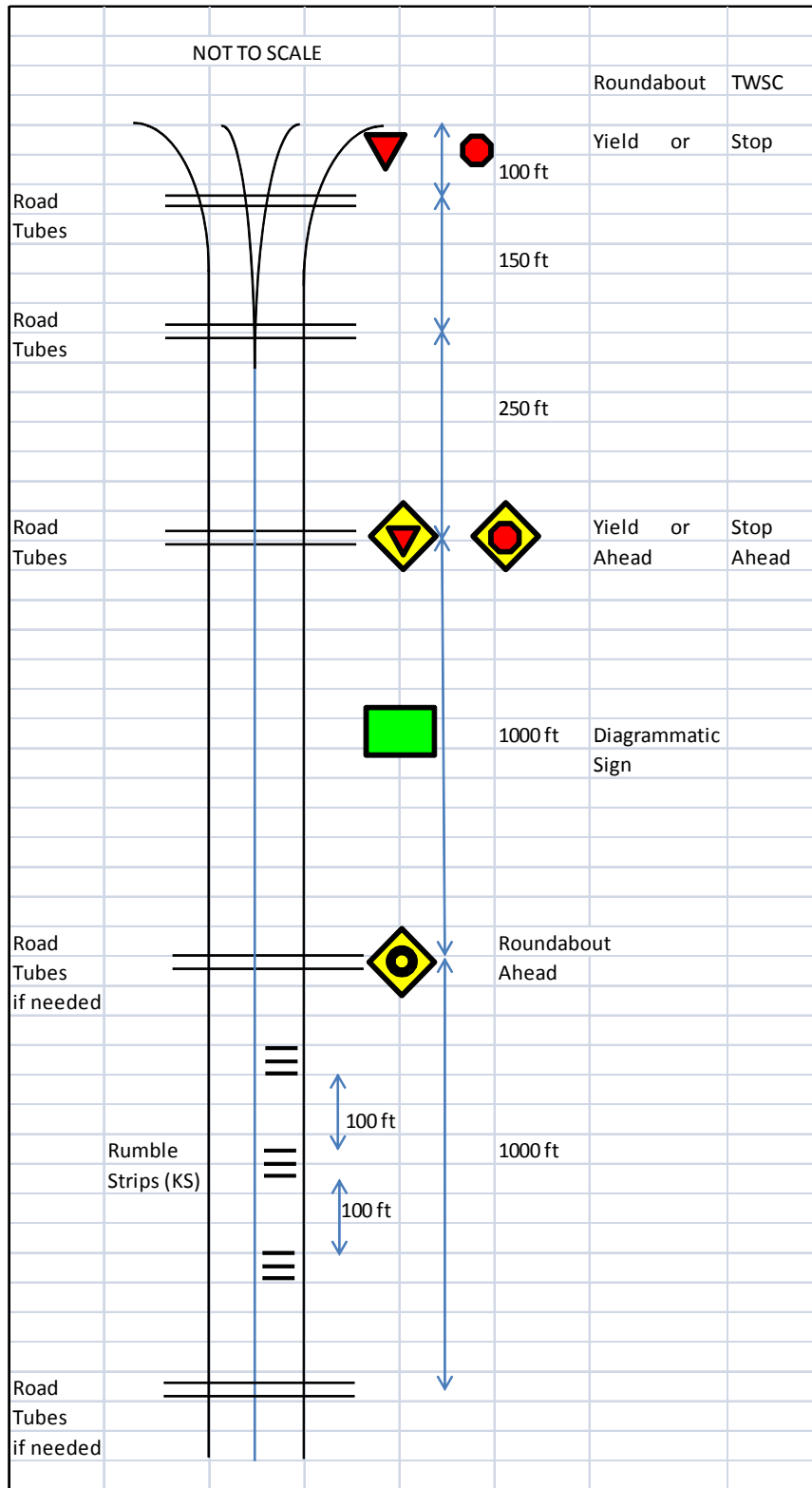


data could be collected. This was due to the number of road tubes that had to be laid down per approach, one to two data collectors, the number of data recorders (twelve) available and the inability to leave the road tubes in place over night. Additionally, it was realized that one of the data recorders was not recording the data accurately which could have been a costly consequence if this had not been realized during this trail data collection effort. Before additional data were collected each data recorder was reset and recalibrated.

Data were collected in November and December 2007 (roundabouts) and September 2009 (two-way stop controlled) and avoided adverse weather and wet, snowy or icy road conditions. Once on site, the data collection team, observed the intersection and its environment and determined which approaches were best for data collection. Approaches with driveways or side roads that may impact the speed data collection were eliminated from consideration. In all, speed data were collected on ten approaches at four different roundabouts and seven approaches at two, two-way stop controlled intersections. Figure 3 shows an example of the road tube locations on one approach and Figure 4 shows the standard approach layout. Appendix H shows additional photos of road tubes at the various distances from the intersection. “Workers Ahead” warning signs were placed during the road tube installation and removal and permission to be in the right of way was obtained from each state Department of Transportation.



**FIGURE 3. Road tube layouts at 250 ft and 100 ft from yield line in Minnesota**



**FIGURE 4. Standard road tube layout**

The data collected at the two-way stop controlled intersections was done over a twenty-four hour period due to the lower volume roadways and their close proximity to the data collection team.

Data reduction was performed on all the speed data after exporting it with TRAX® software. All speed data that were collected during the road tube installation and removal timeframes were deleted from the data set, as well as all erroneous records (i.e. speeds equal to 0 mph, repeat records). Table 2 shows the number of speed data for each intersection. The speed profiles are shown in Appendix I.

**TABLE 2. Speed Data Records**

<b>Intersection</b>	<b>Type</b>	<b>Number of Approaches Studied</b>	<b>Number of Speed Data</b>
New Prague, MN	Yield - Roundabout	4	6,564
Paola, KS	Yield Roundabout	3	6,436
Florence, KS	Yield - Roundabout	2	4,055
Garnett, KS	Yield - Roundabout	1	4,090
Story County, IA	Stop Controlled - TWSC	1	4, 211
Polk County, IA	Stop Controlled - TWSC	2	5, 315

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## CHAPTER 4. CRASH ANALYSIS OF ROUNDABOUTS AT HIGH-SPEED RURAL INTERSECTIONS

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Hillary N. Isebrands

### **Abstract**

Federal, state, and local agencies have identified increased intersection safety as an achievable objective in their campaigns for safer highways. Roundabouts have the potential to reduce the number of fatal and severe crashes. Roundabouts have been successful in Europe and Australia in both the urban and rural environments for decades. The documented safety benefits associated with roundabouts address numerous concerns surrounding injury crashes at intersections; however, applications of roundabouts on two-lane high-speed (40+ mph) rural highways have not been explored to the extent that urban roundabouts have in the United States. This research includes a safety analysis of roundabouts on high-speed rural roadways in the United States. The findings show the average injury crash frequency was reduced by 84%, average injury crash rate was reduced by 89%, angle crashes were reduced by 86%, and fatal crashes were reduced by 100%.

## Introduction

### Background

Intersections are a critical and necessary component in the roadway system; however, they are “a planned point of conflict” (1) which increases the likelihood for crashes.

Intersection related fatalities typically account for approximately 21% of all roadway fatalities in the United States (2). Crashes at intersections account for nearly half of all fatal and injury crashes in the United States and over half of the fatal crashes occur in rural areas. These crashes are occurring on the over 3 million miles (75%) of designated rural highways across the United States each year (3).

Federal, state, and local agencies have identified increased intersection safety as an achievable objective in their campaigns for safer highways. In 2002, the Federal Highway Administration (FHWA) identified safety as one of the three “Vital Few” priority areas of the agency, along with environmental stewardship and streamlining, and congestion mitigation. Under this initiative, FHWA specifically set a goal of reducing intersection fatalities by 10% by 2007, or 921 fatalities per year. Over the past five years, the United States has fallen short of this 10% goal with an average reduction of 1.8%. However, in 2006 and 2007, a 4.5% and 6% reduction in fatalities were recorded, respectively. In addition, under the Highway Safety Improvement Program, FHWA has set aside \$90 million per year until 2009 for the High Risk Rural Roads Program (4). The program’s focus is to significantly reduce fatalities and incapacitating injuries on rural major and minor collectors, and rural local roads.

Modern roundabouts, hereinafter referred to as roundabouts, are consistently gaining recognition as a safety alternative to traditional intersection design in the United States.

Roundabouts have the potential to reduce the number of fatal and severe crashes.

Roundabouts have been successful in Europe and Australia in both the urban and rural environments for decades. The United Kingdom (U.K.) continues to replace many of its' traditional intersections with roundabouts and France builds approximately 1,000 new roundabouts per year (5). It is estimated that there may be as many as 2,500 roundabouts in the United States but still less than 40 are on rural high-speed roadways similar to those found in this research.

### **Need for Research**

One viable alternative to safer intersections is the roundabout. The documented safety benefits associated with roundabouts address numerous concerns surrounding injury crashes at intersections; however, applications of roundabouts on two-lane high-speed (40+ mph) rural highways have not been explored to the extent that urban roundabouts have in the United States.

Despite the potential for roundabouts to reduce crash frequency and severity, apprehension still surrounds this high-speed treatment because of the reduction in approach speed needed to navigate the roundabout, driver unfamiliarity, unbalanced flows, and the ability to accommodate farm equipment and large semi trailers. There is a research need to substantiate the significant safety benefits. This paper addresses the safety benefits of rural roundabouts on high-speed roadways.

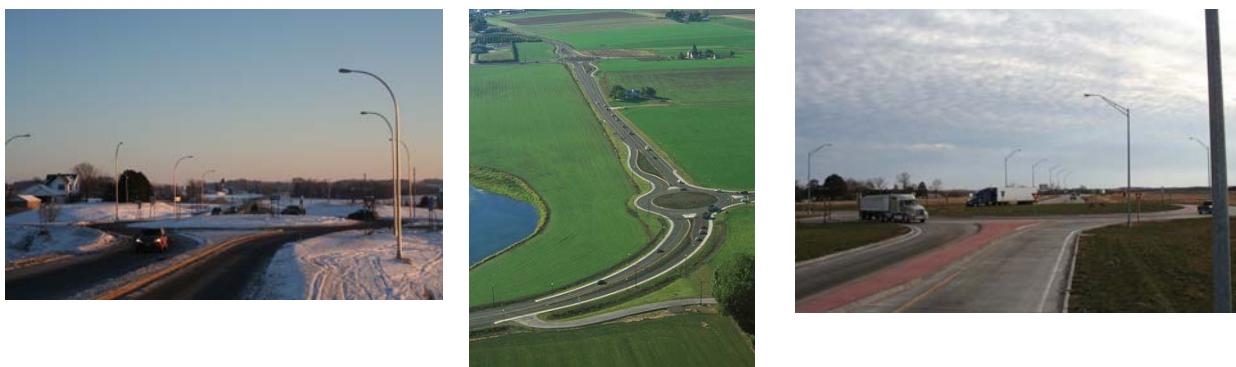


## Roundabouts on Rural High-speed Roadways

Transportation agencies are seeking new safety treatments for minimizing the number of crashes, and more specifically the number of both injury and fatal crashes. Rural areas, in particular, see a large proportion of fatal crashes based on average annual daily traffic (AADT). Roundabouts are one solution that is gaining attention across the United States as a viable intersection alternative that reduces injury crashes significantly.

### Rurality

The definition of rural means different things to different people, depending on what state the person is most familiar with. The United States Department of Agriculture has multiple definitions for a non-metro area with the most rural category defined as “completely rural or less than 2,500 urban population, not adjacent to a metro area” (6). Again, this does not provide clarity for defining rurality. Farmland, forestland, and prairieland can all be defined as rural, but a photo best describes the meaning of rural for this research. Figure 1 shows examples of rurality in the context of the intersections included in this analysis.



**FIGURE 1. Examples of roundabouts in rural settings (Image Sources: Isebrands, CH2MHill, Isebrands)**

## High-speed Roadways

Roundabouts on high-speed roadways are not “high-speed roundabouts.” Drivers at the intersections of high-speed roadways are navigating the roundabout at low speeds between 10 mph and 25mph. A common concern heard in the United States about roundabouts on high-speed roadways is how traffic will be able to reduce their speed from 45, 55, or 65 mph to navigate the roundabout at 15, 20, or 25 mph. Although modern roundabouts may be a “new” intersection design in the United States, our rural roadways have an abundance of situations where the driver must reduce their speeds after they have been driving at high speeds. It is common to see curve, turn, and chevron warning signs with advisory speed plates on rural roadways, as shown in Figure 2. Additionally, our rural roadways have traffic signals, stop signs, and flashing warning lights at intersections that require the driver’s attention and ability to slow the vehicle from high speeds to low speeds, or even come to a complete stop.



**FIGURE 2. Typical curve signing on rural roadways**

Slowing a vehicle from a cruising speed to a slower speed is not a foreign or problematic situation for most drivers; however, roundabouts are new to many drivers and unfamiliarity causes doubt. In this situation, it becomes very important that the transfer of

knowledge from transportation professionals to the driving public be communicated, including the characteristics of roundabouts and their similarities and differences to traditional intersections.

## **Education**

Education of the public is critical to the success of any new type of intersection design, including roundabouts. Beginning educational efforts during the planning stages of a roundabout project by communicating the safety and operational benefits, and providing driving guidelines can prepare the public for an unfamiliar driving experience. It is also critical that the dissemination of project information continue with the public throughout the subsequent stages of the project, including design, construction, and immediately following the opening of the roundabout. An effective educational effort, coupled with sound geometric design, advance signing, and markings can ensure a successful driving experience.

## **Literature**

Although the number of roundabouts on high-speed roadways is relatively small, the safety benefits are evident. From Washington State, to Kansas, to Maryland, significant reductions in injury crashes are documented.

### *General Studies*

Safety benefits of roundabouts have been studied comprehensively in Europe and Australia. In Europe, “safety benefits seem to be greatest for single-lane roundabouts in rural conditions” (7). This is likely attributed to the higher speeds at rural intersections, and the higher likelihood of reducing the severe crash history with the construction of a roundabout.

With a limited number of roundabouts in the United States to perform extensive safety analysis, similarities in accident prediction models from the U.K. and the United States for conventional intersections may allow the United States to conclude that roundabouts have the potential to reduce crashes in the United States, as they do in the U.K. (8).

Persaud et al. (4) conducted an empirical Bayes observational before and after study on 23 intersections in the United States that resulted in a 40% reduction in all crashes, and an 80% reduction in injury crashes. The single-lane rural intersections included in this study resulted in a 58% and an 82% reduction, for total and injury crashes, respectively.

Maryland has approximately 13 roundabouts on high-speed roadways with many of them being constructed in the mid 1990's. Based on the data in a study done by the Maryland State Highway Administration (9), ten of those roundabouts show an average reduction in injury crashes of 79%. These before and after descriptive statistics are for an average of 4.5 years before and 8 years after, which minimizes the potential for regression to the mean.

A 3-year study by Flannery (10) looked at the effect of geometric design on safety performance at eight single lane roundabouts. Approximately 45% of the crashes were loss-of-control and almost all were at high-speed rural locations. The research concluded that the straight approaches and the geometry of the roundabout (entry deflection, entry radius, and inscribed circle diameter) were not sufficient at these locations.

### *Project Related Studies*

Washington State Department of Transportation (WSDOT) considered a roundabout as an intersection reconstruction alternative for a high-speed rural intersection in King

County. Concerns were raised about the safety of roundabouts on high-speed roadways (11). WSDOT designers compared crash rates at U.K. roundabouts versus high-speed signalized intersections, in King County, at rural intersections with roadway speeds over 45 mph. They reported the following information, as shown in Table 1. The crash statistics for the rural roundabouts (50 - 70mph) were taken from a safety study of over 80 roundabouts in the U.K. (12). WSDOT used this crash research to assist in selecting a design alternative for the Novelty Hill Road project. A high-speed rural roundabout was constructed in 2004.

**TABLE 1. Injury Accident Statistics –Roundabouts vs. Signals on High-speed Roadways (13)**

Category	Injury Accidents per 100 Million Vehicles					
	Fatal	Serious	Slight	Total	Number of Sites	Average Daily Traffic
<b>Roundabouts 50–70 mph<sup>1</sup></b>	0.19	3.8	24.7	28.7	11	27,800
<b>Signals 45-55 mph<sup>2</sup></b>	0.56	11.8	39.2	51.5	8	20,400
<b>Novelty Hill Road, Existing<sup>2</sup></b>	0.0	29.9	62.3	92.2	1	13,700
<b>Projected Roundabout<sup>3</sup></b>	0.13	2.54	16.52	19.19		

1 LR1120 “Accidents at 4-arm Roundabouts”

2 WSDOT Accident Records and WSDOT Traffic Counts

3 Projections from RODEL Ltd.

Rosales et al. (14), performed an alternative study for two intersections along a corridor in Washington County, OR, where there was a high number of crashes over a five-year period. The intersection alternative needed to improve safety (i.e. reduce crashes), provide room for large trucks and agricultural equipment, and minimize the environmental impacts (wetlands, farm land). Two roundabout and two traditional intersection alternatives were analyzed. A project advisory committee was established to recommend the best alternative based the criteria above. Roundabout alternatives were chosen for both intersections based on safety and the ability of the roundabout to improve intersection operations and provide priority given to major traffic movement.

A 2005 study for the California Department of Transportation evaluated the perceived concern of roundabouts at high-speed roadways through five case studies of roundabouts in the United States and Canada. The report concluded that there is not statistically sufficient evidence of a correlation between geometric design of high-speed approaches and the intersection safety performance in North America. This study also found that positive safety performance is typically attributed to visible entries, reduced entry speeds, extension of the splitter island to the deceleration length, and landscaped center islands that prevent “see through” (15).

## **Before and After Analysis**

### **Data Collection**

Seventeen intersections on high-speed roadways that were converted to roundabouts were evaluated in this analysis. Before and after crash records were solicited from each agency with jurisdiction over the roundabout. Table 2 shows the intersections that were

included in this analysis. Thirteen of the intersections had four approach legs and approach speeds ranged from 40 mph to 65 mph.

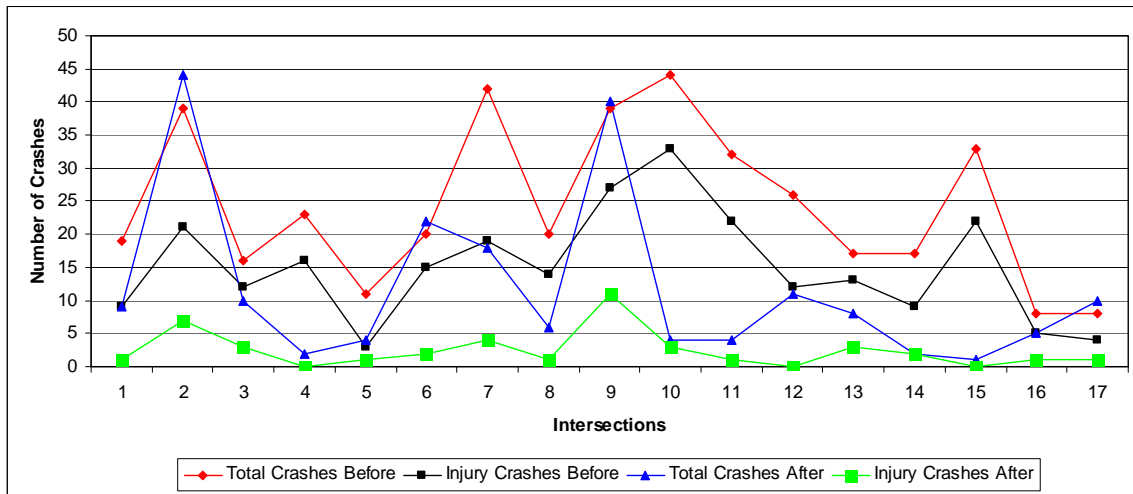
The exposure data was also obtained from the agencies and included either AADT for the intersection or average daily traffic (ADT) for the approaches. The daily entering vehicles (DEV) was calculated as  $ADT/2$ . The DEV was consistent among 16 of the intersections with an average minimum count of 3,015 and an average maximum count of 6,728 over an average 5 year before period. One intersection had a DEV of approximately 16,000.

The number of years of before data averaged 4.6 years with a minimum of 2.5 years and a maximum of 6.6 years. The after data varied more than the before data with an average of 5.5 years with a minimum of 1.8 years and a maximum of 12.7 years of data.

## **Crash Frequency**

Collectively at the seventeen intersections, 414 total crashes and 264 injury crashes were reported prior to the roundabout construction over an average of a 4.6 year period. After the roundabouts were constructed, 200 total crashes and 41 injury crashes were reported over the average of a 5.5 year period. Figure 3 shows the number of crashes by intersection. Only two intersections had an increase in the total number of crashes; in contrast, both of these intersections experienced a 67% and 60% reduction in injury crashes. (Note: the lines shown in the Figures 3 and 4 do not indicate a relationship between the points, but are used to more clearly show the crash trends before and after the installation of roundabouts), the average total crash frequency was reduced by 52% and the average injury crash frequency was reduced by 84%.

Not only did the total crashes decrease, but the number of injury crashes were also reduced and at a higher rate than the total number of crashes. The ratio of injury crashes to total crashes dropped dramatically, from 60% to 20% which is 66% reduction.



**FIGURE 3. Crash frequency by intersection**

## Crash Rate

Crashes per million entering vehicles (MEV) were evaluated to account for the traffic exposure at the intersections. Figure 4 shows the crash rates per MEV by intersection. Only one intersection showed an increase in the total crash rate. This intersection had approximately 5 years of before crash data and 4 years of after crash data. Three intersections reported no injury crashes once the roundabouts were constructed. The average intersection crash rate was reduced by 67% and the average injury crash rate was reduced by 89%.



**TABLE 2. Study Intersection Locations**

	State	City/Town	County	Intersection	Installation year	Legs	Posted Approach Speed Limit (Max)
1	Maryland <sup>1</sup>	Cearfoss/Hagerstown	Washington	MD 63/MD58/Cearfoss Pike	1995	4	50 mph
2	Washington <sup>2</sup>	Duvall	King	SR 203/Novelty Hill Rd	2004	4	50 mph
3	Maryland <sup>1</sup>	Federalsburg	Caroline	MD 307/MD 313/MD 318	1998	4	50 mph
4	Kansas <sup>3</sup>	Florence	Marion	US 50/US 77	2006	5	65 mph
5	Kansas <sup>3</sup>	Garnett	Anderson	US 169/ K- 59	2006	3	65 mph
6	Maryland <sup>1</sup>	Leeds	Cecil	MD 213/Leeds Rd/Elk Mills Rd	1995	4	40 mph
7	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/MD 144	1993	4	45 mph
8	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/Old Fredrick Road	1998	4	45 mph
9	Maryland <sup>1</sup>	Lothian	Anne Arundel	MD 2/MD 408/MD 422	1995	4	50 mph
10	Minnesota <sup>4</sup>	New Prague	Scott	TH 13/CR 2	2005	4	55 mph
11	Maryland <sup>1</sup>	North Harford/Jarrettsville	Harford	MD24/MD165	2000	4	55 mph
12	Kansas <sup>3</sup>	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane	2001	5	65 mph
13	Maryland <sup>1</sup>	Rising Sun	Cecil	MD 273/MD 276	2002	4	45 mph
14	Maryland <sup>1</sup>	Rosemont	Frederick	MD 17/MD 180	2000	4	50 mph
15	Washington <sup>2</sup>	Spokane	Spokane	SR 206/ Bruce Rd	2005	4	50 mph
16	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Martin/Marsh	2004	4	45 mph
17	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Corneilius Schefflin	2004	3	45 mph

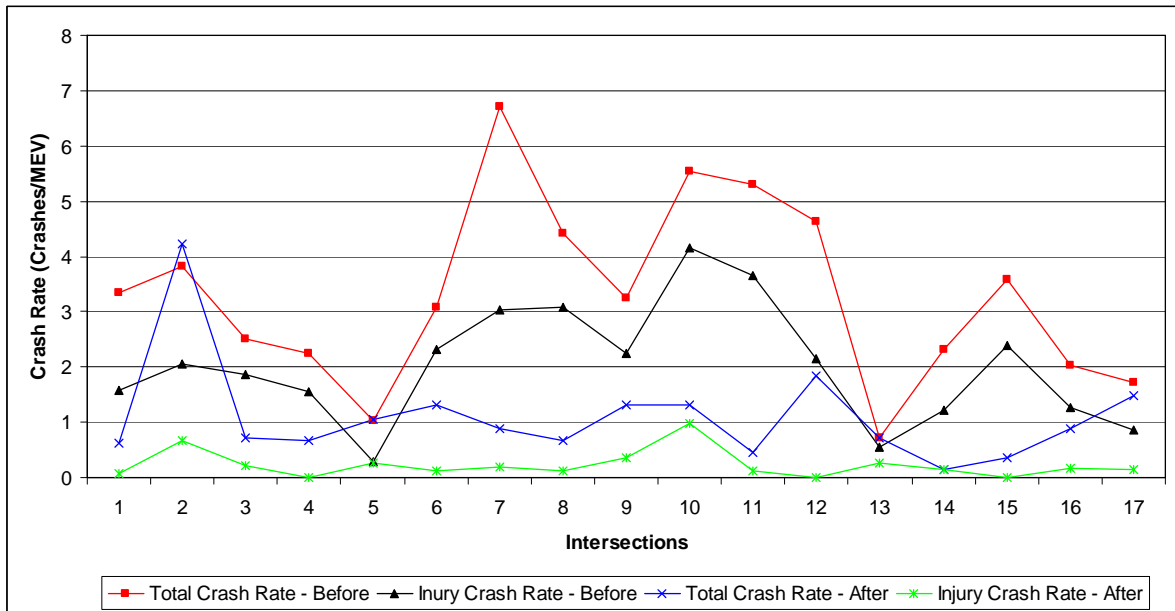
<sup>1</sup> Maryland State Highway Administration, Office of Traffic and Safety, 2007 [9]

<sup>2</sup> Washington DOT, 2008 [16]

<sup>3</sup> Kansas Department of Transportation, Office of Chief Counsel, 2008 [17]

<sup>4</sup> Minnesota Department of Transportation, Office of Traffic and Safety, 2008 [18]

<sup>5</sup> Washington County, Oregon, 2008 [19]



**FIGURE 4. Crash rate by intersection**

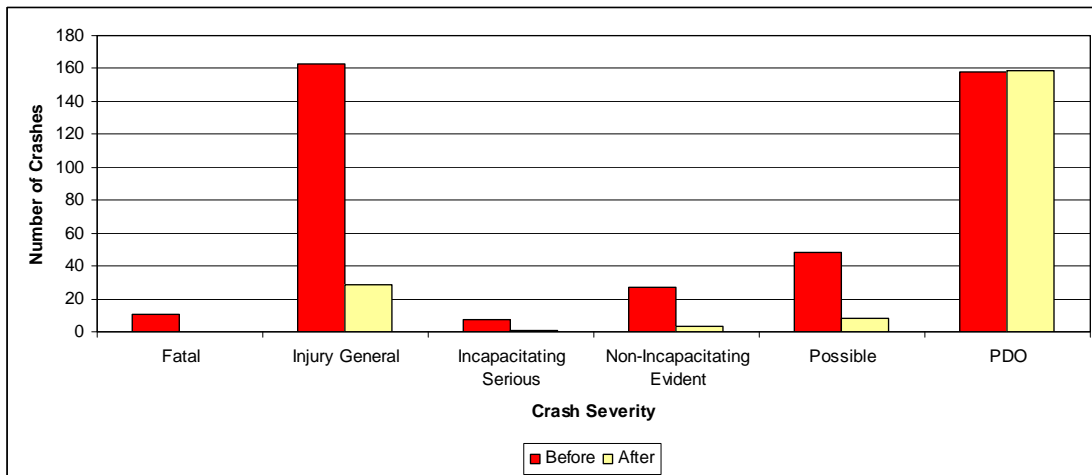
## Crash Severity

When only considering the change in the total number of crashes, it does not distinguish between property damage only (PDO) crashes, which tend to be minor, and the various types of injury crashes. The efforts and benefits in reducing crashes are more significant when injury crashes can be reduced, as was the case with all of the roundabouts in this study. Table 3 and Figure 5 show the percent reductions and number of crashes in the before and after periods.

**TABLE 3. Reduction in Crash Severity**

Crash Severity	Reduction
Fatal	100%
Injury	82%
General <sup>1</sup>	86%
Incapacitating/Serious	89%
Non-incapacitating/Evident	83%
Property Damage Only	No change

<sup>1</sup> Indicates that type of injury was not specified (12 intersections)



**FIGURE 5. Crash severity**

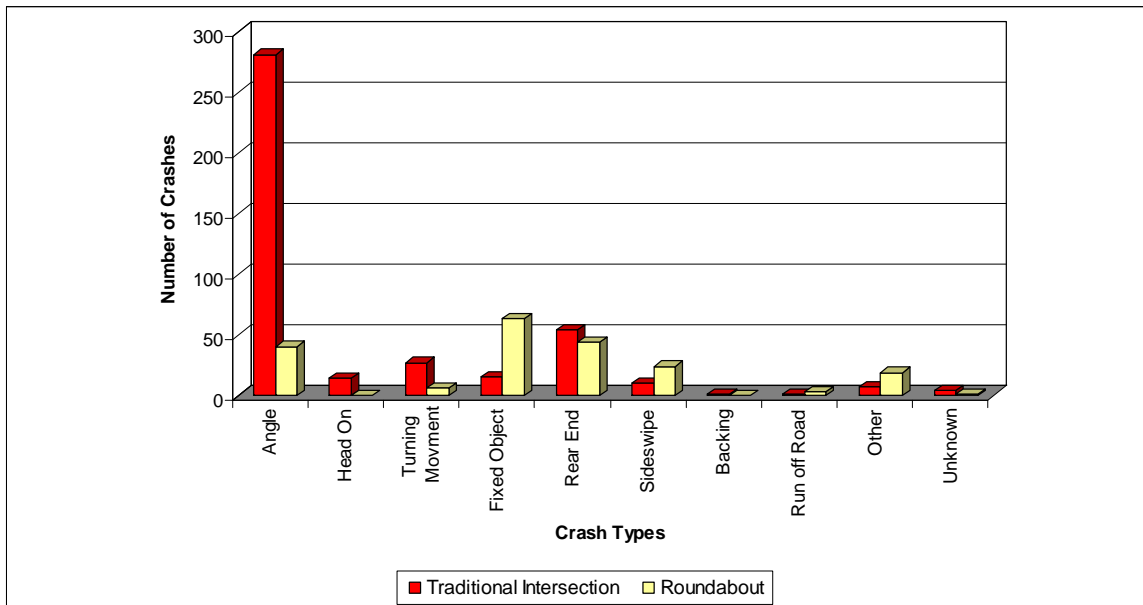
### Crash Types

The very nature of a roundabout intersection changes the types of crashes that occur at the intersection. Typically, certain intersection crash types are associated with more severe injuries, such as angle and turning crashes, whereas rear end and side swipe crashes tend to cause less severe crashes. Figure 6 shows two single vehicle crashes at roundabouts.

For the study intersections, angle crashes were the most dominant type of crash. Angle crashes were reduced by 86%. Fixed object crashes increased by 320%; sideswipe crashes, which are more likely at roundabouts, increased by 140%; and rear end crashes decreased by 19%. Figure 7 illustrates the differences in the number of crashes for each type.



**FIGURE 6. Left – Single vehicle crash in Washington (Image Source: Washington DOT); Right - Truck rollover crash in Kansas (Image Source: © Marion County Record)**



**FIGURE 7. Intersection crash types before and after roundabout**

## **Summary**

Transportation agencies are still in search of solutions that will improve safety, and more specifically reduce the number of injury crashes and their severity. Rural roundabouts provide an effective resolution to an intersection with a poor crash history, and more importantly, an intersection with a history of severe crashes. Furthermore, roundabouts have the potential to prevent similar crashes from occurring at new intersections on rural roadways. Several states have embraced the safety benefits that rural roundabouts provide and these states are continuing to construct roundabouts on high-speed roadways.

The results of this analysis show a 52% and a 67% reduction in total crashes and crash rate, respectively. Moreover, the findings showed an 84% reduction in injury crashes and an 89% reduction in the injury crash rate. No fatal crashes have occurred since the roundabouts were constructed, whereas 11 fatal crashes were reported in the before period. The number of angle crashes were also reduced by 86%.

The next step in this research is to conduct a statistical significance test for the measures of effectiveness to determine if the reductions are significant statistically. Regardless, it is evident that these results demonstrate to the effectiveness of roundabouts in reducing the number of injury crashes at rural intersections on high-speed roadways.

## **Acknowledgements**

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## CHAPTER 5. A STATISTICAL ANALYSIS AND DEVELOPMENT OF A CRASH PREDICTION MODEL FOR ROUNDABOUTS ON HIGH- SPEED RURAL ROADWAYS

A paper submitted to the *Transportation Research Record, Journal of the Transportation Research Board.*

Hillary Isebrands and Shauna Hallmark

### **Abstract**

Roundabouts have proven to be effective in urban and suburban environments in the United States, but little has been reported on their effectiveness in rural environments with high-speed roadways. There is no question that roundabouts reduce speeds of all vehicles at intersections and reduce the frequency of fatal and injury related crashes.

This research is the first comprehensive look at roundabouts in a rural environment with high speed approaches. Nineteen intersections had ample comprehensive crash data to be evaluated and analyzed for safety performance. The findings validated the hypothesis that roundabouts in a rural environment out perform other intersection safety improvements as well as roundabouts in urban and suburban environments. A before and after crash analysis was conducted for the nineteen intersections using a negative binomial regression model . Results showed statistically significant reductions for both the total number of crashes (63%) and injury crashes (88%) when roundabouts were implemented. A before and after empirical Bayes estimation was also conducted and the results were consistent, indicating a 62 to 67% reduction in total crashes and an 85 to 87% reduction in injury crashes at these rural



intersections. Furthermore, results showed that injury producing crash types, such as the angle crash, were reduced by 91%, and were statistically significant.

Finally, this research produced planning level crash prediction models for both total and injury crashes at rural roundabouts on high-speed roadways which supplement the models produced in NCHRP Report 572 Roundabouts in the United States and will be considered for inclusion in the next edition of the AASHTO Highway Safety Manual.

## **Introduction**

Historically, intersection related fatalities account for approximately 21% of all roadway fatalities in the United States and 40% of those fatal crashes occur in rural locations (1). The Federal Highway Administration (FHWA) continues to strive to make improvements in intersection safety (2). Under the Highway Safety Improvement Program, FHWA set aside \$90 million per year until 2009 for the High Risk Rural Roads Program. The program's focus is to significantly reduce fatalities and incapacitating injuries on rural major and minor collectors, and rural local roads. Rural areas, in particular, see a large proportion of fatal crashes based on average annual daily traffic (AADT).

Modern roundabouts are gaining attention across the United States as a viable intersection alternative that reduces injury crashes significantly. Modern roundabouts hereinafter referred to as roundabouts, have been successful in Europe and Australia in both the urban and rural environments for decades. The United Kingdom (U.K.) continues to replace many of its' traditional intersections with roundabouts and France builds

approximately 1,000 new roundabouts per year (3). It is estimated that there are nearly 3,000 roundabouts already in the United States but less than 50 are on rural roadways.

The documented safety benefits associated with roundabouts address numerous concerns surrounding injury crashes at intersections; however, applications of roundabouts on two-lane high-speed (40+ mph) rural highways have not been explored to the extent that urban roundabouts have in the United States. Some skepticism arises from the awareness that rural driving environment takes on a different set of expectations. Often there are few vehicles on the road, street lighting is sparse and intersections are few and far between. Thomas and Nicholson (4) disclose that the rural environment can even induce a lower level of alertness with the decreased level of demand on the driver.

Roundabouts on high-speed roadways are not “high-speed roundabouts.” Drivers at the intersections of high-speed roadways are navigating the roundabout at low speeds, between 10 mph and 25mph which are similar to speeds at roundabouts in urban areas. Well designed roundabouts produce low absolute speeds (15 to 25 mph) for all drivers allowing them to react to potential crashes (4). Roundabouts have been proven (5,6,7) to reduce the number of injury crashes at intersections, albeit a reduction in the total number of crashes is not always experienced, particularly at multi-lane roundabouts. Ultimately, there is a reduced probability of being involved in a high-speed, injury crash at a well-designed roundabout.

So the question remains, how can roundabouts, in a rural environment where there may already be an apathetic driving attitude due to longer distances between developed areas improve the intersection safety experience? The objectives of this research were to provide quantitative evidence of rural roundabout crash data enhanced with statistical analyses that

assesses the safety and effectiveness of roundabouts at rural locations with high-speed approaches. A secondary objective was to develop of crash prediction model specifically for rural roundabouts on high-speed roadways.

## **Background**

The literature specifically pertaining to roundabout in rural locations and/or with high-speed approaches was sparse; however several larger studies have included minimal rural roundabout and/or roundabouts with high-speed approaches.

## **International**

One of the most referred to roundabout safety studies around is a study done by Maycock and Hall (8) in the United Kingdom. They performed an analysis of accidents at four-arm roundabouts. Eighty-four roundabouts were included in the research with 11 sites that would be considered on high-speed roadways (with similar design characteristics to roundabouts in the United States.) Over the 53 intersection crash years, these 11 roundabouts experienced 1-fatal, 20-serious and 129-slight injury crashes which equates to 2.83 crashes per intersection per year. The experience at these 11 roundabouts was slightly lower than the overall average of 3.31 injury crashes per intersection per year. More recently in the United Kingdom, Kennedy et al. (9) conducted a crash study on 1,162 roundabouts and found the average injury crash frequency to be 1.77 injury crashes per intersection per year. Additionally, the research found that single-lane roundabouts for both three-arm and four-arm roundabouts have a lower injury crash frequency.

In New Zealand, Thomas and Nicholson (4) discussed many of the design features of rural roundabouts that are essential to maintaining a high level of safety:

- 1.) Geometric design should minimize the relative speeds between vehicles, as many rural roundabouts can potentially have a higher number of large trucks.
- 2.) Low absolute speeds for all drivers allowing them to react to potential crashes.
- 3.) Adequate deflection to keep speeds low and conflicting speeds consistent.
- 4.) Appropriate approach, entering and intersection sight distances.
- 5.) Avoid inducing curvature (reverse curves) on the approaches
- 6.) Splitter islands should be at least 60m (200 ft) in length but desirable to have it the length of the deceleration distance on the approach to the roundabout.
- 7.) Lighting is required but the lighting configuration should not be misleading.
- 8.) Installation of transverse pavement markings to induce speed reduction on the approaches, where necessary.
- 9.) Driver education.

The study also reported crash frequency data for four rural roundabouts near Christchurch and Rotorua. Overall, the percent reduction in injury crashes ranged from 86% to 100% for the rural roundabouts.

## **United States**

In 2001, Persaud et al. (6) conducted an empirical Bayes observational before-after study on 23 intersections in the United States that resulted in a 40% reduction in all crashes and an

80% reduction in injury crashes. Five rural, single-lane roundabouts experienced a 58% reduction in total crashes and an 82% reduction in injury crashes. Even though the number of rural roundabout was small it was the first indication that roundabouts being placed in urban, suburban and rural locations have a similar safety impact.

The most comprehensive safety study on roundabouts in the United States was published in NCHRP Report 572 (7). Nine of the 55 intersection included in the study were considered rural intersections. All nine roundabouts were single-lane roundabouts. The results of the empirical Bayes before and after study indicated that these nine intersections showed an estimate of the percentage reduction in crashes to be 72% for total crashes and 87% for injury crashes. This compares favorably to the overall percentages for all the intersections, where the reduction for total and injury crashes was 35% and 76%, respectively. The US safety data on roundabouts is consistent with the experiences abroad.

Mandivilli et al. (10) reported on the general crash characteristics of 29 single-lane roundabouts and nine two-lane roundabouts in Maryland constructed from 1993 to 2005. Several of the roundabouts included in this study were rural roundabouts on high-speed roadways. Run-off-road, rear end, entering-circulating and sideswipe crashes accounted for 97% of the 149 total crashes. Of those, 50% were single vehicle run-off-road and “unsafe” speeds were reported at 50% of those crashes. Rear end crashes accounted for 34% of the crashes and entering-circulating (i.e. failure to yield) crashes accounted for 13%. Field observations suggested that speed related issues may have resulted from lack of advanced signing, insufficient street lighting, wide approach lane widths, lack of conspicuous central island landscaping, and short splitter island lengths. The authors suggest several low costs solutions to encourage speed reduction prior to the roundabout, some include enhanced

landscaping, reflective signs on the central island, extension of the splitter island, and enhanced street lighting.

## **Intersection Data**

This research builds on existing, smaller data sets that have included rural roundabouts (6,7). Each of the intersections had to meet several criteria to be included in the data set of rural roundabouts on high-speed roadways. One, the intersection had to be rural in nature and two; the intersection had to have at least one high-speed roadway. The true definition of rural, for this research, relies on a combination of a formal definition and a qualitative assessment of the intersection environment. A formal definition, as cited by the United States Department of Agriculture (11) is an area that is “completely rural or less than 2,500 urban population, not adjacent to a metro area.” The AASHTO Highway Safety Manual (12) sites a rural area with a population of less than 5,000. A more qualitative definition, describes an area surrounded by farmland, forestland, prairieland, or grassland or combination thereof and roads leading up to the intersections are often isolated with high speeds, over 40mph.

The data base of intersections includes 20 rural intersections which were converted to roundabouts in six US states (Maryland, Kansas, Wisconsin, Washington, Oregon, Minnesota) and Ontario, Canada. Nine of these intersections (eight from Maryland) have been included in other before-after studies (6,7), however this new data set builds on the past analyses with more than double the number of intersections and number of years of data, both before and after the roundabout installations. Table 1 provides a summary of each of the intersections.

**TABLE 1. Intersection Locations and Characteristics**

	State	City/Town	County	Intersection	Roundabout installation year	Legs	Posted Approach Speed Limit (Max)
1	Maryland <sup>1</sup>	Cearfoss/Hagerstown	Washington	MD 63/MD58/Cearfoss Pike	1995	4	50 mph
2	Washington <sup>2</sup>	Duwall	King	SR 203/Novelty Hill Rd	2004	4	50 mph
3	Maryland <sup>1</sup>	Federalburg	Caroline	MD 307/MD 313/MD 318	1998	4	50 mph
4	Kansas <sup>3</sup>	Florence	Marion	US 50/US 77	2006	5	65 mph
5	Kansas <sup>3</sup>	Garnett	Anderson	US 169/ K- 59	2006	3	65 mph
6	Wisconsin <sup>5</sup>	Kaukauna	Outagamie	STH 55/CTH KK	2006	4	55 mph
7	Maryland <sup>1</sup>	Leeds	Cecil	MD 213/Leeds Rd/Elk Mills Rd	1995	4	40 mph
8	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/MD 144	1993	4	45 mph
9	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/Old Fredrick Road	1998	4	45 mph
10	Maryland <sup>1</sup>	Lothian	Anne Arundel	MD 2/MD 408/MD 422	1995	4	50 mph
11	Minnesota <sup>4</sup>	New Prague	Scott	TH 13/CR 2	2005	4	55 mph
12	Maryland <sup>1</sup>	North Harford/Jarrettsville	Harford	MD24/MD165	2000	4	55 mph
13	Kansas <sup>3</sup>	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane	2001	5	65 mph
14	Maryland <sup>1</sup>	Rising Sun	Cecil	MD 273/MD 276	2002	4	45 mph
15	Maryland <sup>1</sup>	Rosemont	Frederick	MD 17/MD 180	2000	4	50 mph
16	Wisconsin <sup>6</sup>	Sheboygan Falls	Sheboygan	STH 32/STH 28	2006	4	55 mph
17	Washington <sup>2</sup>	Spokane	Spokane	SR 206/ Bruce Rd	2005	4	50 mph
18	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Martin/Marsh	2004	4	45 mph
19	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Corneilius Schefflin	2004	3	45 mph
20	Ontario <sup>7</sup>	St. Jacobs	Waterloo	Arthur/Sawmill	2006	4	55 mph

<sup>1</sup> Maryland State Highway Administration, Office of Traffic and Safety, 2007 [7]

<sup>2</sup> Washington DOT, 2008 [15]

<sup>3</sup> Kansas Department of Transportation, Office of Chief Counsel, 2008 [16]

<sup>4</sup> Minnesota Department of Transportation, Office of Traffic and Safety, 2008 [17]

<sup>5</sup> Washington County, Oregon, 2008 [18]

<sup>6</sup> Wisconsin Department of Transportation, 2008

<sup>7</sup> Region of Waterloo, Ontario, Canada, 2008

Prior to being converted to a roundabout, one intersection had signal control, two were three-legged intersections with one-way stop controlled and the remaining were two-way stop controlled intersections. Over half of the stopped controlled intersections had intersection control beacons, yellow flashing on the major route and red flashing on the minor route. According to the MUTCD (13), intersection control beacons may be used to provide adequate visibility or where crash rates indicate a need and a conventional traffic signal control is not warranted.

Although the intersection in St. Jacobs, Ontario meets the criteria as rural roundabout with high-speed approaches, several characteristics set it apart from the other 19 intersections and it was removed from the data set for the analysis and crash prediction model

development (i.e. signalized in the before condition, higher traffic volume, decrease in traffic volume in the after condition).The following list highlights those differences:

- Before traffic volumes were over double that of the other intersections
- After traffic volumes decreased by 20%
- Total crashes per year increased by 200% (Injury crashes per year decreased by 25%)
- Two circulating lanes within the roundabout (19 sideswipe crashes)
- Before traffic control was a signal
- 2 years of after crash data

Because of these anomalies, this intersection was removed from the data set.

Major and minor road traffic volumes were all obtained from the jurisdictions in the form of AADT (Annual Average Daily Traffic) or intersection traffic counts converted to AADT. The daily entering vehicles (DEV) was calculated as  $AADT/2$  if it was not provided specifically by direction and approach. The mean DEV for the major and minor roads were approximately 7,000 and 2,800, respectively. The number of years of before and after data averaged 5.2 years. The average increase in volumes from the before to after period was 15%. Table 2 provides a summary of the traffic volumes and crashes.

Crash and intersection data were obtained from the respective jurisdictions, NCHRP Report 572, and field observations (15 intersections). Though, it was inevitable that crash data from seven different jurisdictions would not result in identical reporting methods, careful consideration was made when extracting the crash data from these sources and comparing them to one another. Either crash record summaries/crash diagrams with officer comments were available from all the jurisdictions or preferably data extracted from police



reports was used, when available. In some cases, crash reports were not available for both the before and after periods, only summary data. The total number of crashes that occurred at these intersections in the before and after periods were 504 and 298, respectively. Before and after records indicated that injury crashes, including fatal and possible injury, were 211 and 43, respectively.

**TABLE 2. Intersection Data (19 Intersections)<sup>1</sup>**

	<b>Minimum</b>		<b>Maximum</b>		<b>Mean</b>		<b>Std. Dev</b>	
	Before	After	Before	After	Before	After	Before	After
<b>Major Road DEV</b>	3,181	3,160	12,317	13,775	6,368	7,327	2,721	3,180
<b>Minor Road DEV</b>	1,150	1,377	6,042	5,656	2,624	2,969	1,124	1,061
<b>Total Crashes</b>	8	1	44	48	27	11	13	13
<b>Injury Crashes</b>	3	0	33	11	16	2	8	3
<b>Years</b>	2.5	1.67	8.75	12.7	5.2	5.2	1.7	3.5

## **Descriptive/Summary Statistics**

Although descriptive statistics do not account for the variance between the number of before and after years and changes in traffic volumes, they are able to provide a snapshot of the intersections, crash experience and changes in crash experience after a safety countermeasure, a roundabout in this case, is applied.

For the 19 intersections, 511 total crashes and 299 injury crashes were reported during the before period. This includes 98 data years before and after for the intersections. There was a 59% reduction in total crashes and 85% reduction in injury crashes (After - 212 Total and 44 Injury crashes). Table 3 summarizes the descriptive statistics for the dataset. Only one intersection had an increase in the total number of crashes/year. All intersections

showed a decrease in the injury crashes from 3.8/year to 1.9/year. The ratio of injury crashes to total crashes decreased from 59% to 21% in the after period. Total crash rates and injury crash rates decreased by 64% and 87%, respectively, while the average traffic volumes increased by 9%.

**TABLE 3. Change in Crash Data Before and After Roundabout - Descriptive**

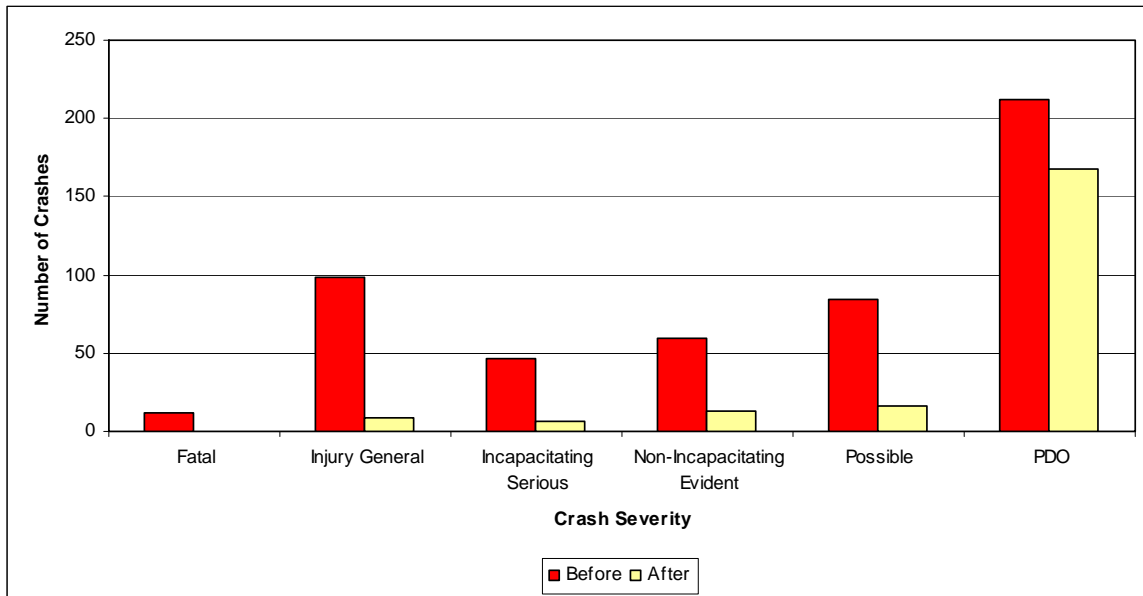
<b>Measure of Effectiveness</b>	<b>Before</b>	<b>After</b>	<b>Percent Change</b>
<b>Total crashes</b>	511	212	-0.59
<b>Injury crashes</b>	299	44	-0.85
<b>Years of data</b>	98.2	98.2	No change
<b>Mean total crashes/year</b>	5.11	2.38	-0.53
<b>Mean injury crashes/year</b>	3.02	0.53	-0.83
<b>Mean crashes/intersection</b>	26.9	11.15	-0.59
<b>Average injury crashes/intersection</b>	15.74	2.32	-0.85
<b>Mean crashes/MEV</b>	1.68	0.61	-0.64
<b>Injury crashes/MEV</b>	0.97	0.13	-0.87

Crash severity shows similar trends. The benefits of reducing injury crashes are more significant than considering overall reduction in crashes (14). Table 4 shows the reductions in injury crashes after roundabouts and Figure 1 illustrates the breakdown of all crashes.

**TABLE 4. Reduction in Crash Severity**

	<b>Before</b>	<b>After</b>	<b>Percent Change</b>
<b>Injury - total</b>	299	44	-85%
<b>Fatal</b>	12 <sup>1</sup>	0	-100%
<b>General<sup>1</sup></b>	98	9	-91%
<b>Incapacitating/Serious</b>	46	6	-87%
<b>Non-incapacitating/ Evident</b>	59	13	-78%
<b>Possible Injury</b>	84	16	-81%
<b>Property damage only</b>	212	168	-21%

<sup>1</sup> Eight intersections had fatal crashes.



**FIGURE 1. Crash severity**

The very nature of a roundabout intersection changes the types of crashes that occur at the intersection (14). While roundabouts tend to decrease the number of angle and turning crashes, they do have the potential to increase sideswipe and rear end crashes (5,7). Mandivilli (10) found that rear-end; run-off-road and sideswipe crashes can increase at some roundabouts. Angle crashes are potentially the most dangerous type of crash, especially when the speed differential between the vehicles is substantial, for example when one vehicle is at free-flow speed (40 – 65 mph) and the other vehicle is starting from a stop condition. An intersection crash resulting from such a situation is shown in Figure 2.



**FIGURE 2. Implications of an angle crash at an intersection (Photo Source: FHWA)**

In the case of these rural intersections, angle and turning crashes make up 74% of all the crashes in the before period. These crashes were reduced 87% from 380 to 48 after a roundabout was constructed. Angle/turning crashes make up only 23% of the total crashes in the after period. Eliminating these dangerous crash types with the installation of a roundabout proves to be a significant contribution in making the intersection safer. Whereas, the angle/turning crashes were predominant at the stop controlled intersections, fixed object (32%), angle/turning (23%) and rear end (21%) crashes each were represented with similar representation, as shown. The number of fatal crashes was reduced from 12 before to zero after the installation of a roundabout. Nine of the twelve fatal crashes were angle crashes.

At roundabouts, sideswipe crashes typically occur upon entering and exiting the circulating roadway and are more likely to occur at multi-lane roundabouts. The crash results of the one two-lane roundabout within this dataset were consistent with this theory in that 23 sideswipe crashes were reported after the roundabout was in operation. Within this data set, the number of fixed object crashes was the most unexpected finding. After further evaluating the crash reports of the three intersections with the most fixed object crashes, which account for nearly 60% of all these crashes, it was determined that the fixed objects referred to in the crash reports were curbs (i.e. splitter island, central island) and sign posts (i.e. yield sign). Forty-one percent of the rear end crashes occurred at one intersection and these crashes took place consistently from year to year.

Other crash statistics of interest are the number of single-vehicle, night; alcohol related and truck related crashes occurring at roundabouts. Three intersections accounted for half of the single-vehicle crashes. Thirty-eight percent of crashes at the roundabouts were single-vehicle crashes. Night crashes were reduced slightly and crashes involving trucks remained unchanged. Although alcohol related crashes were only increased slightly, anecdotal evidence has indicated that impaired drivers have a difficult time negotiating roundabouts. In fact, one jurisdiction targets drivers under the influence at roundabout intersections. Table 5 summarizes these results.

**TABLE 5. Change in Crash Types**

	<b>Before</b>	<b>After</b>	<b>Change</b>
<b>Angle</b>	353	42	-
<b>Turning movement</b>	27	6	-
<b>Head on</b>	19	0	-
<b>Fixed Object</b>	19	68	+
<b>Sideswipe</b>	14	28	+
<b>Rear end</b>	61	44	-
<b>Run off the road</b>	4	7	+
<b>Other</b>	10	16	+
<b>Unknown</b>	4	1	-
<b>Single vehicle</b>	24	80	+
<b>Night</b>	83	71	-
<b>Trucks</b>	28	28	No change
<b>Alcohol related</b>	21	26	+

An area within crash reporting that does not always surface is an investigation of the types of crashes that are producing injuries. Injury crashes were reduced from 299 to 44, which is an 85% reduction. That alone is a staggering safety improvement at these intersections. Table 6 shows a comparison of the crash types and number of injury crashes that resulted from each. Two-hundred and five of those angle/turning crashes were reduced to only six after the roundabouts were installed.

Rear end injury crashes were the most prevalent at the roundabouts in the after condition (28 before and 15 after) and they either occurred when a vehicle within the circulating roadway stopped unexpectedly or a vehicle on the approach. In the after period, it was sometimes difficult to distinguish from the crash records where the crash should be coded as run-off-the-road or fixed object as in many cases they appeared to have happened simultaneously (i.e. hitting the curb). The “incomplete crash records” at five of the intersections (2-before, 3-after), did not distinguish the crash severity by crash type.

**TABLE 6. Injury Crashes by Crash Type<sup>1</sup>**

	<b>Before</b>	<b>After</b>	<b>Change</b>
<b>Angle/turning</b>	205	6	-
<b>Rear end</b>	28	15	-
<b>Head on</b>	8	0	-
<b>Sideswipe</b>	9	5	-
<b>Fixed object</b>	6	6	No change
<b>Run off the road/Loss of control</b>	2	7	+
<b>Other</b>	5	3	-
<b>Incomplete Crash Records</b>	24	3	-
<sup>1</sup> This table excludes fatal crashes.			

In summary, the descriptive statistics show undoubtedly that the number of severe crashes was reduced (85%) at each of these intersections after roundabouts were installed and in most cases total crashes were also reduced. Another finding that can be quantified with this data set are the types of crashes occurring at roundabout are considerably different from four- and three-legged stop controlled intersections and they are the types of crashes that produce less severe crashes. The reductions in crashes at rural intersections with high-speed approaches is consistent with US crash data for all roundabouts (6,10,15) as well as international intersection crash data (16).

## **Before and After Analysis: Estimation of Statistical Significance – Empirical Bayes**

The summary statistics above provide a good understanding of the intersection crash experience but lacks statistical significance of the before and after results. The next two sections provide a better understanding of the statistical significance of this data.

## Methodology

It is commonly documented in research papers that traditional methods for statistical analysis are a way of the past, sometimes called “naïve” analyses (i.e. descriptive statistics). It is becoming more mainstream to utilize sophisticated statistical approaches that before were only tackled by statisticians in the past. By no means can transportation engineers replace statisticians in doing these types of analyses, nor should they, but the Highway Safety Manual (12) and companion software as well as other available literature have made statistical analysis techniques more readily available. For the average jurisdiction across the United States the utilization of these more traditional methods is still in practice but hopefully these methods are being applied knowing the drawbacks (i.e. regression-to-the-mean, sample size, variation in data years) and taking them into account when considering alternative safety treatments.

Although this might be the case, we can not ignore that transportation agencies are using these “naïve” methods. It would be important to know how much different the results are between the methods. Persaud and Lyon (17) provided a comparison of nine empirical Bayes (EB) studies (with a range of treatments being analyzed) with a naïve analysis of the same data. The naïve analysis consisted of computing expected crashes by using the ratio of before crashes to number of years and converting that directly to the estimated number of after crashes using number of years after only. Results showed a notable difference in the reduction in the number and percentage of crashes. For example, the naïve analysis showed a 50% (278 crashes) reduction in crashes and the EB analysis showed a 40% (180) reduction based on the expected number of crashes if the treatment was not implemented. The naïve study estimate showed an inflated estimate of the expected number of crashes without



treatment which then corresponds to a larger reported reduction in crashes. This paper shows evidence that the EB model approach to crash analysis to be more robust than the naïve analysis described, as it responds to regression-to-the-mean and accounts for changes in traffic volume and years of data.

Elvik (18) compared five different versions of EB prediction techniques, including  $k+1$  method, negative binomial distribution (method of moments), negative binomial (maximum likelihood) and two accident prediction models. It was concluded that for estimates of the expected number of accidents, that the EB approach represents the state-of-the-art approach to observational before-and-after studies and should be preferred to alternative approaches.

The EB before and after procedure will ideally account for regression to the mean by considering the variable traffic volumes and before and after period lengths. The most recent roundabout research has estimated the statistical significance of changes in crashes using the EB methodology. Both the Insurance Institute of Highway Safety study (6, 19) and NCHRP Report 572 *Applying Roundabouts in the United States* (7) accepted this method in presenting the safety results for intersections converted to roundabouts.

Equations 1 through 15 are used for the EB before and after procedure.

The change in safety at the treated intersection is shown by:

$$B - A \quad \text{Equation 1}$$

$$m = w_1(x) + w_2(P) \quad \text{Equation 2}$$

$$w_1 = \frac{P}{(k + nP)} \text{ or } \frac{P}{\left(P + \frac{1}{k}\right)} \quad \text{Equation 3}$$

$$w_2 = \frac{k}{(k + nP)} \text{ or } \frac{1}{k \left( P + \frac{1}{k} \right)} \quad \text{Equation 4}$$

$$k = \frac{P^2}{\text{Var}(P)} \quad \text{Equation 5}$$

$$\text{Var}(A) = A \quad \text{Equation 6}$$

Where:

- B** is the expected number of crashes that would have occurred in the after period without the new treatment
- A** is the number of reported crashes in the after period
- P** an estimate of the annual number of crashes that would be expected at intersections with traffic volumes and other characteristics similar to the one being analyzed, the regression prediction
- x** count of crashes
- n** years before conversion
- m** Estimate of the expected number of crashes at the intersection before conversion
- w<sub>1</sub>, w<sub>2</sub>** Weights estimated from the mean and variance of the regression estimate
- k** a constant for a given model and is estimated from the regression calibration process

The significance of the difference ( $B-A$ ) is established from this estimate of the variance of  $B$  and assuming, on the basis of a Poisson distribution of counts, that  $\text{Var}(A) = A$ .

The expected annual number of crashes during the before period is estimated as:

$$m_b = \frac{(k + x_b)}{\left( \frac{k}{P + y_b} \right)} \quad \text{Equation 7}$$

$$R = \frac{P_a}{P_b} \quad \text{Equation 8}$$

$$m_a = R \times m_b \quad \text{Equation 9}$$

$$B = m_a \times y_a \quad \text{Equation 10}$$

$$Var(B) = \frac{(m_a)x(R \times y_a)^2}{\left[\left(\frac{k}{P}\right) + y_b\right]} \quad \text{Equation 11}$$

$$\pi = \sum B \text{ and } \lambda = \sum A \therefore \delta = \pi - \lambda \quad \text{Equation (12a,b,c)}$$

$$Var(\delta) = \sum Var(B) + \sum Var(A) \quad \text{Equation 13}$$

$$\theta = \frac{\left(\frac{\lambda}{\pi}\right)}{\left[1 + \left(\frac{Var(\pi)}{\pi^2}\right)\right]} \quad 100(1 - \theta) \text{ is the percent change in crashes} \quad \text{Equation 14}$$

$$Var(\theta) = \theta^2 \frac{\left[\left(\frac{Var(\lambda)}{\lambda^2}\right) + \left(\frac{Var(\pi)}{\pi^2}\right)\right]}{\left[1 + \frac{Var(\pi)}{\pi^2}\right]^2} \quad \text{Equation 15}$$

Where:

- R** is the ratio of the after period to the before period regression predictions
- y<sub>a</sub>, y<sub>b</sub>** length of the after (before) period in years
- δ** the reduction of the expected number of crashes
- θ** a biased estimate of the index of effectiveness, index of effectiveness

### *Safety Performance Functions (Regression Models)*

As indicated above, the EB analysis requires the use of a safety performance function (SPF) to conduct the estimation. Generally SPF's take the form of Equation 16. It is ideal that the SPF be developed specifically for the intersection and safety data from the jurisdiction where the data is being compared, however this process requires a significant undertaking, especially for a data set that has data from six different states. The resources to create specific SPF's for this data were not available for this research. Despite this limitation, the literature presents several models (20,21,22) that have been developed using intersection and crash data from the state of Minnesota. The robustness of Minnesota crash and intersection

data and with a Minnesota intersection represented in the data, the use of this model was deemed appropriate for use with this analysis. Additionally, utilizing SPF's already established within the literature is an accepted practice that is seen in both Persaud et al. (5) and Rodegerdts et al. (7).

$$\log(\mu) = \alpha_0 + \alpha_1 x \log(DEV) \text{ or } \mu = \exp(\alpha_0) x DEV^{\alpha_1} \quad \text{Equation 16}$$

Bonneson and McCoy (20) developed a model to predict annual expected crash frequency for two-way stopped controlled intersections on rural highways. The data set used to develop this model included 125 rural intersection in Minnesota where 108 of those intersections were on two-lane highways with the majority of the major road ADT's under 4,000 (min -430; max -37,900) and the mean crashes per year were 0.67 (min-0; max-7). Although the current data set has a higher mean traffic volume (6,300 AADT) and a higher number of crashes/year (5 crashes/year) it is assumed that this Bonneson and McCoy model represents a similar rural intersection population for the states in this study. It should also be noted that many of the intersections included in the current data sets have a higher than average number of crashes and thus is one of the reasons they were targeted for a new intersection treatment.

The following model shown in Equations 17a and 17b was developed by Bonneson and McCoy (20) for crashes per year at four-legged intersections with two-way stop controlled intersections.

$$E(m) = 0.692 \left( \frac{T_m}{1,000} \right)^{0.256} \left( \frac{T_c}{1,000} \right)^{0.831} \quad \text{Equation 17a}$$

$$E(m) = 0.000379 (T_m)^{0.256} (T_c)^{0.831} \quad \text{Equation 17b}$$

Where :

$E(m)$  = expected crash frequency per year

$T_m$  = major road traffic volume

$T_c$  = minor road traffic volume

Vogt and Bared (21,22) similarly modeled both rural four- and three-legged intersections with stop control. The research also used intersection and crash data from Minnesota and Washington State, however the final negative binomial models only included the Minnesota data, as it was determined more robust. The Vogt and Bared models for total crashes per year contain more explanatory variables than the Bonneson and McCoy model, as shown in Equations 18 and 19:

Crashes per year for four-legged intersection of two-lane rural roads, stop controlled on the minor.

$$y = (ADT1)^{0.603} x (ADT2)^{0.609} x e^{-10.4} x e^{(0.0449HI+0.289VCI+0.01875SPDI+0.124ND-0.0049HAU)} \quad \text{Equation 18}$$

Crashes per year for three-legged intersection of two-lane rural roads, stop controlled on the minor.

$$y = (ADT1)^{0.805} x (ADT2)^{0.504} x e^{-13.0} x e^{(0.0339HI+0.290VCI+0.0285SPDI)} x e^{(0.173RHRI+0.267RT+0.0045HAU)} \quad \text{Equation 19}$$

Where:

- |             |   |
|-------------|---|
| <b>y</b>    | predicted mean number of intersection or intersection related crashes within 250 ft of the intersection   |
| <b>ADT1</b> | average two-way major road traffic in vehicles per day  |
| <b>ADT2</b> | average two-way minor road traffic in vehicles per day  |
| <b>HI</b>   | sum of degree of curve in degrees per 100 feet for each horizontal curve on major road any portion of which is 250 ft of the intersection center, divided by the number of curves |

<b>VCI</b>	sum of the absolute change in grade in percent per 100 ft for each crest curve on major road any portion of which is within 250ft of the intersection center, divided by the number of such curves
<b>SPDI</b>	average posted speed in miles per hour on the major road in vicinity of the intersection
<b>RHRI</b>	Average Roadside Hazard Rating within 250 ft of intersection center along major road
<b>RT</b>	0 if no right turn lane on major, 1 if right turn lane exists on major road
<b>HAU</b>	angle in degrees between the increasing direction of major road and minor road minus 90 degree, multiplied by 1 if minor road is to the right and by -1 if minor road to the left

No injury models were provided by Bonneson and McCoy, however an approximate model (19) can be derived using the Minnesota four-legged intersection's ratio of injury to total crashes from Vogt and Bared (21,22). The equation above then takes the form as shown in Equations 20, 21, and 22:

$$InjuryCrashes / Year = 0.000194x(MajorRoadAADT)^{0.256} x(MinorRoadAADT)^{0.831}$$

**Equation 20**

Injury crashes per year for four-legged intersection of two-lane rural roads, stop controlled on the minor (21,22).

$$y = (ADT1)^{0.6330} x(ADT2)^{0.6229} x e^{-10.78} x e^{(0.0729HI+0.2789VCI+0.0112SPDI-0.1225RHR+0.124ND+0.0451RT-0.0043HAU)}$$

**Equation 21**

Injury crashes per year for three-legged intersection of two-lane rural roads, stop controlled on the minor (21,22).

$$y = (ADT1)^{0.8122} x (ADT2)^{0.4551} x e^{-13.04} \\ x e^{(0.034HI+0.187VCI+0.016SPDI)} x e^{(0.207RHR-0.012ND+0.362RT+0.0051HAU)}$$

**Equation 22**

## Analysis

Initially both the Bonneson and McCoy, and Vogt and Bared SPF models were used to predict the crash frequency for total and injury intersection crashes at the four-legged intersections and only the Vogt and Bared model SPF was used for the three-legged intersections. The Bonneson and McCoy model better predicted the total and injury crashes for the four-legged intersections, and therefore was used in the EB estimation of significance

Once the best available SPF models were determined, another technique used to more closely represent the specific data set, when SPF's are not available for the specific jurisdictions, is to recalibrate these SPF's (7,23). This is done by using only the crash data one year prior to the installation of the roundabout, to attempt to avoid a random high crash count in the before period that would overestimate the safety performance (7). A yearly calibration factor,  $C_i$ , is determined as shown in Equation 23 and then is added as a multiplier for the SPF.

$$C_i = \frac{\sum \text{observed\_accidents}_i}{\sum \text{predicted\_accidents}_i}$$

**Equation 23**

## Results

The results using the Bonneson and McCoy model and the calibrated Bonneson and McCoy, as described above, were evaluated to determine how well the model fit the data represented in this study. On an individual basis, nine of the intersections' average total observed crashes per year were predicted within 2% of the un-calibrated model, five

intersections were predicted within 3% of the calibrated model, four intersections were over predicted by both models between 12 and 36%, and one intersection was estimated the same for both models. For injury crashes, nine of the intersections' average observed injury crashes per year were predicted within 1% of the un-calibrated model and seven intersections' average observed injury crashes per year were within 2% of the calibrated model. The breakdowns of these comparisons are shown in Appendix E.

The before and after analysis results of rural roundabouts with high-speed approaches are shown in Tables 7 and 8. A range for the estimates is shown, representing both the calibrated and un-calibrated safety performance functions from Bonneson and McCoy. Results for both the calibrated and un-calibrated models are presented here, as there was not overwhelming evidence to choose one over the other.

Both of the estimates of the percentage reduction in crashes for total and injury (including possible injury) crashes ranged from 62% to 67% and 85% to 87%, respectively. These results are consistent with the findings of the nine intersections in the NCHRP Report 572. The EB estimate of crashes that is expected if roundabouts were not installed is shown for the 98 data years in which actual before and after data were available. With longer study periods, as is the case with these data, there are more opportunities for crashes to occur. Consequently, the observed crash history is likely to be more meaningful and the model prediction less important so, as the predicted crashes increase, the EB method places more weight on the number of crashes that actually occur (12).

Only considering intersections with two-way stop control prior to the conversion to a single-lane roundabout, these results show a slightly higher reduction in total and injury crashes from 71% to 74% and 87% to 89%, respectively. The other sub-categories, two-lane



roundabouts and one-way stop control before conversion, only had one and two intersections, respectively, in each of the categories. So although, we can consider those results at the disaggregate level, they may not be representative of a larger subset of the same types of intersections converted to roundabouts. Additional intersections would be needed to better represent these categories.

**TABLE 7 . Before and After Crash Comparison Results for the Calibrated Model**

Control Before	Sites	Lanes	Crashes recorded in after period		EB estimate of crashes expected without roundabouts		Index of Effectiveness and Point Estimate of the Percentage Reduction in Crashes	
			All	Injury	All	Injury	All	Injury
All	19	All	212	44	631.5	347.3	.335 67%	.126 87%
Two-way stop (4 legs)	17	All	197	42	613.6	341.1	0.322 68%	.122 88%
	16	1	149	35	580.3	324.4	.256 74%	.107 89%
	1	2	48	7	33.3	16.6	1.41 -41%	.405 60%
One-way stop (3 legs)	2	1	14	2	17.9	6.3	.739 26%	.276 72%

**TABLE 8. Before and After Crash Comparison Results for the Un-Calibrated Model**

Control Before	Sites	Lanes	Crashes recorded in after period		EB estimate of crashes expected without roundabouts		Index of Effectiveness and Point Estimate of the Percentage Reduction in Crashes	
			All	Injury	All	Injury	All	Injury
All	19	All	212	44	552.5	283.7	.383 62%	.15 85%
Two-way stop (4 legs)	17	All	197	42	536.5	278.7	.368 63%	.15 85%
	16	1	149	35	507.3	265.1	.29 71%	.13 87%
	1	2	48	7	29.1	13.6	1.61 -61%	.49 51%
One-way stop (3 legs)	2	1	14	2	16.0	5	.828 17%	.35 65%

## Prediction Modeling Considerations and Development

According to Ott and Longnecker (24), the Poisson distribution is commonly used for estimating the probability of occurrences of an event that takes place randomly over a specified time period, as long as the assumptions are not unreasonably violated. It assumes that crashes typically occur one at a time and crashes are independent of one another at an intersection. This assumption is consistent with the Maiou and Lum (25) assessment when they concluded that the Poisson regression and negative binomial models are able to effectively explain statistical properties of crashes because of its' ability to process discrete random variables compared to conventional linear regression models.

### Poisson Model

The Poisson model has the form shown in Equation 24.

$$\mu_i = e^{(\beta_0 + \sum_{j=1}^n x_{ij} \beta_j)} \quad \text{Equation 24}$$

$\mu$  = mean number of crashes to be expected at site  $i$

$x_{i1}, \dots, x_{in}$  = values of the highway variables at site  $i$

$\beta_0, \beta_1, \dots, \beta_n$  = coefficients to be estimated by the model

The variance in the number of accidents at a site is equal to the mean  $\mu_i$ .

### Negative Binomial Model

The negative binomial model has the form shown in Equation 25.

$$P(y_i) = \frac{\Gamma\left(y_i + \frac{1}{K}\right)}{y_i! \Gamma\left(\frac{1}{K}\right)} x \left(\frac{Ku_i}{1 + Ku_i}\right)^{y_i} x \left(\frac{1}{1 + Ku_i}\right)^{\frac{1}{K}} \quad \text{Equation 25}$$

$K$  = overdispersion parameter

The variance of the negative binomial model is shown in Equation 26:

$$u_i + K(u_i)^2 \quad \text{Equation 26}$$

### Model Appropriateness

Both the Poisson and negative binomial models are appropriate for crash data, however, it is still important to determine if one model is more adequate in than the other. Two easy ways to measure the accuracy of the Poisson model are deviance and Pearson Chi-Square. If the Poisson model is adequate, the expected value for both deviance and Pearson Chi-Square (value/degrees of freedom) are close to one, otherwise the validity of the model may be in question. A ratio (greater than one) may indicate an over-dispersed response variable. In this case the deviance can be scaled to one for the Poisson model, however this

still leaves some uncertainty in the model as this is just a correction term (26) for testing the parameter estimates under the Poisson model.

The negative binomial model can account for the potential over-dispersion. The negative binomial dispersion accounts for overdispersion because its' variance is always greater than the variance on a Poisson distribution with the same mean (26). As  $k$  approaches zero, the negative binomial model approaches the Poisson model.

## Variables

Both total and injury crashes were modeled using the following explanatory variables.

<b>logDEV</b>	Log of Intersection daily entering volume
<b>LEGS</b>	Number of approach legs
<b>SPDMAX</b>	Maximum posted speed limit on major approach
<b>YEARSBA</b>	Offset variable – number of crash data years

This data set included two intersections with three approaches before and after the conversion of the roundabout and two intersections with four approaches before and five approaches in the after condition.

The statistical before and after study was designed to provide a more robust interpretation of the crash data than the descriptive statistics at rural roundabouts on high-speed roadways. The dataset for rural roundabouts on high speed roadways is the largest available, providing over 98 years of total before crash data and 98 years of total after crash data for the intersections combined. SAS 9.1.3 (27) was used to derive a regression model for the rural roundabout crash data.

The deviance and Pearson Chi Square divided by the degrees of freedom for the Poisson model was not close to one therefore it is expected that the model may be overdispersed and not a good fit for the data. Subsequently, the negative binomial model resulted in deviance and Pearson Chi-Square values divided by degrees of freedom near one for the initial models and thus were assumed to be satisfactory models for this data. No subsequent models were explored.

The number of years before and after was established as an offset variable in the model, as they are not constant and fluctuates between intersections and within intersections from the before to after period. Additionally, because each site was included in the analysis two times, once in the before period and once in the after period, a repeated subject entity had to be included in the analysis. In the before and after crash comparisons, a repeated subject code was needed because each intersection was represented twice in the model, before and after. The “repeated” statement was added to the SAS code in this case and as a result the standard errors are underestimated in the initial model (27) and a generalized estimating equation (GEE) is produced for the final model. The repeated code was not needed for the after only model.

Although both major road DEV and minor road DEV were available, the model was stronger when only DEV for the intersection was used. Separating the major and minor road traffic volumes in the model indicated that the minor DEV was not a significant variable in the model. The combined DEV indicated a better fit model.

### *Results/Statistical Inference*

The statistical results show the estimated reduction in the total crashes after the roundabout was constructed, 63%, is statistically significant (p-value <0.0001) and the estimated reduction in the injury crashes, 88%, is also statistically significant (p-value <0.0001). The regression estimate also showed the changes in the crash types after the roundabout was constructed showed a statistically significant (p-value <0.0001) reduction in the number of angle crashes, 83%. The 15% reduction in rear end crashes, was not statistically significant (p-value 0.4489), however the 366% increase in fixed object crashes was statistically significant (p-value 0.0005) and the 179% increase in sideswipe crashes was not statistically significant (p-value 0.0579) however this increase was just outside the 95% confidence level. The reduction in the PDO crashes was not significant.

Fourteen intersections had detailed enough crash data to estimate the statistical significance of the changes on injury crashes by type. A 91% reduction in injury-angle crashes after roundabouts were constructed which was statistically significant (p-value <0.0001). 46% reduction in injury-rear end crashes was not statically significant (p-value 0.0938) at the 95% confidence level. Table 9 summarizes these results and the SAS output is shown in Appendix F.

**TABLE 9. SAS Contrast Estimate Results (After vs. Before)**

<b>Difference in mean crashes</b>	<b>Estimate of the difference in percentage</b>	<b>Level of significance (p-value)</b>	<b>Significant?</b>
<b>Total crashes</b>	63%	<0.0001	Yes
<b>Injury crashes</b>	88%	<0.0001	Yes
<b>Angle crashes</b>	83%	<0.0001	Yes
<b>Rear end crashes</b>	15%	0.4489	No
<b>Sideswipe crashes</b>	179%	0.0579	No
<b>Fixed object crashes</b>	366%	0.0005	Yes
<b>Injury-angle crashes</b>	91%	<0.0001	Yes
<b>Injury-rear end crashes</b>	46%	0.0938	No

## **Rural Roundabout Prediction Models**

The NCHRP Report 572 (7) provides intersection prediction models based on United States roundabout data. The general models are used for estimating the expected number of crashes at an existing or planned roundabout as a function of the number of approach legs, number of circulating lanes and traffic volumes. There is not, however, intersection-level safety prediction models for total crashes and injury crashes for rural intersections with high speed approaches. This research set out to develop these models for this particular intersection environment and also determine how closely the general roundabout crash prediction models developed in NCHRP Report 572 (7) estimated this data set. Both fatal and possible injury crashes were used to determine an injury crash prediction model for rural roundabouts. All nineteen roundabouts, regardless of the number of legs and traffic volume, were included in one model.

For both the total crash and injury crash prediction models, one intersection acted as an outlier in the model (i.e. the total number of crashes was nearly 10 times higher than each

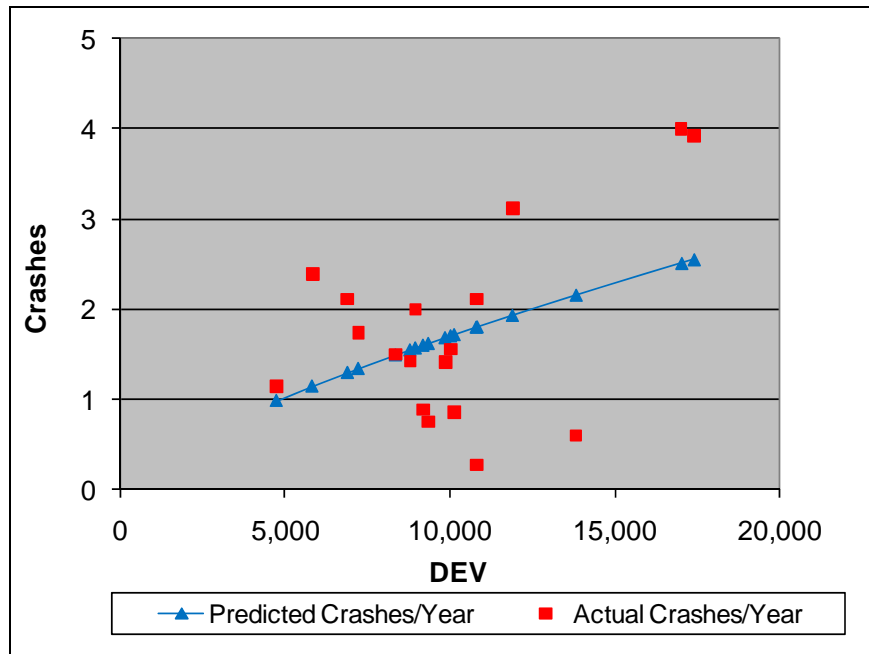
of the other intersections) and thus produced a model that was skewed towards the outlier. This roundabout was the only roundabout that the single approach lanes were widened for a two-lane roundabout. It is expected that two-lane roundabouts would have higher total crashes than single-lane roundabouts. After the one intersection was removed, the prediction models better fit the actual intersection results. The final models are shown in Equations 27 and 28. Figures 3 and 4 also show the predicted number of total and injury crashes relative to the predictive model.

Assessing the goodness of fit for the models showed that the negative binomial model resulted in deviance and Pearson Chi-Square values divided by degrees of freedom near one for the total and injury crash models and thus were assumed to be satisfactory models for this data. With such low crash experience at roundabouts and only eighteen intersections in the final model, this model will likely be improved as the number of rural roundabouts increases. The SAS output is shown in Appendix F.

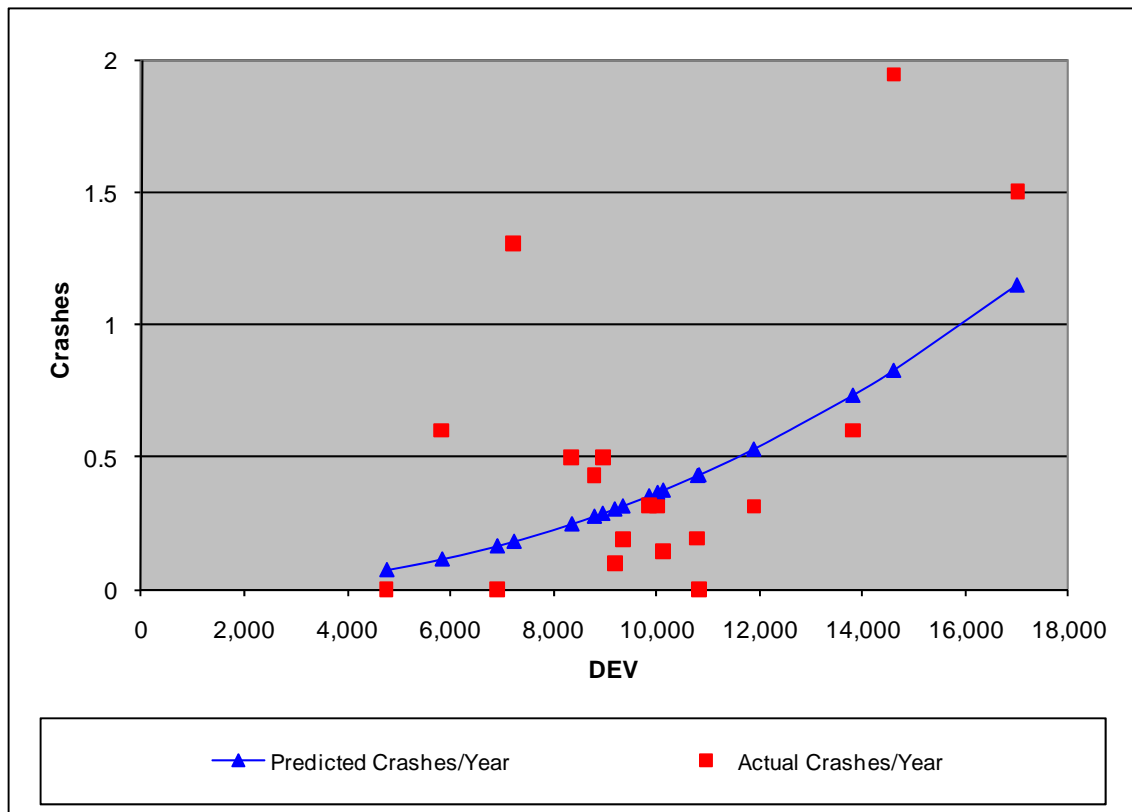
$$\text{Total crashes/year} = e^{-6.1810} \times (\text{DEV})^{0.7274} \text{ dispersion factor, } k=0.1525 \quad \textbf{Equation 27}$$

$$\text{Injury crashes/year} = e^{-21.0032} \times (\text{DEV})^{2.1703} \text{ dispersion factor, } k=0.1204 \quad \textbf{Equation 28}$$





**FIGURE 3. Total crashes predicted and observed**



**FIGURE 4. Injury (fatal and possible) crashes predicted and observed**

Providing a comparison of these crash prediction models, specific to rural roundabouts, to the general roundabout prediction equations provided in NCHRP Report 572 allows for an evaluation. The findings show that on average the NCHRP Report 572 total crash model (for 4 legs) slightly over predict crashes (by 0.57 crashes/year) compared to this new model where crashes are on average slightly under predicted (by 0.07 crashes/year). For the injury crash models, the NCHRP Report 572 general model (for 4 legs) and this new model are very similar in that they both slightly under predict crashes (0.17 and 0.1, respectively). Figures 5 and 6 show the prediction equations compared graphically along with the actual crash data in this data set. (Note: Nine of the roundabouts from NCHRP Report 572 research were included in this data set.)

The NCHRP Report 572 five-legged total crash model over predicts the two five-legged rural roundabouts in this data set by approximately 2 crashes/year. The NCHRP Report 572 three-legged total crash model under predicts the two three-legged rural roundabouts in this data set by about 0.5 and 2 crashes/year, respectively. Similarly, the NCHRP Report 572 injury crash models overpredict the five-legged rural roundabouts by approximately 0.5 injury crashes/year and under predict the injury crashes at three-legged rural roundabouts in this study by slightly less than 0.5 an injury crash/year.

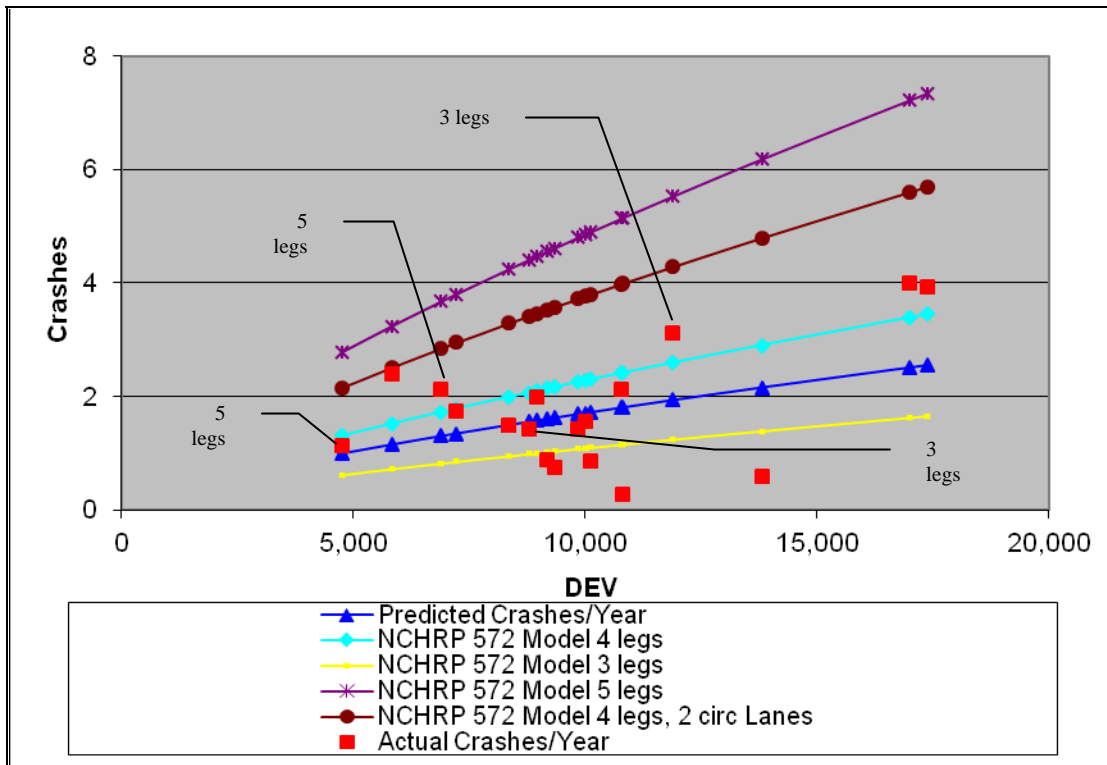


FIGURE 5: Comparison of predicted and observed total crash models

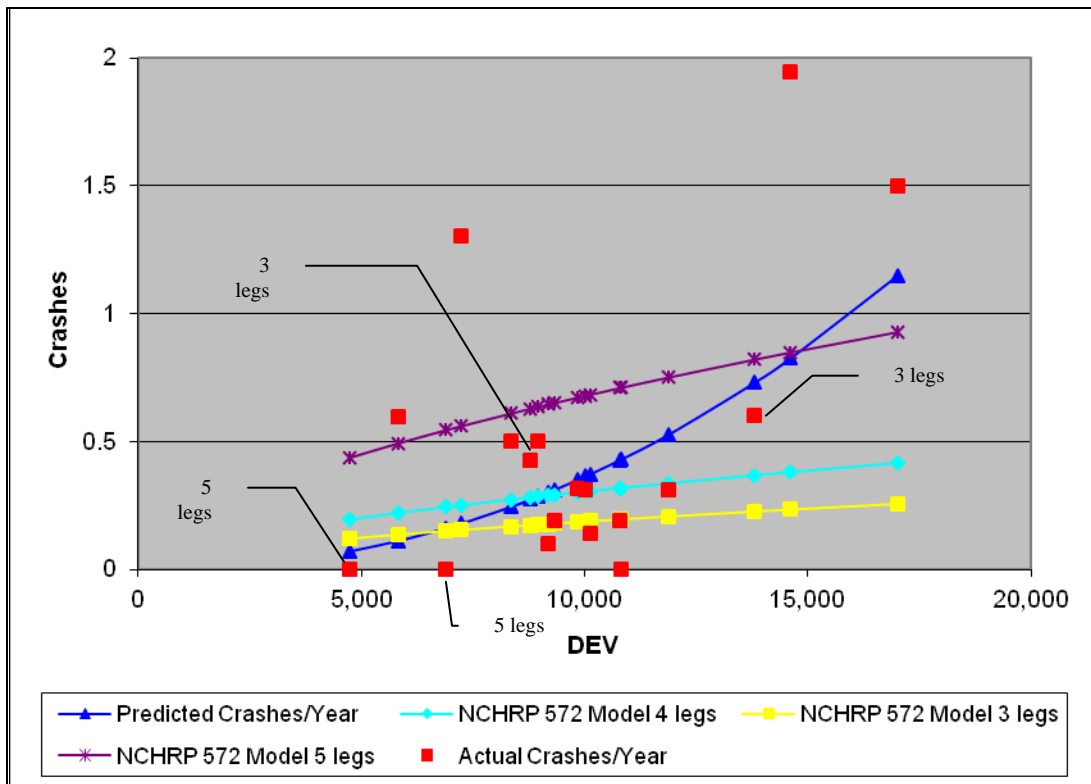


FIGURE 6: Comparison of predicted and observed injury crash models

## Summary and Conclusions

Transportation agencies are in need of intersection treatments that solve crash problems, not just change the crash experience. Roundabouts have proven to be effective in urban and suburban environments in the United States, but little has been reported on their effectiveness in rural environments with high-speed roadways. Roundabouts can provide an effective solution to rural intersections with high-speed approaches that have a poor crash history, and more specifically, an intersection with a history of injury crashes. The nature of the roundabout simply changes the dynamics of vehicles traversing the intersection. Drivers must slow their vehicles to a uniform speed and make an independent decision on how and when to proceed through the circular intersection, whose geometry is such that injury producing crashes (i.e. angle or T-bone) are virtually eliminated. Several states in the United States have embraced the safety benefits that rural roundabouts provide and they continue to increase the number of roundabouts on high-speed roadways.

A negative binomial regression model was created to estimate the effectiveness of roundabouts in these rural locations. The findings of this research show statistically significant reductions (95% level) in the number of total and injury crashes after roundabouts are installed at rural intersections on high-speed roadways. The reductions in total and injury crashes are 63% and 88%, respectively. Both of these statistics indicate a slightly higher reduction in total and injury crashes than the general statistics provided in NCHRP Report 572, where the estimate of total crash reduction is 35% and injury crash reduction is 76%. There are several reasons that this may be the case, 1) rural roundabouts tend to be single lane roundabouts so the total number of crashes sees a larger reduction, and 2) rural

roundabouts tend to be constructed in locations with a poor crash history which might also reduce the crash experience more than urban and suburban roundabouts.

A before and after empirical Bayes estimation was also conducted. The index of effectiveness and percent reduction in crashes were consistent with the negative binomial regression model results, indicating a 62 to 67% reduction in total crashes and an 85 to 87% reduction in injury crashes at these rural intersections.

Dissecting the crash data further for 14 of 19 intersections showed that roundabouts change the types of crashes at intersections and reduce the number of injury type crashes. Angle crashes proved to be the most injury producing type of crashes at these intersections. Not only were potentially dangerous angle crashes decreased by 83%, but the number of actual injury producing angle crashes were reduced by 91%, both statistically significant reductions. Rear end crashes was the second most likely crash type to produce an injury and although the number of injury rear end crashes was reduced by 46%, the finding was not significant and the 95% level.

Furthermore, now planning level total and injury crash prediction models are available for rural roundabouts on high speed roadways. This model supplements the research presented in NCHRP Report 572, by providing more data and rural roundabouts specific models to the literature.

Finally, this research provides additional evidence that the safety benefits of roundabouts in rural environments are similar to what has been documented in urban areas in the United States.

## Limitations

The analyses for the data are limited to the nineteen intersections included in this study. However, when this analysis was conducted these were the only nineteen roundabouts that met the characteristics and had enough before and after data to be evaluated.

Additionally, the crash prediction models fit the data better than the NCHRP Report 572 models though the data presented here were used to create the model. The models presented here need to be calibrated and/or validated with rural roundabouts not included in the original data set.

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## CHAPTER 6. APPROACH SPEED EFFECTS AT RURAL HIGH-SPEED INTERSECTIONS: ROUNDABOUTS VS TWO-WAY STOP CONTROL

A paper to be submitted to the *American Society of Civil Engineers Journal of Transportation Engineering*.

Hillary Isebrands, Shauna Hallmark and Neal Hawkins

### **Abstract**

Speed can increase the risk injury producing crashes, especially at intersections where vehicles may be approaching an intersection and entering an intersection with high speed differentials. It is known that roundabouts force all drivers to reduce their speed in the intersection; however, no advanced approach speed data was available for roundabouts with high speed approaches to verify this phenomenon. This research performed a comparative evaluation of the difference in the average approach speeds between rural roundabouts and rural two-way stop control intersections and between rural roundabouts with and without rumble strips on the intersection approaches. Approach speed data proved that drivers are able to slow down in advance of roundabouts on rural roadways and the mean speeds at 100 ft from the yield line were 2.5 mph lower than mean speeds at 100 ft from the stop bar at stop controlled approaches. Additionally, a comparison between roundabout approaches with and without rumble strips showed mean speeds 4.3 mph and 3.3 mph lower at 100 ft and 250 ft from the yield line, respectively, for the approaches with rumble strips; however, the variation in speeds increased with the introduction of rumble strips.

## Introduction

“Drivers, vehicles and roadways are complicated co-contributors in traffic accidents.”

(1). This statement holds true over 40 years later, despite the advancements we have seen in vehicle safety and improvements in roadway guidelines and designs. Regardless of the engineering advances that have been made, driver error continues to be a major contributor to motor vehicle crashes so roadway and intersection designs should be forgiving to allow roadway users an opportunity to recover. Design can reduce the incidence of human error, chance of human error resulting in a crash and the severity of the consequences of crashes (2).

Fatal crashes still occur in abundance on our roadways and are over-represented on rural roadways. National statistics show that the fatality rate on rural non-interstate roads is 2.35 per 100 million vehicle miles traveled (MVMT). That is nearly three times higher than the urban non-interstate roadway fatality rate (3). Nearly 40 % of those fatalities (2,830) are at rural intersections. The percentage of fatalities occurring at intersections remains steady despite vehicle miles traveled declining in recent years which indicates that fatal crashes at intersection are declining at a pace consistent with crash trends but we still are not seeing any significant reductions with the countermeasures that are being implemented. More alarming is that approximately one-third of all injury crashes and 15% of all fatal crashes occur at traffic signals and stop signs (4).

The type of control and/or design at a rural intersection has varying levels of safety and risk. All way stop control intersections typically have safe crash histories however there is still some risk of a driver running a stop sign. Two way stop control intersections, by design, promote free flow speeds on the major route while the minor road must stop;

introducing risk if a driver runs a stop sign. Similarly, a signalized intersection on high speed rural roadway assigns right of way at the intersection, with actuation on the minor road.

Speed differentials at stop controlled and signalized intersections introduce the risk of high speed, angle crashes which tend to increase the likelihood of a severe injury.

Speed is often a contributing factor to intersection crashes (5), however, only a modest number of studies evaluate speeds at intersections and its' relationship to safety (6). Speed, speed variances, and deceleration rate have been identified as surrogates for crash risk (7,8,9,10,11,12,13). Additionally, surrogate events to crashes, like speed, may provide complementary information to decision makers (14) when determining an appropriate intersection countermeasure that yields the highest benefits.

One forgiving engineering solution that addresses speeds at intersections and that has only recently been recognized by transportation agencies is the modern roundabout, hereinafter referred to as roundabout. The geometric features of a roundabout slow *all* vehicles approaching and entering an intersection. This reduces speed variances between vehicles on the same approach as well as on the other approaches and significantly reduces the probability of right angle - injury prone crashes.

Roundabouts slow *all* approach traffic entering the intersection to a consistent range of speeds – speeds are controlled by the geometry of the roundabout intersection. Although, little published research has focused on the overall safety effectiveness of roundabouts on high speed roadways two studies (15,16; See Chapters 4 and 5 of this dissertation) show substantial reduction in injury crashes at roundabouts . Isebrands (16) reports the average injury crash frequency was reduced by 84%, average injury crash rate was reduced by 89%,

angle crashes were reduced by 86%, and fatal crashes were reduced by 100% at seventeen rural roundabouts with high speed approaches.

In 2008, the Federal Highway Administration (FHWA) issued a memorandum, *Consideration and Implementation of Proven Safety Countermeasures (17)*, which highlighted modern roundabouts as one of these nine proven safety countermeasures. The excerpt below represents the FHWA's position regarding roundabouts:

“Roundabouts are the preferred safety alternative for a wide range of intersections.” ...”Roundabouts should also be considered for all existing intersections that have been identified as needing major safety or operational improvements. This would include freeway interchange ramp terminals and rural intersections.”

This research used field data from six rural intersections (four roundabouts and two two-way stop controlled) to evaluate the differences in the approach speeds at roundabouts and two-way stop controlled intersections with different advanced traffic control.

## **Study Description**

### **Need for Research**

Although modern roundabouts have gained recognition as a viable intersection alternative that improves intersection safety and operations, many transportation agencies are still reluctant to construct roundabouts in rural locations on high-speed roadways (greater than 40 mph). Numerous government agencies and citizens argue that roundabouts are for urban and suburban environments and are not appropriate on rural roadways. Much of the speculation comes from comments such as these

- “Drivers are not used to having to *slow down* on that roadway.”
- “I never had to slow down at that intersection before and if you construct a roundabout I am going to have to slow down and it will take me longer to get home.”
- “How will drivers know there is a roundabout ahead so they can *slow down*?”
- “Drivers won’t be able to navigate the intersection are we are going to see more crashes than we had before.”
- “Roundabouts might be appropriate in other states but we have adverse weather conditions here (i.e. snowy, foggy, and rainy regions) and they just are not going to work.”

Before and after safety data is now available for rural roundabouts on high speed roadways which shows between 84% and 87% reduction in injury crashes (15,16), but concerns still remain on the ability of drivers to slow down in advance of a roundabout in order to navigate it safely. The only speed data that has been collected at roundabouts was a part of the NCHRP Report 572, *Roundabouts in the United States* (15). Although speed based prediction model for roundabouts showed promise from this research, the dataset was not robust enough to recommend a safety prediction model at this time. Additionally, the number of roundabouts and approaches at rural locations was limited and approach speed data was only calculated at locations 200 ft from the yield and at the yield line.

Looking beyond roundabouts, the FHWA is supporting strategies to improve driver awareness on intersections approaches, of traffic control to minimize crash frequency and severity, reduce operating speeds on intersection approaches (18). Speed data in general have not extensively been studied on intersection approaches. A 2008 study, that evaluated three potential speed reduction treatments (transverse pavement markings, rumble strips,

dynamic warning signs) at high speed intersections, concluded that “additional research is needed to fully understand the effects that speed reduction treatments and reduced speed may have on safety” (6).

## **Research Objectives**

Roundabouts on rural high speed roadways can improve the overall safety of the intersection and dramatically reduce the number of serious injury and fatal crashes. The primary objective of this research was to perform a comparative evaluation of the difference in the average approach speeds/speed profiles between roundabouts with and without rumble strips and between roundabouts and two-way stop control intersections, neither with rumble strips. The second objective of this research was to determine if speed and speed variation on the approaches is an appropriate/viable crash surrogate for intersection safety. The third objective of this research was to consider the crash data, more specifically, the types of crashes, contributing factors to the crashes and severity of crashes amongst the intersections and determine if a relationship between approach speed characteristics and crash data could be established.

## **Available Literature**

### *Safety Experience at Intersections on High Speed Roadways*

Prior intersection safety studies have shown fairly inconsistent results in terms of advanced traffic control that yields the best safety results at rural intersections on high speed roadways. What is known is that angle crashes dominate the highest frequency of crash

types at rural intersections followed by rear end crashes (19,20). Furthermore, angle crashes have a higher risk of causing severe injuries.

Research conducted by Agent (21) that evaluated countermeasures at stop controlled intersections in a before and after study. Sixty-five intersections on rural high-speed roadways in Kentucky identifying types of traffic control (stop signs, intersection beacon, signal control), types of accidents, contributing factors and making recommendations for countermeasures at such locations. Intersections that were converted from stop control to stop control with a beacon (eleven), from stop control to signal control (sixteen) and conversions from stop control with beacon to signal control (twenty) showed inconsistent results in before and after safety data. However, several interesting findings were reported for these rural intersections, 1) both the stop controlled and stop controlled with the beacon had higher percentages of angle crashes than the statewide average, 2) injury crashes accounted for 37 percent, 40 % and 34 % of the total crashes for stop controlled, stop controlled with beacon and signal control, respectively, while the statewide average for all intersection is 24 percent, indicating that intersections in these environments are at higher risk for injury crashes, and 3) the most common comments on the crash report were that after stopping the minor road the driver did not see the approaching vehicle (when sight distance was okay), the minor road vehicle did not stop, there was not enough time to stop when the signal turned red, and disregard for traffic signal. The research concluded that advance intersection warning is critical for drivers.

A similar study done in California identified approach characteristics that may affect crash rates at high-speed, isolated signalized intersections (8). Left turn phases for signal, raised medians, wide paved shoulders, and an advance warning sign with a flashing beacon



were significantly correlated to lower crash rates. The authors conclude that in order to minimize the potential surprise of drivers that effective advance warning, efficient traffic control and safe geometric features are necessary.

Thompson et al. (22) states that the number and severity of crashes at rural stop controlled intersections could be enhanced with the use of traffic control devices and found that rumble strips initially reduce approach speeds at a statistically significant level but this research did not address the long term safety effectiveness of transverse rumble strips.

Preston and Storm (23) found that right angle crashes were the most predominant type of crash at rural thru-stop controlled intersections in Minnesota and that these crashes were producing 62% of the series injury crashes and 71% of the fatalities. Fifty-seven percent of the right angle crashes occurred when the vehicle stopped pulled out in front of the vehicle with the right of way and another 26% of the crashes involved vehicles that ran the stop sign, these crashes were more severe. The field review indicated that more, brighter and larger stop signs and warning signs (i.e. use of large stop ahead sign) appear to reduce the number of running the stop sign crashes. Intersections with lighting and stop ahead pavement marking also had less crashes. A systematic approach of these potential mitigation strategies is suggested.

### *Roundabout Safety Experience*

The first quantitative roundabout crash data and safety analysis results were published as a part of NCHRP Report 572 *Roundabouts in the United States* (15). An empirical bayes (EB) statistical analysis showed a 35 % reduction in overall crashes and a 76 % reduction in injury crashes at 55 modern roundabouts. Furthermore, at nine rural locations the total crash

reduction was found to be 71 % and the injury crash reduction was reported at 87 percent. A study of nineteen rural roundabouts on high speed roadways found similar results with an 84% reduction in injury crashes (16).

Internationally, the safety record of roundabouts on high speed roadways has been consistent. New Zealand, Australia, United Kingdom and Belgium indicate that roundabouts have a particularly good safety record in high-speed environments compared to traditional intersection traffic control (24,25,26,27).

A before and after roundabout comparison of 122 intersections in Belgium by Antoine (25) showed a 42% decrease in injury crashes. The reduction varied by environment, 15%, 46% and 50% reduction in urban, suburban and open country (rural environment), respectively. A reduction of 15% of crashes was observed at all other intersection types. Traffic signals in the open country showed a crash frequency that was twice as high as roundabouts. The researchers affirm that in open country traffic signals should be avoided and roundabouts provide a safe intersection.

Design recommendations for approach geometry at roundabouts on high speed roadways vary from country to country and state to state. NCHRP Report 672, *Roundabouts: An Informational Guide, Second Edition* (28) suggests that there may be some benefit on rural high speed roadways to introduce additional design modifications (longer splitter island or horizontal curvature) to slow drivers in advance of the intersections rather than relying on signing. The treatments suggested for roundabouts with high speed approaches include, visibility or conspicuity of the central island (28,29) , outside and inside curbing to define the desired path of the vehicles and subtly encourage additional reduction in speeds with a narrower cross section, splitter islands with a minimum length of 200ft in advance of the

yield line, flatter and longer tapers in advance of the splitter islands, and potentially considering the introduction of approach curvature (26,28,30), however approach curvature is not recommended for design in New Zealand (31). Appropriate design of these curves is critical to their effectiveness and not introducing unintended consequences at the intersection (i.e. loss of control crashes with the curvature). There is no research in the US to suggest that one design is safer than the other.

A review of 50 safety audit reports of roundabouts resulted in a summary of key issues at roundabouts in New Zealand (29). Inadequate signing (location, appropriateness, size and quantity) has been noted as the most common problem by safety auditors according to Transfund New Zealand. Poor signing, inadequate or inappropriately located, (relating to rural environments) can lead to confusion for unfamiliar drivers seeking a particular location and affect the ability of the driver to anticipate the intersection. Transfund suggests providing larger warning signs on high speed approaches and/or increasing the number of signs (i.e. one on each side of the road) and installing large advance directional signs.

### *Approach Speed and Speeds as a Surrogate*

The relationship between intersection speed and safety is one that is speculated about often, but little data exists to clearly identify what that relationship might be. The research that is available is clear – speed can influence the likelihood of a crash and the severity of a crash. Hauer (32) found that on rural roadways that the larger variation from the median traffic speeds the more likely conflicts will occur. In TRB Special Report 254, *Managing Speed: Review of Current Practice for Setting and Enforcing Speed Limits*, (33)

acknowledges that the connection between speed and safety is complex. The report also states the following:

- “The probability of severe injury increases sharply with the impact speed of a vehicle in a collision, reflecting the laws of physics.”
- “Speed is also linked to the probability of being in a crash, although the evidence is not as compelling because crashes are complex events that seldom can be attributed to a single factor.”

The formula for kinetic energy, shown in Equation 1, provides the evidence to why speed and differential in speed makes a difference - velocity is squared. So when a driver reacts to an impending collision, the vehicle decelerates rapidly until the crash occurs but the occupants of the vehicles continue to move at the speed of the vehicle prior to the crash (34) and the risk of injuries and fatalities increases as a function of speed prior to the crash (35).

$$KE = \frac{1}{2} Mass \times Velocity^2$$

**Equation 1**

Harder et al. (36) performed a before and after simulation study of advance stop line rumble strips at rural intersections in Minnesota. The drivers in the simulator removed their foot from the brake at approximately the same time (~1100 ft) with and without the rumble strips but they applied the brake earlier (550 ft vs. 485 ft) and more often when rumble strips were present. It was theorized that the braking pattern associated with rumble strips is more controlled and might imply safer approaches to intersections, however on the flip side braking earlier may increase incidences of rear end collisions if vehicles are following too closely. This study suggested additional research in this area.

NCHRP Report 613 *Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections* (6,37), summarizes a before and after study of three speed reduction

treatments (rumble strips, peripheral transverse marking, dynamic warning sign) at ten intersections (19 approaches). Results showed that dynamic warning signs reduced the mean speed 1.7 mph, 2.3 mph and 2.8 mph at the following locations, respectively, sign, perception-reaction location (250 ft upstream) and the accident avoidance location; transverse pavement markings reduced overall mean speeds marginally by 0.6 mph; and transverse rumble strips produced statistically significant speed reductions at the perception-reaction location (1.3 mph) and there was no statistical significance at the location of the rumble strips or at the accident avoidance location (100 ft upstream). No documented safety effects were reported as a part of this study.

Although speed studies that have been done at intersections do show safety countermeasures with promise, no treatment can compare to the safety benefits of a roundabout. Roundabouts were recognized in NCHRP Report 613 (6) as a highly effective intersection treatment to reduce vehicle speeds at intersections on high speed roadways. NCHRP Report 572 *Roundabouts in the United States* (15,38) documented speed data at 200 ft upstream of the yield line, at the yield line, at the midpoint of the adjacent splitter island and at the exit point of the roundabout and concluded that vehicle speed is a driver's response to the design of the roadway.

Roundabouts, by design, slow all vehicles entering the intersection; however crashes still occur at roundabouts. Reported crashes at roundabouts with high speed approaches tend to be overrepresented by single vehicle crashes (38 percent). A study from the Insurance Institute of Highway Safety (39), reports that speed related issues at roundabouts may result from a lack of advanced signing, insufficient street lighting, wide approach lane widths, lack of conspicuous central island landscaping, and short splitter island lengths. Mandavilli et al.

(39) suggest several low costs solutions to encourage speed reduction prior to the roundabout, some include enhanced landscaping, reflective signs on the central island, extension of the splitter island, and enhanced street lighting. Turner and Roozenburg (24) report that there is a relationship between accidents, speed, traffic volume and sight distance at roundabouts.

Crashes still remain to be rare and random events and transportation agencies strive to assess risk on their roadways without waiting for a crash to occur. In the absence of crash data, surrogate events to crashes may provide complementary information to decision makers (14). Research identifies traffic conflicts, delay, encroachment, violations, road user behavior, and speed all as crash surrogates (3,7,10,11). Speed is a factor in 31% of all fatal crashes and of those 51% (5,398) are on non-interstate roadways with a posted speed limit of 40 mph or more (4). Specifically related to intersections, Perkins and Thompson (40) stated that candidate surrogates for rural non-signalized intersections are traffic volume, approach speed, sight distance and traffic conflicts. Therefore, speed can be a viable crash surrogate.

Specific to roundabouts, Chen et al. (13) utilized the speed data collected at roundabouts under the NCHRP Report 572 (15) study in an exploratory analysis of safety performance and its relation to speed. The study demonstrated that “it is viable to use speed as a surrogate measure in estimating the safety implications of decisions in designing a roundabout.”

## **Data Collection Methodology**

Field and observational data were collected at four rural roundabout intersections and two, two-way stop control intersections on rural high speed roadways. Speed data from each

of the intersections were used to compare the speed profiles and speed variance of vehicles approaching these intersections. Data were not collected under adverse weather conditions. Most of the data collection was done with one or two people.

### **Site Selection**

This research was not a funded research project so limited resources were available to collect field data. At the time of data collection there were only approximately nineteen intersections that fit the characteristics for this research. Data collection sites were considered by intersection characteristics (rural, high speed approaches), available before and after crash data, cooperation of agency owning the roadways and proximity to Iowa. These criteria resulted in four candidate roundabouts and included rural New Prague, Minnesota and Paola, Florence and Garnett, Kansas. Additionally, two rural two-way stop controlled intersections emulating the same criteria as the roundabout were selected. The two locations in Iowa were rural Story County and rural Polk County. Table 1 shows a summary of the field locations.

**TABLE 1. Field Data Collection Sites**

<b>Intersection Type</b>	<b>Location (nearest town)</b>	<b>Roadways</b>	<b>Intersection Approaches</b>	<b># of Approaches w/ Speed Data</b>
<b>Roundabout</b>	NE of New Prague, MN	State Highway 13 and County Highway 2	4	55mph (4)
	North of Paola, KS	State Highway 68 and Old Kansas City Rd.	5	65mph (1) 55mph (2)
	West of Florence, KS	US 50 and US 77	5	65 mph (1) 55 mph (1)
	South of Garnett, KS	US 169 and US 59	3	65 mph (1)
<b>Two-way Stop Control</b>	NW of Ames, IA (Story County)	County Road R-38 and County Road E-36	4	55 mph (3)
	SE of Alleman, IA (Polk County)	State Highway 87 and County Road F22	4	55 mph (4)

The roundabout sites could be divided into three sub categories, posted speed limit of 65mph with rumble strips, posted speed limit of 55mph with rumble strips and posted speed limit of 55 mph without rumble strips. The two-way stop controlled intersections have posted speed limits of 55 mph. Lighting was present at all the intersections.

## **Equipment**

Various speed data collection equipment was considered for this research. The equipment used had to be readily available, could be installed and removed by one person, easy to transport in an automobile, reliable and ease in data reduction. TRAX® road tubes (JAMAR Technologies) were available for this research and had recently been calibrated using a radar gun and speed trailer. A total of twelve road tube data recorders were available



for use which dictated the number of approaches and number of locations where data could be collected at each intersection. Figure 1 shows the road tubes at the Roundabout Ahead Sign, the series of three rumble strips and the road tubes at 2, 250 ft in Paola, KS.



**FIGURE 1. Photo showing road tubes at 1,500 ft and series of three rumble strips**  
**Layouts and Data Collection**

Road tube spacing and locations were considered carefully prior to data collection as well as in the field. Specific site conditions dictated the final data collection efforts, excluding approaches where driveway would impact locations the speed data. Speed data were collected on ten approaches at four different roundabouts and seven approaches at two, two-way stop controlled intersections. Locations included 100 ft, 250 ft and 500 ft from the yield/stop line on all approaches as well as at 1,500 ft from the yield line/stop line, typically

at the “Roundabout Ahead Sign” warning sign for the roundabouts. The road tubes placed at 500 ft typically corresponded with the location of the Yield Ahead signs. Speeds at 2,500 ft were also collected on three roundabout approaches. The stop controlled intersection had stop ahead signs installed approximately 500 ft from the stop line. Figure 2 shows a typical layout for the data collection of the roundabouts and two-way stop controlled intersection and Table 2 lists distance of the data collection points and the advanced traffic control on the approaches.



**FIGURE 2. Typical intersection approach with traffic control and data collection locations**

**TABLE 2. Distances from Yield Line/Stop Line**

		Feet from Yield Line														
Location	Approach	Yield Sign	Road Tube	Nose of Splitter Island	Road Tube	Diagrammatic Sign	Road Tube	Yield Ahead Sign	Roundabout Ahead	Road Tube	Rumble Strip 3	Rumble Strip 2	Rumble Strip 1	Road Tube	Speed Limit	Advisory Speed Plate
<b>Paola</b>																
	EB	0	100	165	250	530	500	888	1429	1429	1553	1677	1801	2250	65	15
	NB	0	100	250	250	na	500	393	738	750 <sup>a</sup>	862	986	1110	na	55	15
	SB	0	100	250	250	na	500	531	728	na	852	976	1100	na	55	15
<b>Garnett</b>																
	NB	0	100	235	250	326	500	576	1526	1526	2068	2192	2316	2750	65	20
<b>Florence</b>																
	SB	0	100	155	250	410	500	607	1214	1214	1338	1462	1586	2500	55	20
	EB	0	100	155	250	558	500	820	1558	1558	1682	1806	1930	na	65	20
<b>New Prague</b>																
	NB	0	100	300	250	440	500	840	1290	1290	na	na	na	na	55	20
	SB	0	100	300	250	500	500	975	1475	1475	na	na	na	na	55	20
	EB	0	100	200	250	450	500	900	1350	1350	na	na	na	na	55	20
	WB	0	100	200	250	460	500	910	1360	na	na	na	na	na	55	20
<b>Story County</b>																
	WB	0	100	250	500	500	1500									
	NB	na	100	250	na	500	na									
	SB	na	100	250	na	500	na									
<b>Polk County</b>																
	NB	0	100	250	500	500	1500									
	SB	0	100	250	500	500	1500									
	EB	na	100	250	na	500	na									
	WB	na	100	250	na	500	na									

<sup>a</sup> - The fourth road tube was placed at the Roundabout Ahead Signs. On this approach that distance was 750 ft rather than 1500 ft in advance of the yield line.

### *Speed Data*

With a limited number of roundabouts to study on rural roadways it was important to gather as many data points as possible on each of the approaches. A minimum of four hours and a maximum of eight hours of data were collected at the roundabout approaches and an average of eighteen hours of data was collected at the two-way stop controlled approaches (due to the closer proximity of the intersection to the data collection team.)

The speed data collected on the through approaches at the two-way stop controlled intersections was collected in order to verify the suspected large speed differentials between turning and through traffic as well as the speed differentials between the major and minor approaches.

### *Crash Data*

The crash data used for the roundabouts was obtained as a part of the safety analysis that was done in for Chapters 4 and 5. The Iowa Traffic Safety Data Service (ITSDS) provided crash data history for the two Iowa intersections.

### **Data Reduction**

The speed data for the road tubes was exported using the TRAX® software. All speed data that were collected during the road tube installation and removal timeframes was deleted from the data set, as well as all erroneous records (i.e. speeds equal to 0 mph, repeat records) were excluded from the data set. Over 30,700 speed data points (speeds) were recorded.

## Data Analysis and Results

The analysis done was to test the statistical significance between approach speeds at roundabouts and two-way stop controlled intersections. Two comparative studies were made for 1) six roundabout approaches with rumble strips and four roundabout approaches without rumble strips, and 2) the four roundabout approaches without rumble strips and three stop controlled approaches at two-way stop controlled intersections. Additionally, the variance in speeds for each of the intersection types was evaluated.

## Methodology

Each data set was determined to be normally distributed and both speed data comparisons involved two sets of data with unequal sample sizes. To test the statistical significance of the means, the test statistic (t-test) is an appropriate choice for this data (37,41), as shown in Equation 2. The computed value of “t” was compared to the critical value of “t” for the sample size based on the specified level of significance. All statistical tests were performed at the 95 percent confidence level.

$$t = \frac{\overline{X}_1 - \overline{X}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad \text{Equation 2}$$

Where:

t = statistic of the t distribution

X<sub>1</sub> = mean of the first sample

X<sub>2</sub> = mean of the second sample

s<sub>1</sub> = standard deviation of the first sample

$s_2$  = standard deviation of the second sample

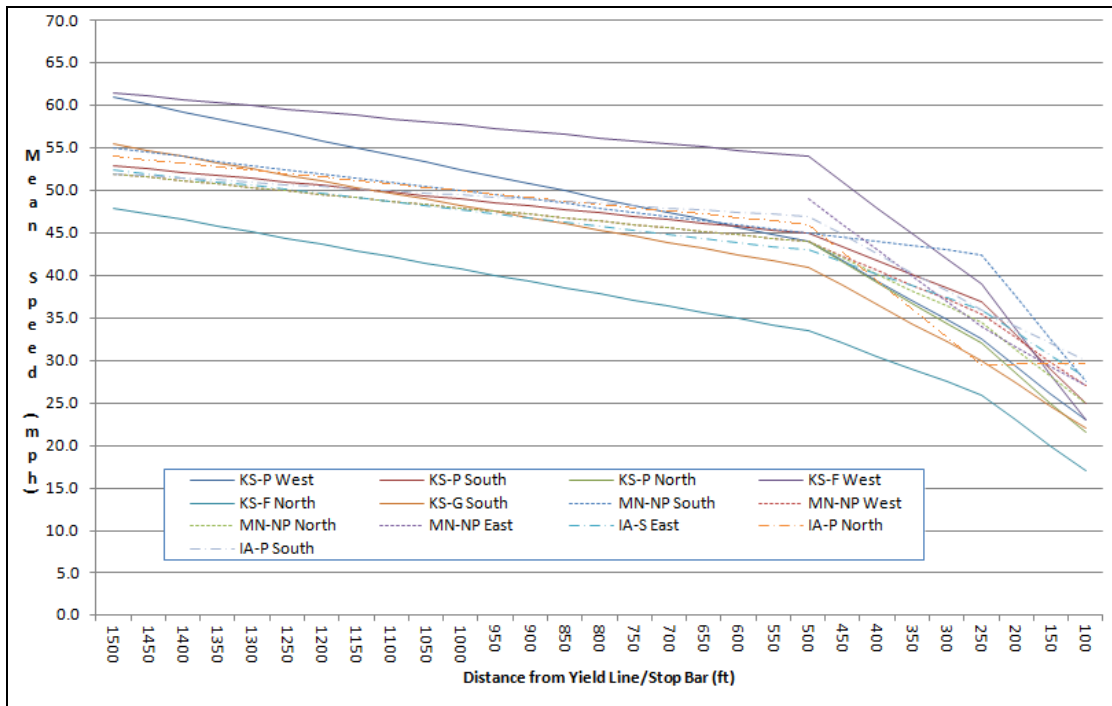
$N_1$  = number of observations in the first sample

$N_2$  = number of observations in the second sample

## **Speed Data**

Speed data from the through approaches on the two-way stop controlled intersections was reviewed but not further analyzed as a part of this study because of the bi-modal distribution. This resulted because of vehicles slowing to turn or through vehicles slowing for turning vehicles decelerating or accelerating on the major roadway. Table 3 shows these mean speeds. Documenting these findings is important here as the operations and speed data on the approaches to roundabouts is expected to be significantly different because *all* vehicles slow at roundabouts.

Speed profiles were created for each approach based on the speed data collection points. As is shown in Figure 3, the speed profiles for the roundabouts with rumble strips (solid lines) show greater variation in mean speeds, whereas the roundabouts without rumble strips and the stop controlled approaches have a smaller variance in mean speeds.



**FIGURE 3. Speed profiles**

The mean and 85<sup>th</sup> percentile speeds are shown in Table 3 by approach and the descriptive statistics by intersection types are shown in Table 4. Based on the descriptive statistics, the mean speeds do not indicate large discrepancies between the intersection categories, however the sample variances does show a considerable difference on the approaches with rumble strips.

**TABLE 3. Mean and 85<sup>th</sup> Percentile Speeds for Individual Approaches**

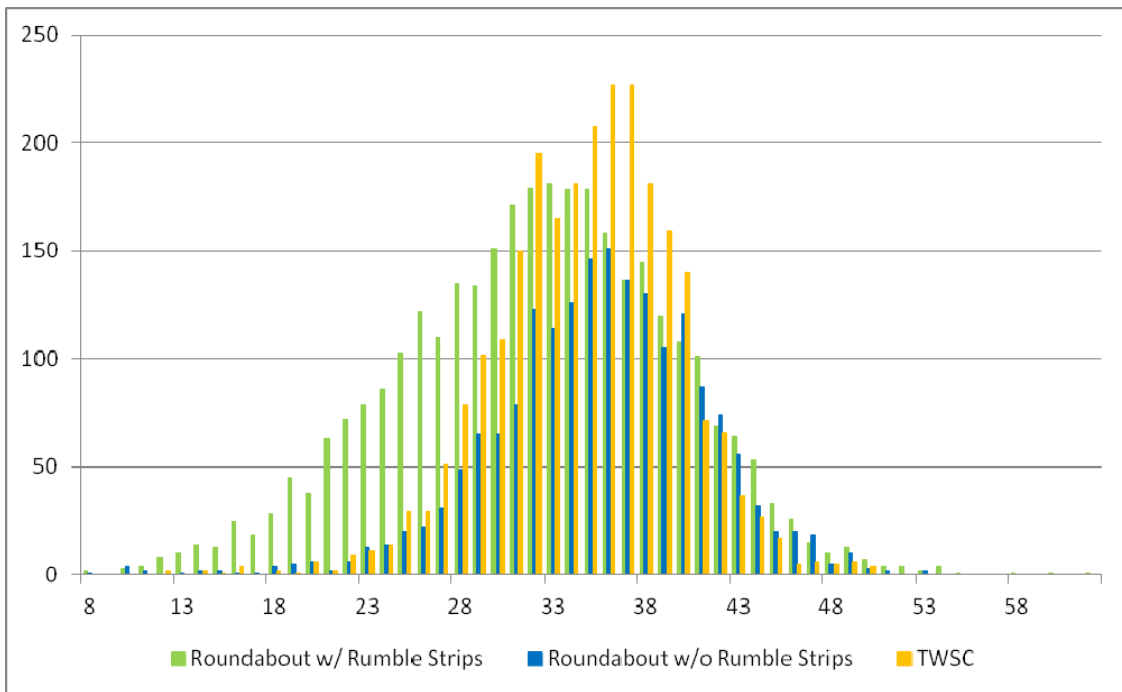
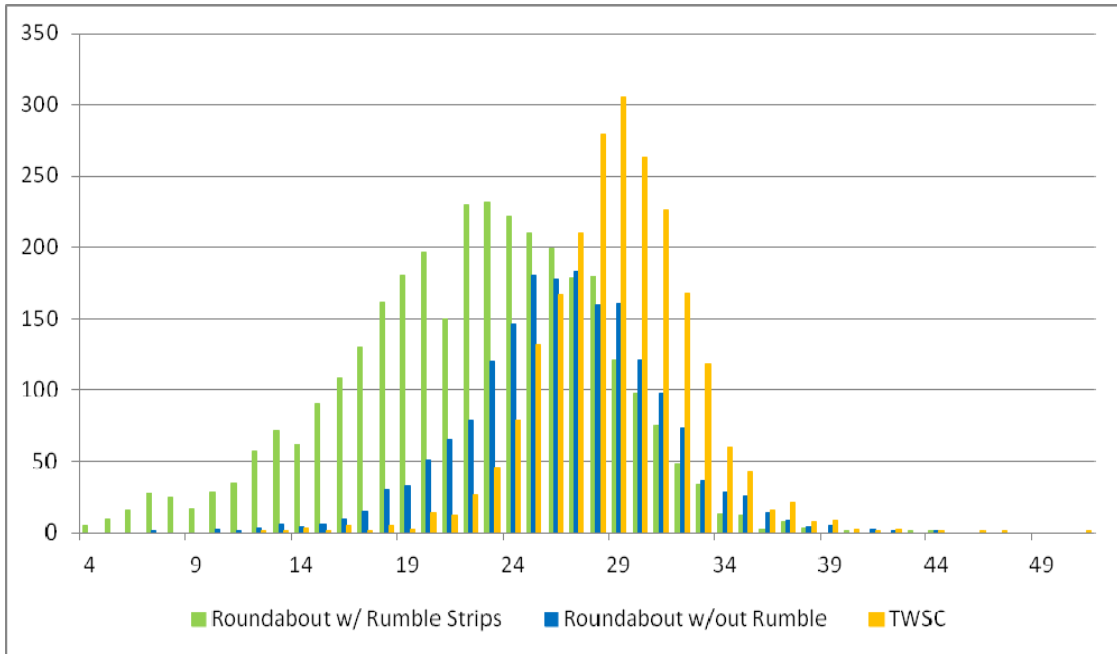
Treatment	Number of Intersections	Approach	Mean Speeds (mph)				85th Percentile Speed (mph)			
			100 ft	250 ft	500 ft	1500 ft	100 ft	250 ft	500 ft	1500 ft
Roundabout w/ Rumble Strips	KS-P	W	23	32.5	44	61	28	38.5	50	65.5
		S	25	37	45	53	29	42	50.5	58
		N	21.5	32	44		25.5	36	49.5	
	KS-G	S	22	30	41	55.5	28	36.5	47.5	61
		KS-F	N	17	26	33.5	48	22	32	40
		W	23	39	54	61.5	28	46	62	67.5
Roundabout w/o Rumble Strips	MN-NP	N	25	35.5	44	52	28.5	41.5	49	56
		S	27.5	34.5	45	55	31.5	39	51.5	60
		E	27	34	49		30.5	39	54	
		W	27	38	44	52	31	42	49	56
TWSC	IA-S	E	28	36	43	52.5	30.5	39.5	47	57
		N	24.5	34	41		28	38.5	47	
		N-Thru	59	58.5	59.5		62.5	62.5	63.5	
		S	28	35			31.5	39.5		
		S-Thru	60.5	56	57		66	60	63.5	
	IA-P	N	29.5	29.5	46	54	32.5	32.5	51	59.5
		S	30	36	47	52	32	39.5	51.5	57
		E	30.5	38	41		34.5	42	45	
		E-Thru	60	54.5	55		64.5	58.5	59	
		W	31	43.5	43		36	48	48	
	W-Thru	55	64.5	58		59.5	69.5	62		



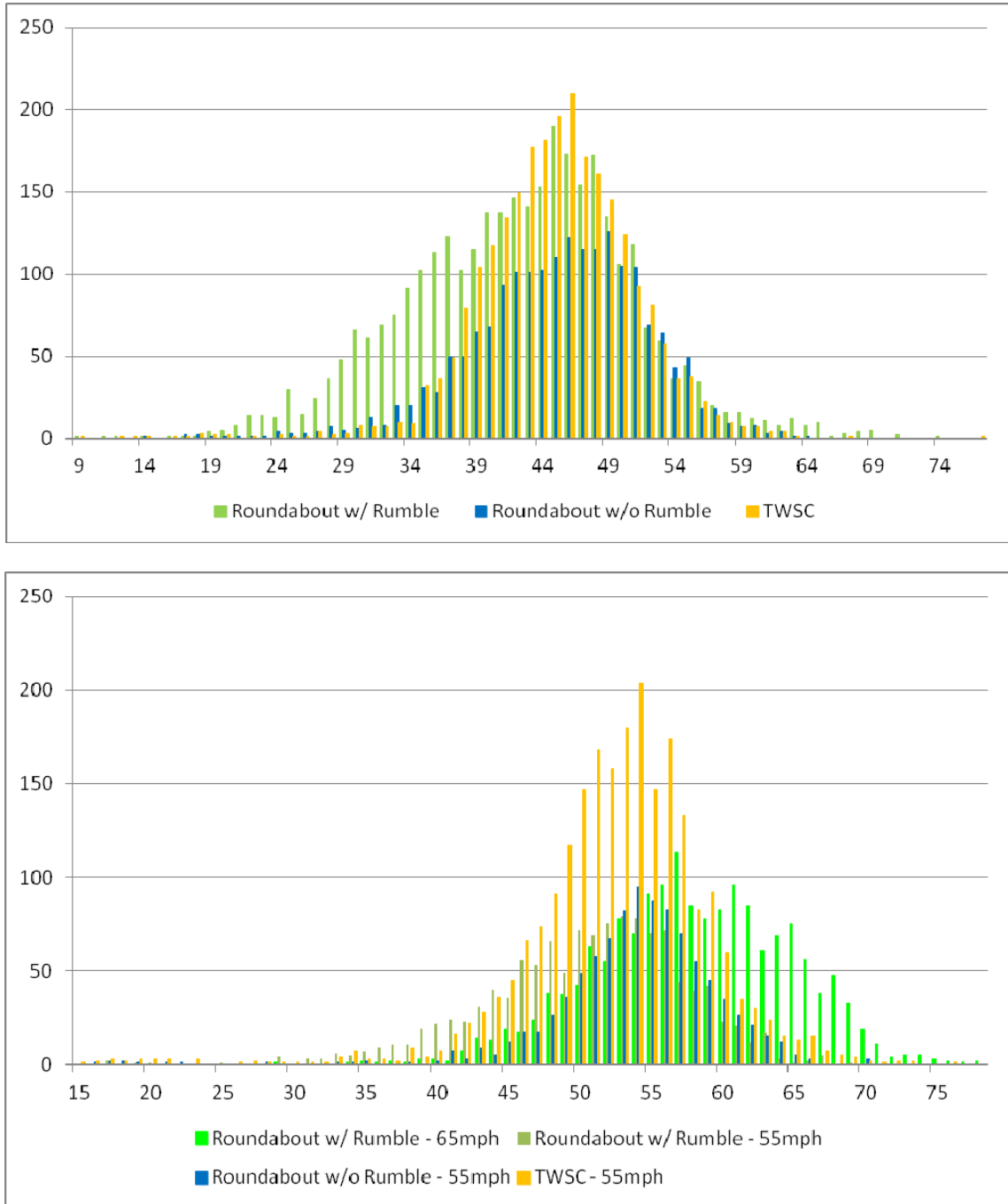
**TABLE 4. Descriptive Statistics**

Treatment	Number of Intersections	Approaches	Road Tube Location	Number of Measurements	mph			
					Mean	Standard Deviation	Sample Variance	Speed Range
Roundabout w/ Rumble Strips	3	6	100 ft	3234	22.1	6.0	35.4	4 to 44
		6	250 ft	3225	32.2	7.5	55.6	8 to 62
		6	500 ft	3267	42.4	8.5	71.7	9 to 74
		2	1500 ft-55	1208	50.4	7.0	47.3	17 to 69
		1	2500 ft-55	643	49.2	5.8	29.7	20 to 64
		3	1500 ft-65	1652	57.9	6.9	48.7	29 to 78
		2	2500 ft-65	1405	61.0	5.4	34.1	27 to 91
Roundabout w/o Rumble Strips	1	4	100 ft	1847	26.4	4.4	19.3	10 to 44
		4	250 ft	1875	35.5	5.7	32.8	8 to 53
		4	500 ft	1883	45.3	6.6	43.5	14 to 64
		3	1500 ft	959	53.9	5.9	35.2	16 to 70
Stop Controlled	2	3	100 ft	2224	28.9	3.5	12.4	12 to 51
		3	250 ft	2529	34.8	4.9	23.7	12 to 50
		3	500 ft	2507	45.0	5.8	34.0	9 to 77
		3	1500 ft	2264	52.5	6.5	42.5	15 to 76

Figures 4 and 5 further illustrate the variance in the speeds for the intersections at the various data collection locations. Looking at the speed data graphically it is evident that the intersections are operating quite differently. At every data collection point along the approach, the stop controlled approaches have a narrower distribution, less variance in speed, and the roundabout approaches with the rumble strips show a greater variance in speeds but a lower mean speed. At 250 ft and 500 ft the roundabout approaches without rumble strips and the stop controlled approaches have more similar distributions but still the mean speeds are



**FIGURE 4. Speed data at 100 ft (top) and 250 ft (bottom) from yield/stop line**



**FIGURE 5. Speed data at 500 ft (top) and 1500\* ft (bottom) from yield/stop line**

Not only is the sample variance an interesting finding, but also the number of vehicles that would likely not be able to stop and the yield line or stop bar. Considering the accident-avoidance distances documented in Ray et al. (37), at 100 ft from the yield line/stop bar a vehicle would need to be driving 32 mph or less to skid and stop short of a collision at the intersection. At the roundabouts with rumble strips, only 2.3 % (seventy-four) of the vehicles speeds exceeded 32 mph; at the roundabouts without rumble strips 6.8 % (125) of the vehicles exceeded the 32 mph; and at the stop controlled approaches, 12.5 % (279) of the vehicles would not be likely to avoid a crash. More of a concern here is at the stop controlled approaches, as it is possible that the vehicles at the roundabout that exceed the crash avoidance distances could have observed that the circulating roadway is clear and they can enter the roundabout at the advisory speeds (15 or 20 mph in this case).

Additionally, the number of vehicles exceeding the speed limit at free flow speeds, approximately 1,500 ft from the intersection (but after the rumble strips, if applicable) was inconsistent. On the roundabout approaches with rumble strips, 14 percent of vehicles were exceeding the 65 mph speed limit but only 2% were more than 5 mph over and on the 55 mph approaches 23 % were over the speed limit and 5 % were more than 5 mph over. However, at the roundabout approaches without rumble strips 39 % of vehicles exceeded the 55 mph speed limit and 9% over more than 5 mph over and the two-way stop controlled intersections were similar with 31 % over the posted 55 mph speed limit and 7% exceeding 5 mph over.

The test of statistical significance for the mean speeds on the roundabout approaches with and without rumbles strips shows statistically significant difference in mean speeds at 100 ft, 250 ft, 500 ft and 1,500 ft from the intersection at the 95 percent confidence level. Tables 5 and 6 show the differences in speeds and P-values. The only distance that was not statistically significant comparing the roundabouts without rumble strips and stop controlled approaches was at 500 ft.

**TABLE 5. Test of Statistical Significance for Roundabouts with and without Rumble Strips**

Distance from Yield Line	Mean Speed (mph)		Difference	P-Value	Significant
	Roundabout w/ Rumble Strips	Roundabout w/o Rumble Strips			
100 ft	22.1	26.4	4.3	0	Yes
250 ft	32.2	35.5	3.3	0	Yes
500 ft	42.4	45.3	2.9	0	Yes
1500 ft	50.4	53.9	3.4	0	Yes

**TABLE 6. Test of Statistical Significance for Roundabouts and Stop Controlled Approaches**

Distance from Yield Line/Stop Bar	Mean Speed (mph)		Difference	P-Value	Significant
	Roundabout w/o Rumble Strips	Stop Controlled			
100 ft	26.4	28.9	2.5	0	Yes
250 ft	35.5	34.8	-0.7	0	Yes
500 ft	45.3	45.0	-0.3	0.1257	No
1500 ft	53.9	52.6	-1.3	0	Yes

## Crash Data

It has already been discussed that roundabouts change the intersection environment for drivers so it only makes sense that the number and types of crashes that occur at roundabout are different. For the roundabout intersections, before and after crash data was

reviewed and crash was also obtained for the two-way stop controlled intersections. Considering the descriptive statistics for these intersections where speed data were collected, it is evident that the conversion from two-way stop controlled intersections to roundabouts radically reduced the total number of crashes as well as the number of injury crashes.

At these four roundabouts only twenty-one (21) total crashes and four (4) injury crashes have occurred in the ten data years and . Before the roundabouts 139 total crashes and 76 injury crashes occurred during the 29 data years. Considering the crashes that have occurred at the roundabouts since installation it is difficult to find a pattern as so few crashes occur after a roundabout is constructed. Four of the twenty-one crashes were speed related, two of those being injury crashes. The other two injury crashes were failure to yield right of way. Seven of the crashes were single vehicle crashes.

Nine years of crash data were available for the two, two-way stop controlled intersections in Iowa. Seventeen crashes occurred at those intersections during that time, including five injury crashes. Nine of those crashes were either “ran stop sign” or “failure to yield right of way” and two of those were injury (including a fatal) crashes.

## **Conclusions and Discussion**

The analysis of speed data shows that there is a statistically significant difference in the speed selection for drivers when approaching different types of intersections and associated traffic control. The difference in mean speeds varied by distance as the driver approached the intersections. When comparing the roundabout (without rumble strips) and the stop controlled approaches, at 1,500 ft in advance of the intersection, drivers approaching a roundabout were on average traveling 1.3 mph higher than when approaching a stop

controlled intersection and at 250 ft this difference was only 0.7 mph. At 100 ft in advance, which is by far a more critical zone for compliance, vehicle approaches the roundabout were found to be traveling on average 2.5 mph lower. Drivers approaching roundabouts were found to exhibit similar mean speeds and similar speed distributions at 250 ft, 500 ft and 1,500 ft. These small, yet statistically significant differences in mean speed indicates that, in fact, drivers are selecting approach speeds to roundabouts similar to that of a more familiar stop controlled intersection. However, between 250 ft and the yield line/stop bar, a distance from the intersection where the driver may or may not be able to bring their vehicle to a complete stop, the mean speed is higher (2.5 mph) and 12.5 % of the drivers exceeded the 32 mph speed at which a driver could potentially avoid a crash.

Albeit the differences in mean speeds are statistically significant, the speeds difference between intersection types is low (within 1.3 mph). Even with advanced traffic control signing (Roundabout Ahead sign, Yield Ahead Sign, and a Diagrammatic sign in some cases) at the roundabout, approach speeds were found to be very similar to a stop controlled approach until you get to within 100 ft of the intersection. Drivers on a roundabout approach are already under the influence of the splitter island, outside curb and alignment deflection and these factors could be contributing to lower mean speeds, which are 2.5 mph less than at a stop controlled approach. A higher percentage (6.8 vs. 12.5 percent) of drivers at the stop controlled intersections appear to be at riskier speeds within 100 ft of the intersection.

A statistically significant difference was also realized for the mean speeds (2.9 to 4.3 mph lower) on the approaches to a roundabout with rumble strips compared to roundabouts without. With the advanced traffic control (signing) and lighting being nearly identical, the

only notable difference between these approaches was the presence of rumble strips at the Kansas roundabouts. The data shows that rumble strips initiate lower speeds, earlier (further from the intersection) and is consistent with the Minnesota simulation study on rumble strips (36). The rumble strips do seem to introduce noticeable variability in the speeds at all data collection points. More specifically, the rumble strips seem to change driver behavior (i.e. slowing down sooner) between the rumble strips and 500 ft in advance of the roundabout. Although slower is viewed as safer, and in the case here the rumble strips seem to provide that effect, the increased speed variability may offset those benefits by introducing the potential for rear end crashes.

Speed and variation in speed are certainly good candidates as crash surrogates but because roundabouts change the driving environment and driver must slow before entering the intersection it seems as if speed/speed variation data might need to be coupled with observing if those speeds cause erratic moves on the approach to a roundabout that may very well be a potential crash situation that could be avoided due to the already evident slower speeds.

Although roundabouts significantly reduce the number of property damage and injury crashes on rural high speed roadways, compared to a two-way stop controlled intersections, there is not enough crash data at roundabouts currently (that was why they were constructed in the first place) to isolate the effects of the rumble strips in advance of roundabouts and whether or not they provide additional safety benefits. It is however evident that rumble strips change driver's behavior in advance of roundabouts in this study.

It is getting more difficult to find reasons not to implement roundabouts especially on facilities with higher risk (i.e. two lane rural roadways). Roundabouts change how drivers



approach and navigate the intersection, because they physically change the geometry of an intersection approach and how vehicles interact with each other. As documented in this study, roundabouts also reduce vehicle approach speed within the critical decision area (within 100 ft) of the intersection.

Rural intersections with a poor safety history are prime candidates for a roundabout. Investing in an intersection alternative that lowers speeds and significantly reduces the risk of someone in your community getting injured is an intersection alternative worth constructing. Roundabouts prevent high speed angle crashes that results from drivers running stop signs and red lights.

The implementation rate of roundabouts on high speed rural approaches is significantly higher in the last three years due to several states who continue to aggressively construct roundabouts in rural locations. Numerous other states are also quickly realizing the considerable safety benefits of rural roundabouts on high speed roadways and are including roundabouts as viable alternative in the project development process. There are few intersection safety countermeasures that deliver a high a safety yield than as a roundabout. Roundabouts on rural high speed roadways are saving lives.

## **Limitations and Future Research**

Limited funds were available for this research and the number of rural roundabouts was also confined to less than twenty at the time of data collection. However, this was the first speed data set documented for rural roundabouts with high speed approaches that could be supplemented with additional data at similar locations to help understand how different traffic control in roundabout approaches effect speeds . Additionally, it would be of interest

to isolate the speeds for different vehicle types at the Kansas because of a higher than average truck volume.

## Acknowledgements

Dennis Kroeger was a critical partner in the data collection efforts for this research. Dennis passed away prematurely in September 2009.

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## CHAPTER 7. GENERAL CONCLUSIONS

### Discussion of Results

With nearly 3,000 fatalities and tens of thousands more injury crashes at rural intersections annually, safer intersections in these environments are a necessity. Roundabouts are a proven safety countermeasure. By design, roundabouts command a change in driver behavior – slower speeds for all traffic. This research expanded the data available for study and results show that rural roundabouts with high speed approaches significantly reduced total crashes by 62 to 67% and injury crashes by 85 to 88 % at nineteen rural roundabouts. Moreover, the number of angle crashes, which tend to have a higher likelihood of causing injuries at high speeds, were reduced by 83%, also a statistically significant reduction.

The approach speed data analysis proved that drivers are able to slow down in advance of roundabouts on rural roadways. Even more noteworthy, was that the mean speeds at 100 ft from the yield line were 2.5 mph lower than mean speeds at 100 ft from the stop bar at stop controlled approaches. This difference was statistically significant at the 95 percent level and indicates that drivers are able to take the cues from the advanced traffic control and approach geometry to adjust their speeds before entering the roundabout.

The comparison between the roundabout approaches with and without rumble strips showed mean speeds 4.3 mph and 3.3 mph lower at 100 ft and 250 ft from the yield line, respectively, for the approaches with rumble strips; however, the variation in speeds increased with the introduction of rumble strips. There is not enough crash data at these intersections – which is what the owning agencies were striving for when constructing the roundabouts - to determine if the variation in speeds has an effect on crash experience.

Rural intersections with a poor safety history are prime candidates for roundabouts, primarily if those crashes have produced injuries. In addition to the safety and approach speed statistical analyses presented as a part of this research, a crash prediction model specifically for rural roundabouts on high speed roadways is presented. Crash prediction models can help agencies assess the potential safety benefits (reduced crashes) gained by safety countermeasures. These models supplement the models presented in NCHRP Report 572 and the crash modification factors for roundabouts in the Highway Safety Manual.

The results of this research support decision-making to invest in an intersection alternative that lowers speeds and significantly reduces the risk of injury crashes. Roundabouts eradicate the risk of drivers running stop signs and red lights. The current roundabout safety research demonstrates that roundabouts are reducing fatal and injury crashes in all roadway environments in the United States. Furthermore, the research presented here provides evidence that rural roundabouts on high speed roadways are reducing intersection injury crash experiences unlike any other intersection countermeasure.

Roundabouts save lives.

## **Limitations of Research**

Limited resources were available for this research. The number of rural roundabouts on high speed roadways was minimal at the time of this research but this data set more than doubled the rural roundabouts on high speed roadways evaluated under previous research and provides the groundwork for research in this area.



## **Recommendations for Future Research**

Just as the *NCHRP Report 572 Roundabouts in the United States* increased the data available for study of roundabouts from twenty-three to fifty-five, this safety research expanded the data for rural roundabout from nine to nineteen. It is recommended that as the number of rural roundabouts increase, the crash prediction models be adjusted and calibrated, as needed.

The data collected for this research can be expanded and evaluated in different ways, including determining if there are distinct patterns with the types of crashes that do occur at rural roundabouts (not enough crash data yet – which is a good problem to have) as well as parsing

## APPENDIX A. CANDIDATE INTERSECTIONS

	State	City	County/ Region	Intersection
1	Ontario, Canada	Ancaster	Hamilton	Hamilton Dr/Wilson Street/Meadowbrook Dr (Hwy 403)
2	Quebec, Canada	Chambly	Montreal	Frchette Blvd/Anne-Le-Seigneur Blvd
3	Ontario, Canada	Cambridge	Waterloo	Townline rd/Can-Amara Pkwy
4	Colorado	Eagle	Eagle	SH-6/I-70 spur/Eby Creek Rd
5	Connecticut	Killingworth	Middlesex	Rte 80/Rte 81
6	Kansas	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane
7	Kansas	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane
8	Kansas	Florence	Marion	US-50 & US-77
9	Maryland	Leeds	Cecil	MD 213/Leeds Rd/Elk Mills Rd (Lanzi Circle)
10	Maryland	Jarrettsville/North Harford	Harford	MD24/MD165
11	Maryland	Lothian	Anne Arundel	MD 2/MD 408/MD 422
12	Maryland	Cearfoss/Hagerstown	Washington	MD 63/MD58/Cearfoss Pike
13	Maryland	Federalsburg	Caroline	MD 307/MD 313/MD 318
14	Maryland	Frederick	Frederick	MD 80/Sugarloaf Pkwy
15	Maryland	Lisbon	Howard	MD 94/MD 144
16	Maryland	Lisbon	Howard	MD 94/Old Fredrick Road
17	Maryland	Millington	Kent	US 301 NB Ramps/MD 291
18	Maryland	Millington	Kent	US 301 SB Ramps/MD 291
19	Maryland	Rising Sun	Cecil	MD 273/MD 276
20	Maryland	Rosemont	Frederick	MD 17/MD 180
21	Maryland	Taneytown	Carroll	MD 140/MD 832
22	Michigan	Sterling Heights	Macomb	M-53 Freeway/18 1/2 Mile Rd
23	Minnesota	New Prague	Scott	SH 13/CR 2
24	Nevada	Carson City	Carson City	5th St/Edmonds
25	New York	Kingston	Ulster	I-587/Rt 28/I-87/Washington Ave
26	Oregon	Verboort	Washington	Cornelius-Schefflin Rd/Verboot rd
27	Oregon	Verboort	Washington	Martin-Marsh Rd/Verboort rd
28	Washington	Duvall	King	State Route 203/NE 124th St
29	Washington	Spokane	Spokane	SR206/Mt. Spokane park Drive/Bruce Road

## APPENDIX B. FINAL LIST OF INTERSECTIONS

	State	City/Town	County	Intersection	Roundabout installation year	Legs	Posted Approach Speed Limit (Max)	Average Daily Entering Volume Before
1	Maryland <sup>1</sup>	Cearfoss/Hagerstown	Washington	MD 63/MD58/Cearfoss Pike	1995	4	50 mph	6,974
2	Washington <sup>2</sup>	Duvall	King	SR 203/Novelty Hill Rd	2004	4	50 mph	11,500
3	Maryland <sup>1</sup>	Federalburg	Caroline	MD 307/MD 313/MD 318	1998	4	50 mph	6,587
4	Kansas <sup>3</sup>	Florence	Marion	US 50/US 77	2006	5	65 mph	4,848
5	Kansas <sup>3</sup>	Garnett	Anderson	US 169/ K- 59	2006	3	65 mph	5,086
6	Wisconsin <sup>6</sup>	Kaukauna	Outagamie	STH 55/CTH KK	2006	4	55 mph	9,000
7	Maryland <sup>1</sup>	Leeds	Cecil	MD 213/Leeds Rd/Eik Mills Rd	1995	4	40 mph	8,270
8	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/MD 144	1993	4	45 mph	7,450
9	Maryland <sup>1</sup>	Lisbon	Howard	MD 94/Old Fredrick Road	1998	4	45 mph	8,504
10	Maryland <sup>1</sup>	Lothian	Anne Arundel	MD 2/MD 408/MD 422	1995	4	50 mph	13,808
11	Minnesota <sup>4</sup>	New Prague	Scott	TH 13/CR 2	2005	4	55 mph	6,700
12	Maryland <sup>1</sup>	North Harford/Jarrettsville	Harford	MD24/MD165	2000	4	55 mph	8,058
13	Kansas <sup>3</sup>	Paola	Miami	K-68/old Kansas City Rd/Hedge Lane	2001	5	65 mph	6,260
14	Maryland <sup>1</sup>	Rising Sun	Cecil	MD 273/MD 276	2002	4	45 mph	15,767
15	Maryland <sup>1</sup>	Rosemont	Frederick	MD 17/MD 180	2000	4	50 mph	13,467
16	Wisconsin <sup>6</sup>	Sheboygan Falls	Sheboygan	STH 32/STH 28	2006	4	55 mph	8,150
17	Washington <sup>2</sup>	Spokane	Spokane	SR 206/ Bruce Rd	2005	4	50 mph	10,200
18	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Martin/Marsh	2004	4	45 mph	9,253
19	Oregon <sup>5</sup>	Verboort	Washington	Verboort Rd/Corneilius Schefflin	2004	3	45 mph	10,980
	<sup>1</sup> Maryland State Highway Administration, Office of Traffic and Safety, 2007 [7]							
	<sup>2</sup> Washington DOT, 2008 [15]							
	<sup>3</sup> Kansas Department of Transportation, Office of Chief Counsel, 2008 [16]							
	<sup>4</sup> Minnesota Department of Transportation, Office of Traffic and Safety, 2008 [17]							
	<sup>5</sup> Washington County, Oregon, 2008 [18]							
	<sup>6</sup> Wisconsin Department of Transportation, 2008							

**APPENDIX C. BEFORE AND AFTER AERIALS AND PHOTOS OF  
SELECT INTERSECTIONS**



Florence, KS (Photo Source: © 2011 Isebrands)



Rural Garnett, KS (Photo Source: © 2011 Isebrands)



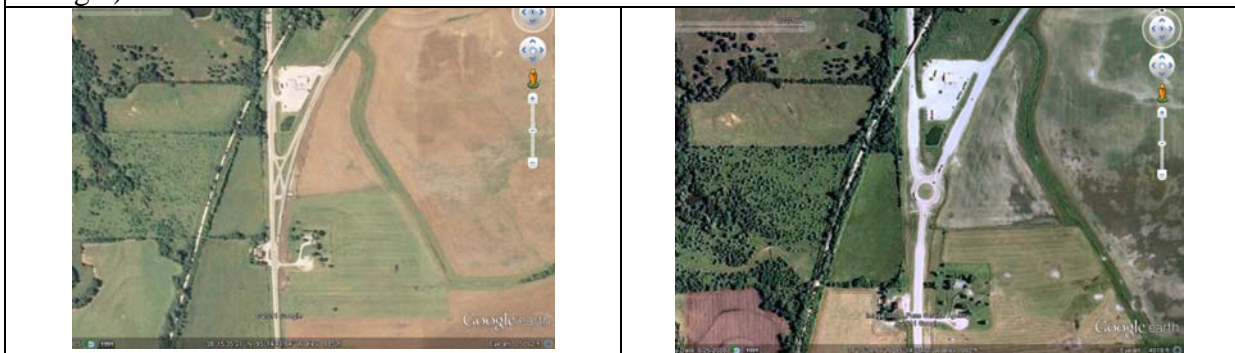
Rural New Prague, MN (Photo Source: © 2011 Isebrands)



Florence, KS (Image Source: © 2011 Google)



Rural Paola, KS (Image Source: US Geological Survey, © 2011 Google – left; © 2011 Google)



Rural Garnett, KS (Image Source: © 2011 Google)



Rural Lothian, MD (Image Source: US Geological Survey, © 2011 Google – left; © 2011 Google – right )



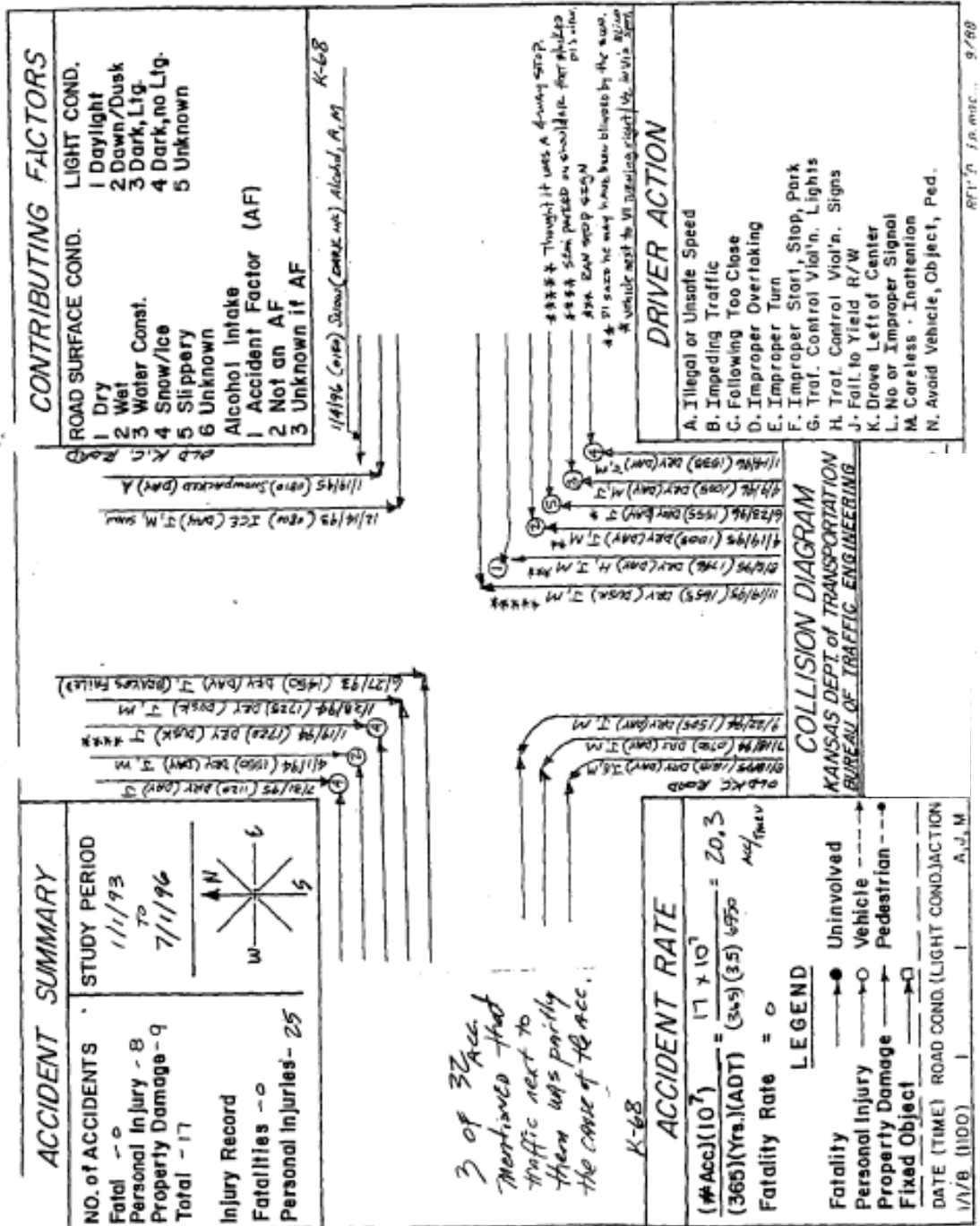
Rural Duvall, WA (Image Source: 2007 Europa Technologies, Image © 2007 DigitalGlobe via Google Earth - left; © 2011 Google - right)



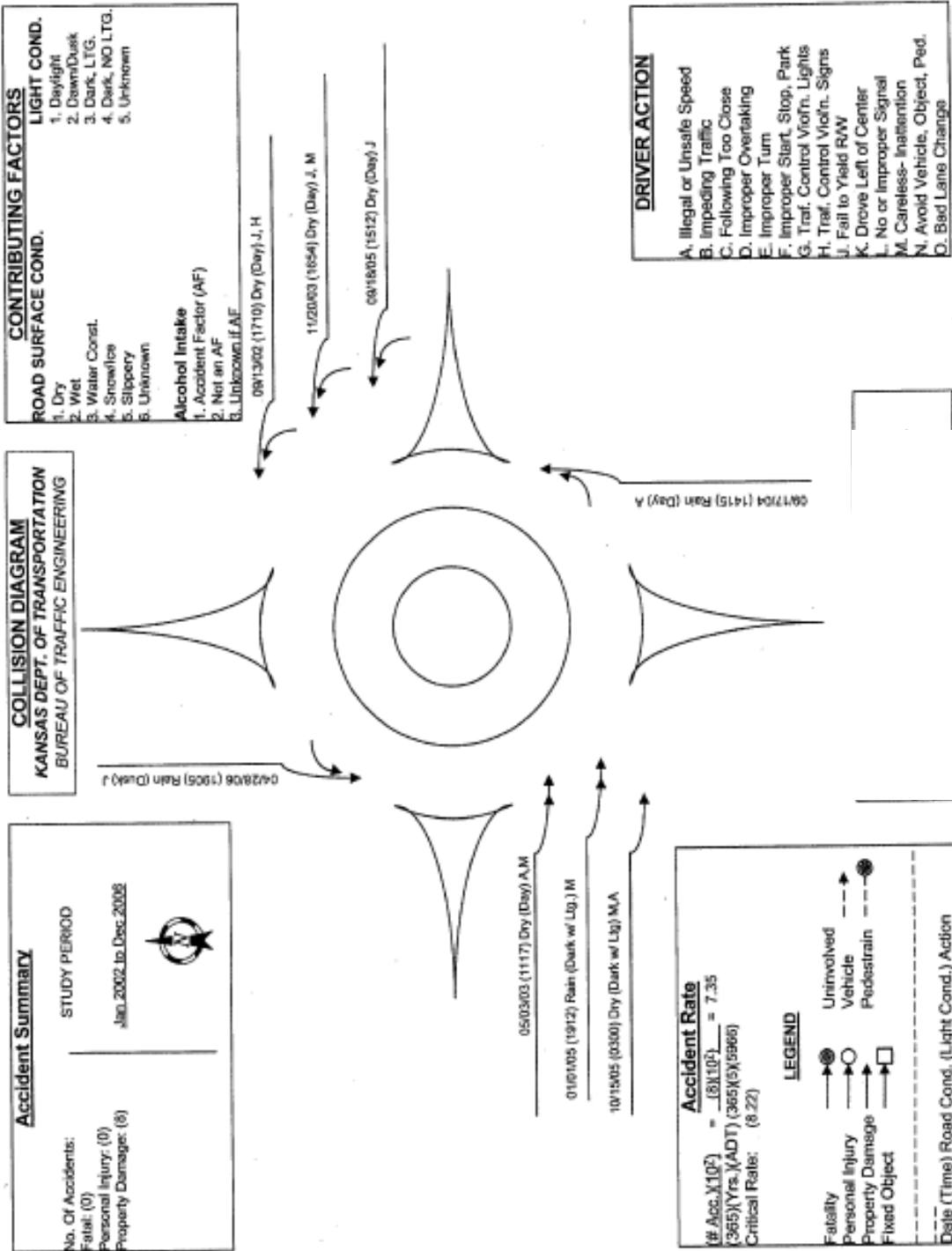
Rising Sun, MD (Image Source: US Geological Survey via Google Earth – left; © 2011 Google - right)



APPENDIX D. CRASH DIAGRAM EXAMPLES



RPT. N. J.A. 9/88



## APPENDIX E. EB SAFETY PERFORMANCE FUNCTION – CALIBRATION COMPARISON

			Average DEV Before	Average DEV After	% Change	Years of Data Before	Years of Data After			No Calibration Expected Injury Crashes/ Year After	Actual Injury Crashes/ Year Before	Calibrated Model Expected Injury Crashes/ Year			No Calibration Expected Total Crashes/ Year After	Actual Total Crashes / Year Before	Calibrated Model Expected Total Crashes/ Year	
1	MD	Cearfoss/Hagerstown	6,974	9,183	32%	5	10.1	<0	1	2.1	1.8	2.5			1	4.6	3.8	5.2
2	WA	Duvall	11,500	14,606	27%	5.6	3.6	0-5	2	3.8	3.8	4.6			2	8.1	7.0	9.2
3	MD	Federalsburg	6,587	8,787	33%	3.8	7	6-10	3	3.1	3.2	4.1			3	5.3	4.2	6.5
4	KS	Florence	4,848	4,751	-2%	8.75	1.75	11-20	4	0.7	2.5	0.9			4	3.5	4.3	4.0
5	KS	Garnett	5,086	5,828	15%	5.3	1.67	21-30	5	0.7	2.5	0.7			5	3.6	3.4	3.6
6	MD	Leeds	8,270	10,793	31%	5	10.4	31+	6	2.5	3.0	2.9			6	3.7	4.0	4.1
7	MD	Lisbon	7,450	9,850	32%	5	12.7		7	3.0	3.8	3.7			7	7.6	8.4	8.8
8	MD	Lisbon	8,504	10,125	19%	4	7		8	3.5	3.5	4.4			8	6.0	5.0	7.0
9	MD	Lothian	13,808	17,383	26%	5	10.2		9	4.7	5.4	5.7			9	8.1	7.8	9.2
10	MN	New Prague	6,700	7,225	8%	6.6	2.3		10	4.9	5.0	5.5			10	7.2	6.7	7.8
11	MD	North Harford	8,058	9,341	16%	5	5.3		11	3.4	4.4	4.3			11	6.1	6.4	7.2
12	KS	Paola	6,260	6,900	10%	8.1	5.2		12	2.3	2.1	2.6			12	5.4	4.8	5.9
13	MD	Rising Sun	15,767	17,006	8%	4	2		13	2.6	3.3	3.2			13	4.1	4.3	4.8
14	MD	Rosemont	13,467	13,814	3%	3	5		14	2.9	3.0	3.4			14	5.6	5.7	6.1
15	WA	Spokane	10,200	10,821	6%	6	3.6		15	2.8	3.7	3.2			15	4.7	5.5	5.1
16	OR	Verboort	9,253	10,016	8%	2.5	3.2		16	1.9	2.0	2.5			16	3.4	3.2	4.1
17	OR	Verboort	10,980	11,886	8%	2.5	3.2		17	1.2	1.6	1.6			17	3.2	3.2	3.7
18	WI	Kaukauna	9,000	8,950	-1%	6.5	2		18	2.3	3.4	2.9			18	5.3	6.5	6.1
19	WI	Shebyogan Falls	8,150	8,350	2%	6.5	2		19	1.3	1.4	1.6			19	3.0	3.1	3.5
						98.15	98.22			49.6	59.2	60.6			98.4	97.2	112.1	

**APPENDIX F. STATISTICAL ANALYSIS OUTPUT - SAS**

TOTAL CRASHES negbin

The GENMOD Procedure

Model Information

Data Set WORK.WORK0  
 Distribution Negative Binomial  
 Link Function Log  
 Dependent Variable CRASHTOT CRASHTOT  
 Offset Variable logYEARBA

Number of Observations Read 38  
 Number of Observations Used 38

Class Level Information

Class	Levels	Values
SITEID	19	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PERIODID	2	0 1

Parameter Information

Parameter	Effect	PERIODID
Prm1	Intercept	
Prm2	PERIODID	0
Prm3	PERIODID	1
Prm4	logDEV	

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	35	39.1392	1.1183
Scaled Deviance	35	39.1392	1.1183
Pearson Chi-Square	35	56.9804	1.6280
Scaled Pearson X2	35	56.9804	1.6280
Log Likelihood		1575.3931	

Algorithm converged.

TOTAL CRASHES negbin

The GENMOD Procedure

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits	Chi-Square
-----------	----	----------	----------------	----------------------------	------------

Intercept		1	-6.3942	2.6435	-11.5754	-1.2130	5.85
PERIODID	0	1	0.9926	0.1985	0.6036	1.3816	25.01
PERIODID	1	0	0.0000	0.0000	0.0000	0.0000	.
logDEV		1	0.7785	0.2842	0.2216	1.3355	7.51
Dispersion		1	0.2316	0.0698	0.0948	0.3684	

Analysis Of Initial  
Parameter Estimates

Parameter		Pr > ChiSq
Intercept		0.0156
PERIODID	0	<.0001
PERIODID	1	.
logDEV		0.0061
Dispersion		

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

GEE Model Information

Correlation Structure	Exchangeable
Subject Effect	SITEID (19 levels)
Number of Clusters	19
Correlation Matrix Dimension	2
Maximum Cluster Size	2
Minimum Cluster Size	2

Algorithm converged.

Exchangeable Working  
Correlation

Correlation 0.0182635268

-----  
TOTAL CRASHES negbin

The GENMOD Procedure

Analysis Of GEE Parameter Estimates  
Empirical Standard Error Estimates

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	Pr >  Z
Intercept	-6.3895	3.2383	-12.7365	-0.0426	-1.97	0.0485
PERIODID 0	0.9921	0.1924	0.6150	1.3692	5.16	<.0001
PERIODID 1	0.0000	0.0000	0.0000	0.0000	.	.
logDEV	0.7780	0.3704	0.0521	1.5040	2.10	0.0357

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha	Confidence Limits		Chi-Square	Pr > ChiSq
B-A	0.9921	0.1924	0.05	0.6150	1.3692	26.58	<.0001

-----  
FREQ

The FREQ Procedure

Table of PERIODID by CRASHTOT

PERIODID(PERIODID)	CRASHTOT(CRASHTOT)						Total
Frequency,	1,	2,	3,	4,	5,	6,	
Percent ,							
Row Pct ,							
Col Pct ,							
0	0	0	0	0	0	0	19
	0.00	0.00	0.00	0.00	0.00	0.00	50.00
	0.00	0.00	0.00	0.00	0.00	0.00	
	0.00	0.00	0.00	0.00	0.00	0.00	
1	1	1	2	4	1	1	19
	2.63	2.63	5.26	10.53	2.63	2.63	50.00
	5.26	5.26	10.53	21.05	5.26	5.26	
	100.00	100.00	100.00	100.00	100.00	100.00	
Total	1	1	2	4	1	1	38
	2.63	2.63	5.26	10.53	2.63	2.63	100.00

(Continued)

Table of PERIODID by CRASHTOT

PERIODID(PERIODID)	CRASHTOT(CRASHTOT)						Total
Frequency,	8,	9,	10,	11,	16,	17,	
Percent ,							
Row Pct ,							
Col Pct ,							
0	2	0	0	0	1	2	19
	5.26	0.00	0.00	0.00	2.63	5.26	50.00
	10.53	0.00	0.00	0.00	5.26	10.53	
	66.67	0.00	0.00	0.00	100.00	100.00	
1	1	1	2	1	0	0	19
	2.63	2.63	5.26	2.63	0.00	0.00	50.00
	5.26	5.26	10.53	5.26	0.00	0.00	
	33.33	100.00	100.00	100.00	0.00	0.00	
Total	3	1	2	1	1	2	38
	7.89	2.63	5.26	2.63	2.63	5.26	100.00

(Continued)

FREQ

The FREQ Procedure

Table of PERIODID by CRASHTOT

PERIODID(PERIODID)	CRASHTOT(CRASHTOT)						Total
Frequency,	18,	19,	20,	22,	32,	33,	
Percent ,							
Row Pct ,							
Col Pct ,							
0	1	1	3	0	1	1	19
	2.63	2.63	7.89	0.00	2.63	2.63	50.00
	5.26	5.26	15.79	0.00	5.26	5.26	
	50.00	100.00	100.00	0.00	100.00	100.00	
1	1	0	0	1	0	0	19

	2.63	0.00	0.00	2.63	0.00	0.00	50.00
	5.26	0.00	0.00	5.26	0.00	0.00	
	50.00	0.00	0.00	100.00	0.00	0.00	
Total	2	1	3	1	1	1	38
	5.26	2.63	7.89	2.63	2.63	2.63	100.00

(Continued)

Table of PERIODID by CRASHTOT

PERIODID(PERIODID)	CRASHTOT(CRASHTOT)							Total
Frequency,								
Percent ,								
Row Pct ,								
Col Pct ,	38,	39,	40,	42,	44,	48,		
0	1	3	0	2	1	0		19
	2.63	7.89	0.00	5.26	2.63	0.00		50.00
	5.26	15.79	0.00	10.53	5.26	0.00		
	100.00	100.00	0.00	100.00	100.00	0.00		
1	0	0	1	0	0	1		19
	0.00	0.00	2.63	0.00	0.00	2.63		50.00
	0.00	0.00	5.26	0.00	0.00	5.26		
	0.00	0.00	100.00	0.00	0.00	100.00		
Total	1	3	1	2	1	1		38
	2.63	7.89	2.63	5.26	2.63	2.63		100.00

FREQ

The MEANS Procedure

Analysis Variable : CRASHTOT CRASHTOT

PERIODID	Obs	N	Median	Range	Mean
0	19	19	20.00	36.00	26.89
1	19	19	6.00	47.00	11.16

Analysis Variable : CRASHTOT CRASHTOT

PERIODID	Obs	Std Dev	N Miss
0	19	12.22	0
1	19	12.82	0

FREQ

The UNIVARIATE Procedure

Variable: CRASHTOT (CRASHTOT)

PERIODID = 0

Moments

	N	Sum Weights
Mean	19	511
Std Deviation	26.8947368	149.321637
Skewness	12.2197233	-1.5666768
	0.00166054	

Uncorrected SS	16431	Corrected SS	2687.78947
Coeff Variation	45.4353704	Std Error Mean	2.80339679

Basic Statistical Measures

Location		Variability	
Mean	26.89474	Std Deviation	12.21972
Median	20.00000	Variance	149.32164
Mode	20.00000	Range	36.00000
		Interquartile Range	22.00000

NOTE: The mode displayed is the smallest of 2 modes with a count of 3.

Tests for Location: Mu0=0

Test	-Statistic-	-----p Value-----
Student's t	t 9.593625	Pr >  t  <.0001
Sign	M 9.5	Pr >=  M  <.0001
Signed Rank	S 95	Pr >=  S  <.0001

Quantiles (Definition 5)

Quantile	Estimate
100% Max	44
99%	44
95%	44
90%	42
75% Q3	39
50% Median	20
25% Q1	17
10%	8
5%	8
1%	8
0% Min	8

FREQ

The UNIVARIATE Procedure  
 Variable: CRASHTOT (CRASHTOT)  
 PERIODID = 0

Extreme Observations

----Lowest----		----Highest---	
Value	Obs	Value	Obs
8	37	39	19
8	35	39	25
16	5	42	11
17	29	42	15
17	27	44	21

FREQ

The UNIVARIATE Procedure  
 Variable: CRASHTOT (CRASHTOT)  
 PERIODID = 1



Moments

N	19	Sum Weights	19
Mean	11.1578947	Sum Observations	212
Std Deviation	12.8247294	Variance	164.473684
Skewness	2.08442195	Kurtosis	3.85662907
Uncorrected SS	5326	Corrected SS	2960.52632
Coeff Variation	114.938613	Std Error Mean	2.94219471

Basic Statistical Measures

Location		Variability	
Mean	11.15789	Std Deviation	12.82473
Median	6.00000	Variance	164.47368
Mode	4.00000	Range	47.00000
		Interquartile Range	7.00000

Tests for Location: Mu0=0

Test	-Statistic-	-----p Value-----	
Student's t	t 3.792371	Pr >  t	0.0013
Sign	M 9.5	Pr >=  M	<.0001
Signed Rank	S 95	Pr >=  S	<.0001

Quantiles (Definition 5)

Quantile	Estimate
100% Max	48
99%	48
95%	48
90%	40
75% Q3	11
50% Median	6
25% Q1	4
10%	2
5%	1
1%	1
0% Min	1

FREQ

The UNIVARIATE Procedure  
 Variable: CRASHTOT (CRASHTOT)  
 PERIODID = 1

Extreme Observations

----Lowest----		----Highest---	
Value	Obs	Value	Obs
1	34	11	26
2	8	18	16
3	32	22	14
3	30	40	20
4	24	48	4

INJURY CRASHES negbin

The GENMOD Procedure

Model Information

Data Set WORK.WORK1  
 Distribution Negative Binomial  
 Link Function Log  
 Dependent Variable CRASHINJ CRASHINJ  
 Offset Variable logYEARBA

Number of Observations Read 38  
 Number of Observations Used 38

Class Level Information

Class	Levels	Values
SITEID	19	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PERIODID	2	0 1

Parameter Information

Parameter	Effect	PERIODID
Prm1	Intercept	
Prm2	PERIODID	0
Prm3	PERIODID	1
Prm4	logDEV	

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	35	42.9611	1.2275
Scaled Deviance	35	42.9611	1.2275
Pearson Chi-Square	35	43.8182	1.2519
Scaled Pearson X2	35	43.8182	1.2519
Log Likelihood		547.0177	

Algorithm converged.

INJURY CRASHES negbin

The GENMOD Procedure

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Intercept	1	-6.6943	2.6829	-11.9527	-1.4360	6.23
PERIODID	0	2.0905	0.2199	1.6595	2.5216	90.36
PERIODID	1	0.0000	0.0000	0.0000	0.0000	.
logDEV	1	0.6371	0.2876	0.0735	1.2008	4.91
Dispersion	1	0.1271	0.0667	-0.0035	0.2578	

Analysis Of Initial  
 Parameter Estimates

Parameter		Pr > ChiSq
Intercept		0.0126
PERIODID	0	<.0001
PERIODID	1	.
logDEV		0.0267
Dispersion		

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

GEE Model Information

Correlation Structure	Exchangeable
Subject Effect	SITEID (19 levels)
Number of Clusters	19
Correlation Matrix Dimension	2
Maximum Cluster Size	2
Minimum Cluster Size	2

Algorithm converged.

Exchangeable Working  
Correlation

Correlation 0.0737304398

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INJURY CRASHES negbin

The GENMOD Procedure

Analysis Of GEE Parameter Estimates  
Empirical Standard Error Estimates

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	Pr >  Z
Intercept	-6.4260	2.9360	-12.1805	-0.6715	-2.19	0.0286
PERIODID 0	2.0806	0.2097	1.6696	2.4916	9.92	<.0001
PERIODID 1	0.0000	0.0000	0.0000	0.0000	.	.
logDEV	0.6082	0.3203	-0.0196	1.2360	1.90	0.0576

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha	Confidence Limits		Chi-Square	Pr > ChiSq
B-A	2.0806	0.2097	0.05	1.6696	2.4916	98.45	<.0001

-----  
INJURY FREQ

The FREQ Procedure

Table of PERIODID by CRASHINJ

PERIODID(PERIODID) CRASHINJ(CRASHINJ)

Frequency,

Percent	Row Pct	Col Pct	0	1	2	3	4	Total
0	0.00	0.00	0.00	0.00	0.00	0.00	5.26	19
0	0.00	0.00	0.00	0.00	0.00	0.00	10.53	19
0	0.00	0.00	0.00	0.00	0.00	0.00	66.67	19
1	7.89	21.05	2.63	10.53	2.63	5.26	50.00	38
1	15.79	42.11	5.26	21.05	5.26	10.53	50.00	38
1	100.00	100.00	100.00	100.00	100.00	33.33	50.00	38
Total	7.89	21.05	2.63	10.53	7.89	100.00		

(Continued)

Table of PERIODID by CRASHINJ

PERIODID(PERIODID)	CRASHINJ(CRASHINJ)	5	7	9	11	12	Total
0	1	0	3	0	1	1	19
0	2.63	0.00	7.89	0.00	2.63	5.26	50.00
0	5.26	0.00	15.79	0.00	5.26	100.00	50.00
0	100.00	0.00	100.00	0.00	100.00	100.00	50.00
1	0	1	0	1	0	0	19
1	0.00	2.63	0.00	2.63	0.00	5.26	50.00
1	0.00	5.26	0.00	5.26	0.00	10.53	50.00
1	0.00	100.00	0.00	100.00	0.00	100.00	50.00
Total	2.63	2.63	7.89	2.63	2.63	100.00	38

(Continued)

INJURY FREQ

The FREQ Procedure

Table of PERIODID by CRASHINJ

PERIODID(PERIODID)	CRASHINJ(CRASHINJ)	13	14	15	17	19	Total
0	1	1	1	1	1	1	19
0	2.63	2.63	2.63	2.63	2.63	2.63	50.00
0	5.26	5.26	5.26	5.26	5.26	5.26	50.00
0	100.00	100.00	100.00	100.00	100.00	100.00	50.00
1	0	0	0	0	0	0	19
1	0.00	0.00	0.00	0.00	0.00	0.00	50.00
1	0.00	0.00	0.00	0.00	0.00	0.00	50.00
1	0.00	0.00	0.00	0.00	0.00	0.00	50.00
Total	2.63	2.63	2.63	2.63	2.63	100.00	38

(Continued)

Table of PERIODID by CRASHINJ



Mean	15.73684	Std Deviation	8.07494
Median	15.00000	Variance	65.20468
Mode	22.00000	Range	29.00000
		Interquartile Range	13.00000

Tests for Location: Mu0=0

Test	-Statistic-	-----p Value-----
Student's t	t 8.494836	Pr >  t  <.0001
Sign	M 9.5	Pr >=  M  <.0001
Signed Rank	S 95	Pr >=  S  <.0001

Quantiles (Definition 5)

Quantile	Estimate
100% Max	33
99%	33
95%	33
90%	27
75% Q3	22
50% Median	15
25% Q1	9
10%	4
5%	4
1%	4
0% Min	4

-----  
INJURY FREQ

The UNIVARIATE Procedure  
Variable: CRASHINJ (CRASHINJ)  
PERIODID = 0

Extreme Observations

----Lowest----		----Highest---	
Value	Obs	Value	Obs
4	19	22	6
4	5	22	12
5	18	22	17
9	16	27	10
9	15	33	11

-----  
INJURY FREQ

The UNIVARIATE Procedure  
Variable: CRASHINJ (CRASHINJ)  
PERIODID = 1

Moments

N	19	Sum Weights	19
Mean	2.31578947	Sum Observations	44
Std Deviation	2.70909234	Variance	7.33918129
Skewness	2.21180538	Kurtosis	5.48732046
Uncorrected SS	234	Corrected SS	132.105263
Coeff Variation	116.983533	Std Error Mean	0.62150841

## Basic Statistical Measures

Location		Variability	
Mean	2.315789	Std Deviation	2.70909
Median	1.000000	Variance	7.33918
Mode	1.000000	Range	11.00000
		Interquartile Range	2.00000

## Tests for Location: Mu0=0

Test	-Statistic-	-----p Value-----	
Student's t	t 3.726079	Pr >  t	0.0015
Sign	M 8	Pr >=  M	<.0001
Signed Rank	S 68	Pr >=  S	<.0001

## Quantiles (Definition 5)

Quantile	Estimate
100% Max	11
99%	11
95%	11
90%	7
75% Q3	3
50% Median	1
25% Q1	1
10%	0
5%	0
1%	0
0% Min	0

-----  
INJURY FREQ

The UNIVARIATE Procedure  
Variable: CRASHINJ (CRASHINJ)  
PERIODID = 1

## Extreme Observations

----Lowest----		----Highest---	
Value	Obs	Value	Obs
0	36	3	33
0	32	3	34
0	23	4	27
1	38	7	21
1	37	11	29

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CRASH TYPES negbin

The GENMOD Procedure

## Model Information

Data Set WORK.WORK2  
Distribution Negative Binomial





Intercept		1	-8.0600	4.2290	-16.3487	0.2286
CRASHTOT		1	0.0338	0.0072	0.0198	0.0478
TYPESID	1	1	1.0349	0.4405	0.1716	1.8982
TYPESID	2	1	0.8523	0.4504	-0.0304	1.7351
TYPESID	3	1	0.3005	0.4697	-0.6200	1.2210
TYPESID	4	1	1.5168	0.4322	0.6696	2.3640
TYPESID	5	0	0.0000	0.0000	0.0000	0.0000
PERIODID	0	1	0.2640	0.4705	-0.6582	1.1861
PERIODID	1	0	0.0000	0.0000	0.0000	0.0000
logDEV		1	0.6872	0.3830	-0.0635	1.4379
SPDMAX		1	0.0378	0.0169	0.0046	0.0709
LEGS		1	-0.6231	0.2117	-1.0379	-0.2082

Analysis Of Initial Parameter Estimates

Parameter		Chi-Square	Pr > ChiSq
Intercept		3.63	0.0567
CRASHTOT		22.26	<.0001
TYPESID	1	5.52	0.0188
TYPESID	2	3.58	0.0584
TYPESID	3	0.41	0.5223
TYPESID	4	12.31	0.0004
TYPESID	5	.	.
PERIODID	0	0.31	0.5747
PERIODID	1	.	.
logDEV		3.22	0.0728
SPDMAX		4.98	0.0256
LEGS		8.66	0.0032

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CRASH TYPES negbin

The GENMOD Procedure

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits
PERIODID*TYPESID	0 1 1	1.4933	0.5599	0.3958	2.5907
PERIODID*TYPESID	0 2 1	-0.0992	0.5815	-1.2390	1.0406
PERIODID*TYPESID	0 3 1	-1.2875	0.6370	-2.5360	-0.0391
PERIODID*TYPESID	0 4 1	-1.8031	0.5920	-2.9634	-0.6427
PERIODID*TYPESID	0 5 0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 1 0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 2 0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 3 0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 4 0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 5 0	0.0000	0.0000	0.0000	0.0000
Dispersion	1	0.6915	0.1418	0.4135	0.9695

Analysis Of Initial Parameter Estimates

Parameter		Chi-Square	Pr > ChiSq
PERIODID*TYPESID	0 1	7.11	0.0077
PERIODID*TYPESID	0 2	0.03	0.8645
PERIODID*TYPESID	0 3	4.09	0.0432
PERIODID*TYPESID	0 4	9.28	0.0023
PERIODID*TYPESID	0 5	.	.
PERIODID*TYPESID	1 1	.	.
PERIODID*TYPESID	1 2	.	.
PERIODID*TYPESID	1 3	.	.
PERIODID*TYPESID	1 4	.	.

PERIODID\*TYPEID 1 5 . .  
Dispersion

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

GEE Model Information

Correlation Structure	Exchangeable
Subject Effect	SITEID (19 levels)
Number of Clusters	19
Correlation Matrix Dimension	10
Maximum Cluster Size	10
Minimum Cluster Size	10

Algorithm converged.

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CRASH TYPES negbin

The GENMOD Procedure

Exchangeable Working  
Correlation

Correlation -0.001606133

Analysis Of GEE Parameter Estimates  
Empirical Standard Error Estimates

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	Pr >  Z
Intercept	-8.0564	3.7636	-15.4329	-0.6799	-2.14	0.0323
CRASHTOT	0.0338	0.0112	0.0119	0.0558	3.02	0.0025
TYPEID 1	1.0347	0.4394	0.1735	1.8959	2.35	0.0185
TYPEID 2	0.8524	0.4140	0.0411	1.6638	2.06	0.0395
TYPEID 3	0.2999	0.7916	-1.2516	1.8514	0.38	0.7048
TYPEID 4	1.5171	0.4225	0.6890	2.3452	3.59	0.0003
TYPEID 5	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID 0	0.2626	0.4072	-0.5355	1.0608	0.64	0.5190
PERIODID 1	0.0000	0.0000	0.0000	0.0000	.	.
logDEV	0.6861	0.3458	0.0084	1.3637	1.98	0.0472
SPDMAX	0.0379	0.0115	0.0153	0.0605	3.28	0.0010
LEGS	-0.6228	0.1241	-0.8660	-0.3796	-5.02	<.0001
PERIODID*TYPEID 0 1	1.4939	0.5746	0.3677	2.6201	2.60	0.0093
PERIODID*TYPEID 0 2	-0.0989	0.4727	-1.0254	0.8276	-0.21	0.8342
PERIODID*TYPEID 0 3	-1.2871	0.6313	-2.5244	-0.0499	-2.04	0.0414
PERIODID*TYPEID 0 4	-1.8031	0.5008	-2.7846	-0.8216	-3.60	0.0003
PERIODID*TYPEID 0 5	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 1	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 2	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 3	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 4	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 5	0.0000	0.0000	0.0000	0.0000	.	.

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha
B-A	-0.0764	0.2150	0.05

Contrast Estimate Results

Label	Confidence Limits		Chi-Square	Pr > ChiSq
B-A	-0.4978	0.3450	0.13	0.7223

CRASH TYPES negbin

The GENMOD Procedure

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha
TYPE-ANG in Before v.s. After	1.7565	0.3386	0.05
TYPE-REN in Before v.s. After	0.1637	0.2162	0.05
TYPE-SWI in Before v.s. After	-1.0245	0.5403	0.05
TYPE-FIX in Before v.s. After	-1.5405	0.4406	0.05
TYPE-OTH in Before v.s. After	0.2626	0.4072	0.05

Contrast Estimate Results

Label	Confidence Limits		Chi-Square	Pr > ChiSq
TYPE-ANG in Before v.s. After	1.0928	2.4202	26.91	<.0001
TYPE-REN in Before v.s. After	-0.2600	0.5874	0.57	0.4489
TYPE-SWI in Before v.s. After	-2.0835	0.0345	3.60	0.0579
TYPE-FIX in Before v.s. After	-2.4041	-0.6769	12.22	0.0005
TYPE-OTH in Before v.s. After	-0.5355	1.0608	0.42	0.5190

CRASH SEVERITY2 negbin

The GENMOD Procedure

Model Information

Data Set	WORK.WORK3		
Distribution	Negative Binomial		
Link Function	Log		
Dependent Variable	CRASHSEV	CRASHSEV	
Offset Variable	logYEARBA		

Number of Observations Read	76
Number of Observations Used	76

Class Level Information

Class	Levels	Values
SITEID	19	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19
PERIODID	2	0 1
SEVID	2	1 2

Parameter Information

Parameter	Effect	PERIODID	SEVID
Prm1	Intercept		
Prm2	CRASHTOT		
Prm3	SEVID		1

Prm4	SEVID		2
Prm5	PERIODID	0	
Prm6	PERIODID	1	
Prm7	logDEV		
Prm8	LEGS		
Prm9	PERIODID*SEVID	0	1
Prm10	PERIODID*SEVID	0	2
Prm11	PERIODID*SEVID	1	1
Prm12	PERIODID*SEVID	1	2

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	69	81.8515	1.1863
Scaled Deviance	69	81.8515	1.1863
Pearson Chi-Square	69	85.7952	1.2434
Scaled Pearson X2	69	85.7952	1.2434
Log Likelihood		1144.2811	

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CRASH SEVERITY2 negbin

The GENMOD Procedure

Algorithm converged.

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald 95% Confidence Limits	Chi-Square
Intercept	1	-2.3161	1.9464	-6.1311 1.4988	1.42
CRASHTOT	1	0.0342	0.0043	0.0257 0.0427	61.88
SEVID 1	1	-1.3551	0.2045	-1.7559 -0.9543	43.92
SEVID 2	0	0.0000	0.0000	0.0000 0.0000	.
PERIODID 0	1	-0.1059	0.1632	-0.4259 0.2140	0.42
PERIODID 1	0	0.0000	0.0000	0.0000 0.0000	.
logDEV	1	0.3432	0.1841	-0.0177 0.7041	3.47
LEGS	1	-0.2327	0.1375	-0.5021 0.0367	2.87
PERIODID*SEVID 0 1	1	1.7095	0.2411	1.2369 2.1820	50.27
PERIODID*SEVID 0 2	0	0.0000	0.0000	0.0000 0.0000	.
PERIODID*SEVID 1 1	0	0.0000	0.0000	0.0000 0.0000	.
PERIODID*SEVID 1 2	0	0.0000	0.0000	0.0000 0.0000	.
Dispersion	1	0.0671	0.0288	0.0107 0.1235	

Analysis Of Initial Parameter Estimates

Parameter	Pr > ChiSq
Intercept	0.2341
CRASHTOT	<.0001
SEVID 1	<.0001
SEVID 2	.
PERIODID 0	0.5165
PERIODID 1	.
logDEV	0.0623
LEGS	0.0905
PERIODID*SEVID 0 1	<.0001
PERIODID*SEVID 0 2	.
PERIODID*SEVID 1 1	.
PERIODID*SEVID 1 2	.
Dispersion	

NOTE: The negative binomial dispersion parameter was estimated by maximum

likelihood.

GEE Model Information

Correlation Structure	Exchangeable
Subject Effect	SITEID (19 levels)
Number of Clusters	19
Correlation Matrix Dimension	4

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CRASH SEVERITY2 negbin

The GENMOD Procedure

GEE Model Information

Maximum Cluster Size	4
Minimum Cluster Size	4

Algorithm converged.

Exchangeable Working  
Correlation

Correlation     -0.13755872

Analysis Of GEE Parameter Estimates  
Empirical Standard Error Estimates

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	Pr >  Z
Intercept	-2.4024	1.3894	-5.1257	0.3208	-1.73	0.0838
CRASHTOT	0.0337	0.0059	0.0222	0.0452	5.73	<.0001
SEVID 1	-1.3606	0.2024	-1.7572	-0.9640	-6.72	<.0001
SEVID 2	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID 0	-0.0886	0.2151	-0.5102	0.3330	-0.41	0.6804
PERIODID 1	0.0000	0.0000	0.0000	0.0000	.	.
logDEV	0.3564	0.1361	0.0896	0.6231	2.62	0.0088
LEGS	-0.2367	0.0833	-0.3999	-0.0735	-2.84	0.0045
PERIODID*SEVID 0 1	1.7133	0.2010	1.3194	2.1073	8.52	<.0001
PERIODID*SEVID 0 2	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*SEVID 1 1	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*SEVID 1 2	0.0000	0.0000	0.0000	0.0000	.	.

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha
SEVE-INJ in Before v.s. After	1.6247	0.1830	0.05
SEVE-PDO in Before v.s. After	-0.0886	0.2151	0.05

Contrast Estimate Results

Label	Confidence Limits		Chi-Square	Pr > ChiSq
SEVE-INJ in Before v.s. After	1.2661	1.9833	78.86	<.0001
SEVE-PDO in Before v.s. After	-0.5102	0.3330	0.17	0.6804

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INJURY BY TYPE negbin

The GENMOD Procedure

Model Information

Data Set	WORK.WORK4	
Distribution	Negative Binomial	
Link Function	Log	
Dependent Variable	INJCRASHTYPES	INJCRASHTYPES
Offset Variable	logYEARBA	

Number of Observations Read	140
Number of Observations Used	140

Class Level Information

Class	Levels	Values
SITEID	14	1 2 4 5 6 8 11 13 14 15 16 17 18 19
PERIODID	2	0 1
TYPESID	5	1 2 3 4 5

Parameter Information

Parameter	Effect	PERIODID	TYPESID
Prm1	Intercept		
Prm2	CRASHINJ		
Prm3	TYPESID		1
Prm4	TYPESID		2
Prm5	TYPESID		3
Prm6	TYPESID		4
Prm7	TYPESID		5
Prm8	PERIODID	0	
Prm9	PERIODID	1	
Prm10	logDEV		
Prm11	LEGS		
Prm12	PERIODID*TYPESID	0	1
Prm13	PERIODID*TYPESID	0	2
Prm14	PERIODID*TYPESID	0	3
Prm15	PERIODID*TYPESID	0	4
Prm16	PERIODID*TYPESID	0	5
Prm17	PERIODID*TYPESID	1	1
Prm18	PERIODID*TYPESID	1	2
Prm19	PERIODID*TYPESID	1	3
Prm20	PERIODID*TYPESID	1	4
Prm21	PERIODID*TYPESID	1	5

INJURY BY TYPE negbin

The GENMOD Procedure

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	127	141.3208	1.1128
Scaled Deviance	127	141.3208	1.1128
Pearson Chi-Square	127	197.8890	1.5582
Scaled Pearson X2	127	197.8890	1.5582
Log Likelihood		164.8259	

Algorithm converged.

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	
Intercept	1	-12.1275	3.6608	-19.3026	-4.9524	
CRASHINJ	1	0.0441	0.0148	0.0151	0.0731	
TYPESID	1	1.1012	0.8467	-0.5582	2.7607	
TYPESID	2	1.1240	0.8465	-0.5350	2.7831	
TYPESID	3	0.9326	0.8657	-0.7642	2.6294	
TYPESID	4	1.4200	0.8214	-0.1898	3.0299	
TYPESID	5	0.0000	0.0000	0.0000	0.0000	
PERIODID	0	1.1091	0.8264	-0.5107	2.7289	
PERIODID	1	0.0000	0.0000	0.0000	0.0000	
logDEV	1	0.9792	0.3360	0.3206	1.6378	
LEGS	1	-0.0966	0.2615	-0.6092	0.4160	
PERIODID*TYPESID	0 1	1	1.3918	0.9192	-0.4098	3.1935

Analysis Of Initial Parameter Estimates

Parameter	Chi-Square	Pr > ChiSq	
Intercept	10.97	0.0009	
CRASHINJ	8.90	0.0028	
TYPESID	1	1.69	0.1934
TYPESID	2	1.76	0.1842
TYPESID	3	1.16	0.2814
TYPESID	4	2.99	0.0838
TYPESID	5	.	.
PERIODID	0	1.80	0.1796
PERIODID	1	.	.
logDEV	8.49	0.0036	
LEGS	0.14	0.7118	
PERIODID*TYPESID	0 1	2.29	0.1300

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INJURY BY TYPE negbin

The GENMOD Procedure

Analysis Of Initial Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	
PERIODID*TYPESID	0 2	1	-0.4492	0.9389	-2.2894	1.3910
PERIODID*TYPESID	0 3	1	-1.4087	0.9998	-3.3683	0.5510
PERIODID*TYPESID	0 4	1	-2.1345	0.9819	-4.0589	-0.2101
PERIODID*TYPESID	0 5	0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 1	0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 2	0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 3	0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 4	0	0.0000	0.0000	0.0000	0.0000
PERIODID*TYPESID	1 5	0	0.0000	0.0000	0.0000	0.0000
Dispersion	1	0.2146	0.1825	-0.0313	0.5722	

Analysis Of Initial Parameter Estimates

Parameter	Chi-Square	Pr > ChiSq	
PERIODID*TYPESID	0 2	0.23	0.6323
PERIODID*TYPESID	0 3	1.98	0.1589
PERIODID*TYPESID	0 4	4.73	0.0297

PERIODID*TYPEID	0	5	.	.
PERIODID*TYPEID	1	1	.	.
PERIODID*TYPEID	1	2	.	.
PERIODID*TYPEID	1	3	.	.
PERIODID*TYPEID	1	4	.	.
PERIODID*TYPEID	1	5	.	.
Dispersion				

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

GEE Model Information

Correlation Structure	Exchangeable
Subject Effect	SITEID (14 levels)
Number of Clusters	14
Correlation Matrix Dimension	10
Maximum Cluster Size	10
Minimum Cluster Size	10

Algorithm converged.

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INJURY BY TYPE negbin

The GENMOD Procedure

Exchangeable Working  
Correlation

Correlation -0.019710884

Analysis Of GEE Parameter Estimates  
Empirical Standard Error Estimates

Parameter	Estimate	Standard Error	95% Confidence Limits		Z	Pr >  Z
Intercept	-11.6795	2.6138	-16.8024	-6.5566	-4.47	<.0001
CRASHINJ	0.0471	0.0092	0.0290	0.0651	5.11	<.0001
TYPEID 1	1.0964	0.4771	0.1614	2.0314	2.30	0.0215
TYPEID 2	1.1187	0.6123	-0.0814	2.3188	1.83	0.0677
TYPEID 3	0.9290	0.8680	-0.7722	2.6302	1.07	0.2845
TYPEID 4	1.4154	0.7942	-0.1413	2.9720	1.78	0.0747
TYPEID 5	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID 0	1.0658	0.7819	-0.4667	2.5984	1.36	0.1729
PERIODID 1	0.0000	0.0000	0.0000	0.0000	.	.
logDEV	0.9599	0.2412	0.4872	1.4326	3.98	<.0001
LEGS	-0.1632	0.0975	-0.3543	0.0280	-1.67	0.0944
PERIODID*TYPEID 0 1	1.3935	0.8762	-0.3238	3.1109	1.59	0.1117
PERIODID*TYPEID 0 2	-0.4418	0.7430	-1.8980	1.0145	-0.59	0.5521
PERIODID*TYPEID 0 3	-1.4044	1.0143	-3.3923	0.5835	-1.38	0.1662
PERIODID*TYPEID 0 4	-2.1267	1.0632	-4.2105	-0.0429	-2.00	0.0455
PERIODID*TYPEID 0 5	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 1	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 2	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 3	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 4	0.0000	0.0000	0.0000	0.0000	.	.
PERIODID*TYPEID 1 5	0.0000	0.0000	0.0000	0.0000	.	.

Contrast Estimate Results

Label	Estimate	Standard Error	Alpha
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B-A	0.5500	0.2830	0.05
TYPE-ANG in Before v.s. After	2.4594	0.3336	0.05

## Contrast Estimate Results

Label	Confidence Limits		Chi-Square	Pr > ChiSq
B-A	-0.0046	1.1045	3.78	0.0519
TYPE-ANG in Before v.s. After	1.8056	3.1131	54.36	<.0001

## INJURY BY TYPE negbin

The GENMOD Procedure

## Contrast Estimate Results

Label	Estimate	Standard Error	Alpha
TYPE-REN in Before v.s. After	0.6241	0.3724	0.05
TYPE-SWI in Before v.s. After	-0.3386	0.5270	0.05
TYPE-FIX in Before v.s. After	-1.0609	0.7335	0.05
TYPE-OTH in Before v.s. After	1.0658	0.7819	0.05

## Contrast Estimate Results

Label	Confidence Limits		Chi-Square	Pr > ChiSq
TYPE-REN in Before v.s. After	-0.1059	1.3540	2.81	0.0938
TYPE-SWI in Before v.s. After	-1.3715	0.6943	0.41	0.5206
TYPE-FIX in Before v.s. After	-2.4985	0.3768	2.09	0.1481
TYPE-OTH in Before v.s. After	-0.4667	2.5984	1.86	0.1729

TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Model Information

Data Set WORK.WORK0  
 Distribution Negative Binomial  
 Link Function Log  
 Dependent Variable CRASHTOT CRASHTOT  
 Offset Variable logYEARBA

Number of Observations Read 18  
 Number of Observations Used 18

Class Level Information

Class	Levels	Values
SITEID	18	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	16	18.2609	1.1413
Scaled Deviance	16	18.2609	1.1413
Pearson Chi-Square	16	15.3032	0.9564
Scaled Pearson X2	16	15.3032	0.9564
Log Likelihood		245.3728	

Algorithm converged.

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Intercept	1	-6.1810	3.8508	-13.7285	1.3664	2.58
logDEV	1	0.7274	0.4160	-0.0879	1.5428	3.06

Analysis Of Parameter Estimates

Parameter	Pr > ChiSq
Intercept	0.1085
logDEV	0.0804

TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Dispersion	1	0.1525	0.0983	-0.0250	0.3451	

Analysis Of Parameter Estimates

Parameter Pr > ChiSq  
Dispersion

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Model Information

Data Set WORK.WORK0  
Distribution Negative Binomial  
Link Function Log  
Dependent Variable CRASHTOT CRASHTOT  
Offset Variable logYEARBA

Number of Observations Read 18  
Number of Observations Used 18

Class Level Information

Class	Levels	Values
SITEID	18	1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	16	18.2609	1.1413
Scaled Deviance	16	18.2609	1.1413
Pearson Chi-Square	16	15.3032	0.9564
Scaled Pearson X2	16	15.3032	0.9564
Log Likelihood		245.3728	

Algorithm converged.

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Intercept	1	-6.1810	3.8508	-13.7285	1.3664	2.58
logDEV	1	0.7274	0.4160	-0.0879	1.5428	3.06

Analysis Of Parameter Estimates

Parameter Pr > ChiSq  
Intercept 0.1085  
logDEV 0.0804

TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Dispersion	1	0.1525	0.0983	-0.0250	0.3451	

Analysis Of Parameter Estimates

Parameter Pr > ChiSq

Dispersion

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

Observation Statistics

Observation	CRASHTOT	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
1	9	2.3125354 2.7694216 21.022769 -1.14413	9.1251092 0.140913 -6.949406 -0.984881	1 3.2124711 -0.939306 -1.130655	15.949406 12.100384 -1.091186
2	10	1.9459101 2.3707306 14.328304 -0.141767	9.0810286 0.1487304 -0.705211 -0.139209	2 3.9007387 -0.132848 -0.14154	10.705211 7.9982627 -0.135289
3	2	0.5596158 0.5371239 3.4104157 0.2119049	8.4661104 0.3518995 0.2889214 0.2188588	3 1.404442 0.1967 0.2132594	1.7110786 0.8584848 0.1904502
4	4	0.5128236 0.6389602 3.2464864 1.2097489	8.6704292 0.2748077 2.1054901 1.4395969	4 1.836032 1.3474119 1.2405578	1.8945099 1.1055545 1.1322823
5	4	0.6931472 1.131338 4.120624 0.4062926	9.0994088 0.1452407 0.9001987 0.4308744	5 2.3011069 0.4213296 0.4074007	3.0998013 2.3318721 0.3972924
6	22	2.3418058 2.9162044 23.904079 0.4168445	9.2866531 0.1315558 3.5289537 0.4390116	6 5.5222909 0.4203129 0.4187375	18.471046 14.272859 0.39909

TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Observation Statistics

Observation	CRASHTOT	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
7	18	2.541602 3.049494	9.1952267 0.1328175	7 4.4419551	21.104663 16.267618

		27.379965	-3.104663	-0.329059	-0.344476
		-0.360276	-0.344152	-0.358921	
8	6	1.9459101	9.2227629	8	11.867848
		2.4738329	0.1312843	2.8789136	9.1753482
		15.350461	-5.867848	-1.016185	-1.201896
		-1.24696	-1.054285	-1.234277	
9	40	2.3223877	9.763248	9	25.622673
		3.2434776	0.2498328	7.5547096	15.702412
		41.810227	14.377327	1.2822236	1.1141863
		1.4240772	1.6388511	1.5110085	
10	4	0.8329091	8.8853025	10	3.0506412
		1.1153518	0.200741	2.2878444	2.0583539
		4.5212885	0.9493588	0.4490487	0.4218676
		0.4420709	0.4705538	0.4446891	
11	4	1.6677068	9.1421686	11	8.4739993
		2.1370026	0.1384222	2.5967266	6.4604571
		11.115106	-4.473999	-1.015163	-1.206069
		-1.250061	-1.052192	-1.237398	
12	11	1.6486586	8.8392767	12	6.6700046
		1.8976206	0.215631	4.3892793	4.370999
		10.178214	4.3299954	1.1805083	1.0306087
		1.1284086	1.292533	1.1572363	
13	8	0.6931472	9.7413215	13	4.9445553
		1.598287	0.2421072	3.5679541	3.0764172
		7.9471104	3.0554447	1.0375394	0.9162945
		1.0219727	1.1572009	1.0498675	
14	3	1.6094379	9.5334378	14	10.626556
		2.3633562	0.1756432	2.2556765	7.5315572
		14.993406	-7.626556	-1.445294	-1.90413
		-2.055127	-1.559906	-1.992522	
15	3	0.6931472	9.0300168	15	2.9472129
		1.0808599	0.159939	2.0447194	2.1541264
		4.0322906	0.0527871	0.0255406	0.0254415
		0.0261383	0.0262401	0.0261436	
16	1	1.2809338	9.289244	16	6.4058856
		1.8572172	0.1316801	1.8893305	4.9487203
		8.2921176	-5.405886	-1.519153	-2.107524
		-2.169129	-1.563559	-2.139754	

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TOTAL CRASHES negbin AFTER ONLY

The GENMOD Procedure

Observation Statistics

Observation	CRASHTOT	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
17	5	1.1631508	9.2119391	17	5.3827531
		1.6832	0.1317704	2.8615843	4.1575866
		6.9689543	-0.382753	-0.122262	-0.124434
		-0.127664	-0.125436	-0.127554	
18	10	1.1631508	9.3831165	18	6.0965329
		1.8077202	0.1417445	4.1340786	4.6177431
		8.0488915	3.9034671	1.1380925	0.996976
		1.0319712	1.1780412	1.0423471	

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Values of CRASHTOT, Pred, Xbeta, and Std

CRASHTOT	Pred	Xbeta	Std
9	15.949406	2.7694216	0.140913
10	10.705211	2.3707306	0.1487304

2	1.7110786	0.5371239	0.3518995
4	1.8945099	0.6389602	0.2748077
4	3.0998013	1.131338	0.1452407
22	18.471046	2.9162044	0.1315558
18	21.104663	3.049494	0.1328175
6	11.867848	2.4738329	0.1312843
40	25.622673	3.2434776	0.2498328
4	3.0506412	1.1153518	0.200741
4	8.4739993	2.1370026	0.1384222
11	6.6700046	1.8976206	0.215631
8	4.9445553	1.598287	0.2421072
3	10.626556	2.3633562	0.1756432
3	2.9472129	1.0808599	0.159939
1	6.4058856	1.8572172	0.1316801
5	5.3827531	1.6832	0.1317704
10	6.0965329	1.8077202	0.1417445

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 INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

Model Information

Data Set	WORK.WORK1
Distribution	Negative Binomial
Link Function	Log
Dependent Variable	CRASHINJ
Offset Variable	logYEARBA

Number of Observations Read	18
Number of Observations Used	18

Class Level Information

Class	Levels	Values
SITEID	18	1 2 3 4 5 6 7 8 9 11 12 13 14 15 16 17 18 19

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	16	20.6072	1.2879
Scaled Deviance	16	20.6072	1.2879
Pearson Chi-Square	16	29.8231	1.8639
Scaled Pearson X2	16	29.8231	1.8639
Log Likelihood		-11.2776	

Algorithm converged.

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Intercept	1	-21.0032	8.6458	-37.9486	-4.0578	5.90
logDEV	1	2.1703	0.9270	0.3535	3.9872	5.48

Analysis Of Parameter Estimates

Parameter	Pr > ChiSq
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Intercept            0.0151  
logDEV                0.0192

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INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Dispersion	1	0.1204	0.2417	-0.1429	0.5940	

Analysis Of Parameter Estimates

Parameter      Pr > ChiSq

Dispersion

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

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INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

Model Information

Data Set                            WORK.WORK1  
Distribution                        Negative Binomial  
Link Function                        Log  
Dependent Variable                   CRASHINJ      CRASHINJ  
Offset Variable                      logYEARBA

Number of Observations Read      18  
Number of Observations Used       18

Class Level Information

Class	Levels	Values
SITEID	18	1 2 3 4 5 6 7 8 9 11 12 13 14 15 16 17 18 19

Criteria For Assessing Goodness Of Fit

Criterion	DF	Value	Value/DF
Deviance	16	20.6072	1.2879
Scaled Deviance	16	20.6072	1.2879
Pearson Chi-Square	16	29.8231	1.8639
Scaled Pearson X2	16	29.8231	1.8639
Log Likelihood		-11.2776	

Algorithm converged.

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Intercept	1	-21.0032	8.6458	-37.9486	-4.0578	5.90
logDEV	1	2.1703	0.9270	0.3535	3.9872	5.48

Analysis Of Parameter Estimates

Parameter	Pr > ChiSq
Intercept	0.0151
logDEV	0.0192

INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

Analysis Of Parameter Estimates

Parameter	DF	Estimate	Standard Error	Wald	95% Confidence Limits	Chi-Square
Dispersion	1	0.1204	0.2417	-0.1429	0.5940	

Analysis Of Parameter Estimates

Parameter	Pr > ChiSq
Dispersion	

NOTE: The negative binomial dispersion parameter was estimated by maximum likelihood.

Observation Statistics

Observation	CRASHINJ	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
1	1	2.3125354	9.1251092	1	3.0458987
		1.113796	0.2773055	1.8271454	1.7687748
		5.2451554	-2.045899	-1.002768	-1.212912
		-1.326118	-1.096361	-1.291363	
2	7	1.2809338	9.5891877	2	2.9724769
		1.0893956	0.3212197	2.9708291	1.5837833
		5.5788052	4.0275231	2.004757	1.6260544
		1.8727039	2.3088503	1.9889173	
3	3	1.9459101	9.0810286	3	1.9184192
		0.6515015	0.3060224	1.7233651	1.0530689
		3.4948634	1.0815808	0.7038378	0.6394851
		0.6897891	0.7592039	0.6999601	
4	0	0.5596158	8.4661104	4	0.1262659
		-2.069365	0.8219098	0.1225135	0.0252159
		0.6322617	-0.126266	-0.352669	-0.500632
		-0.523844	-0.369021	-0.512282	
5	1	0.5128236	8.6704292	5	0.1877358
		-1.672719	0.6403941	0.2011402	0.053511
		0.6586453	0.8122642	1.853836	1.2828142
		1.3350966	1.929391	1.3897676	
6	1	0.6931472	9.0994088	6	0.5704267
		-0.561371	0.2936989	0.5596035	0.3207768
		1.014371	0.4295733	0.5501956	0.4930891
		0.5043491	0.5627596	0.5070701	



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 INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

## Observation Statistics

Observation	CRASHINJ	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
7	2	2.3418058 1.493669 6.719667 -1.16889	9.2866531 0.2098863 -2.453405 -1.001127	7 2.3418552 -0.938037 -1.149724	4.4534051 2.9514584 -1.095228
8	4	2.541602 1.4950403 7.1243712 -0.195748	9.1952267 0.2390254 -0.459516 -0.191111	8 2.7973988 -0.175529 -0.19503	4.4595165 2.7914445 -0.179789
9	1	1.9459101 0.9591109 4.074228 -1.078536	9.2227629 0.227336 -1.609375 -0.914485	9 1.6929669 -0.869114 -1.063767	2.6093755 1.6711977 -1.025026
10	3	0.8329091 -0.886289 1.0084013 2.5629407	8.8853025 0.4564651 2.5878174 4.1055938	11 0.5092404 3.934359 2.7219265	0.4121826 0.168479 2.4560464
11	1	1.6677068 0.5059917 2.7993458 -0.536395	9.1421686 0.2670427 -0.65863 -0.490462	12 1.291228 -0.466917 -0.532259	1.6586296 0.9827483 -0.510645
12	0	1.6486586 -0.17043 2.224421 -1.406745	8.8392767 0.4948698 -0.843302 -0.971154	13 0.6950372 -0.874979 -1.335642	0.8433018 0.3197047 -1.267433
13	3	0.6931472 0.8317888 5.4270289 0.4923072	9.7413215 0.438581 0.7025754 0.5210712	14 1.9189577 0.4102563 0.5034343	2.2974246 0.972569 0.3876095
14	3	1.6094379 1.2969044 6.3780998 -0.338467	9.5334378 0.2836613 -0.657955 -0.324673	15 2.4000581 -0.286649 -0.335474	3.6579554 2.0979035 -0.298827
15	1	0.6931472 -0.711974 0.9598474 0.630376	9.0300168 0.3423496 0.5093252 0.7259922	16 0.4901308 0.7065413 0.635791	0.4906748 0.2508333 0.6134869
16	0	1.2809338 0.4384202 2.3373915 -1.734314	9.289244 0.2095015 -1.550256 -1.175712	17 1.101013 -1.143007 -1.70841	1.5502561 1.0281949 -1.68607

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 INJURY CRASHES negbin AFTER ONLY

The GENMOD Procedure

## Observation Statistics

Observation	CRASHINJ	logYEARBA Xbeta Upper StResdev	logDEV Std Resraw StReschi	SITEID HessWgt Reschi Reslik	Pred Lower Resdev
17	1	1.1631508	9.2119391	18	1.1651623

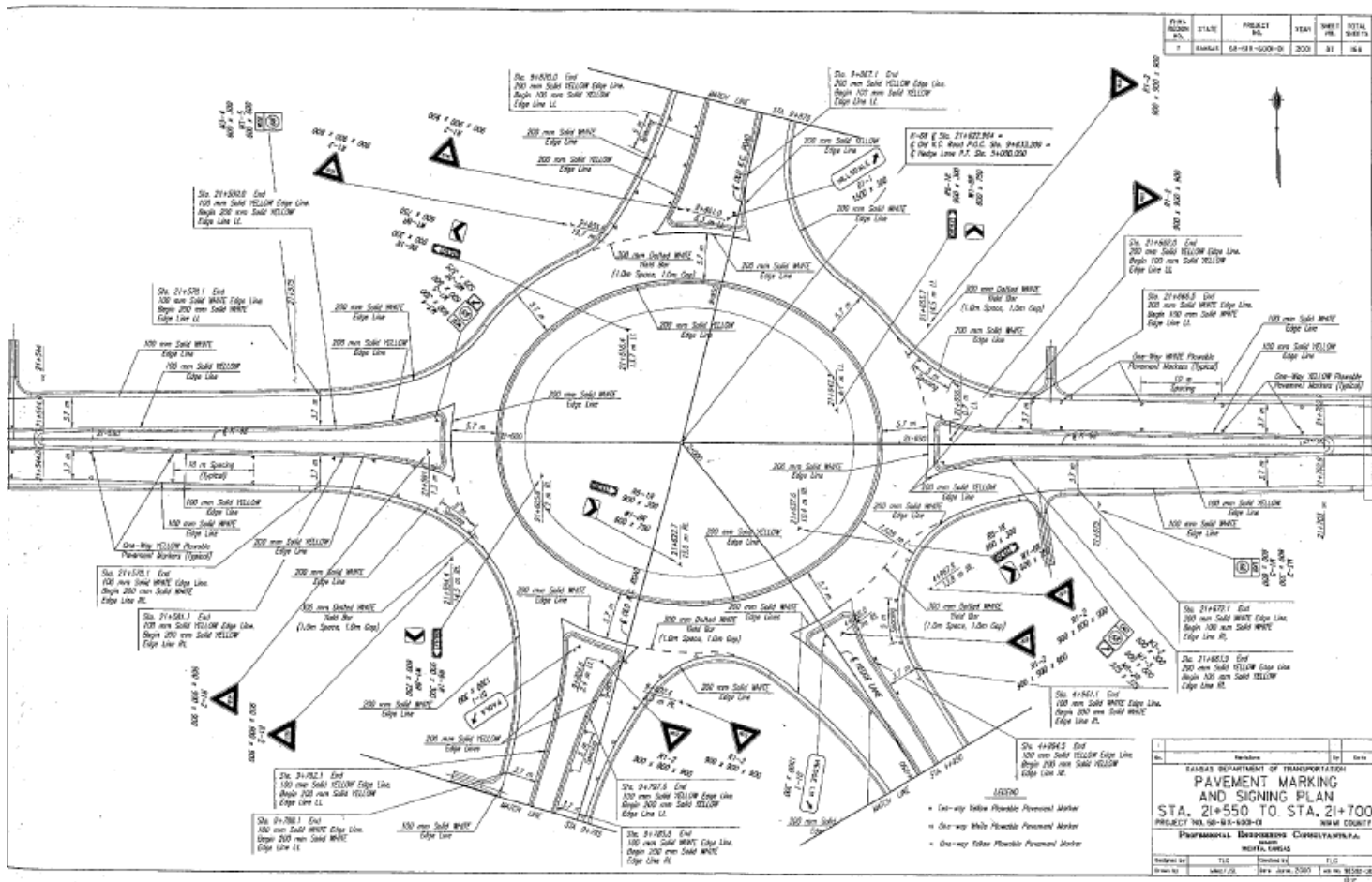
		0.1528604	0.2316658	1.0040323	0.7399325
		1.8347663	-0.165162	-0.143291	-0.147334
		-0.151297	-0.147145	-0.151085	
18	1	1.1631508	9.3831165	19	1.689396
		0.5243711	0.2140672	1.3070968	1.1104964
		2.570075	-0.689396	-0.483512	-0.53045
		-0.548572	-0.50003	-0.545549	

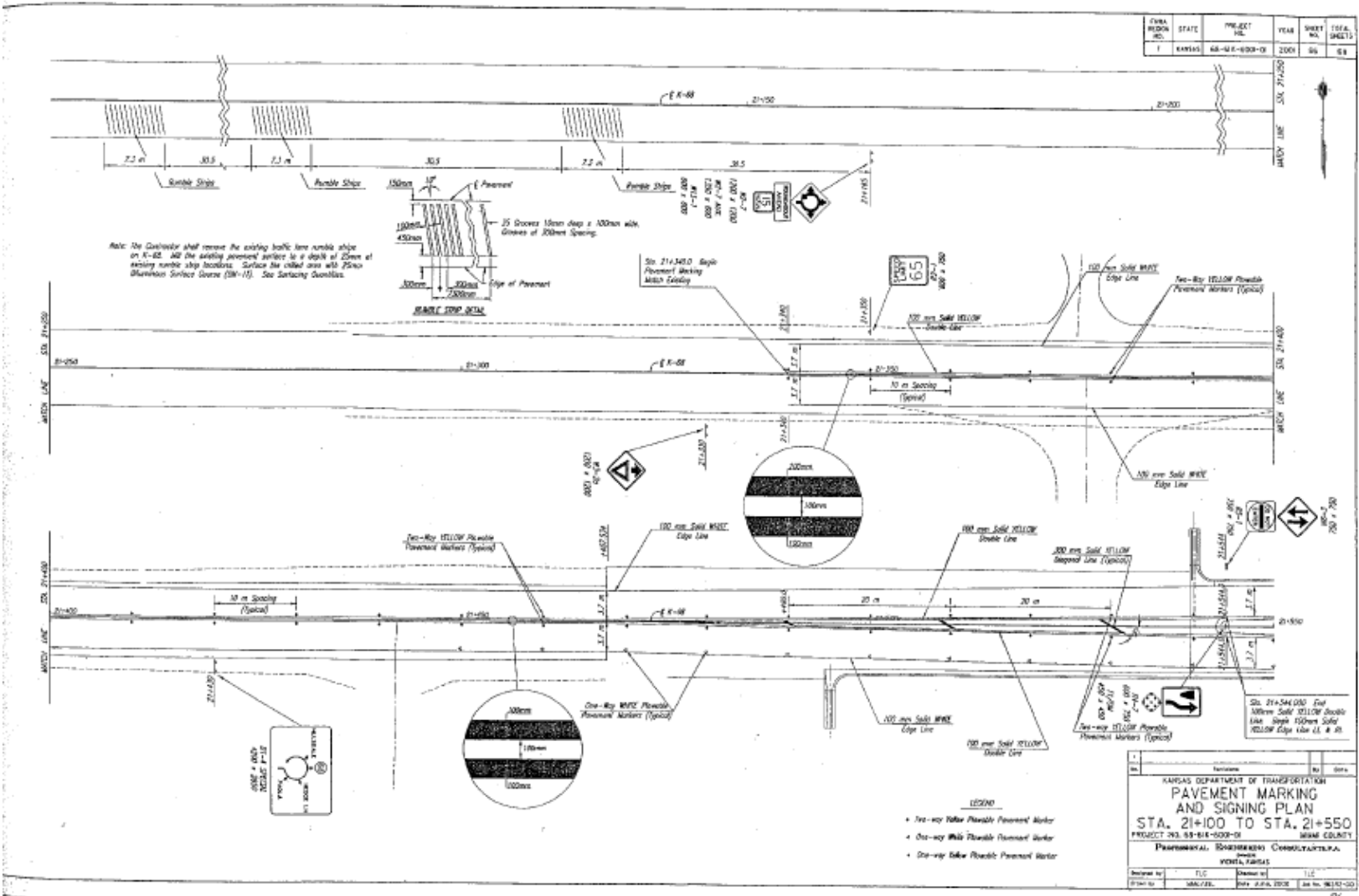
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Values of CRASHINJ, Pred, Xbeta, and Std

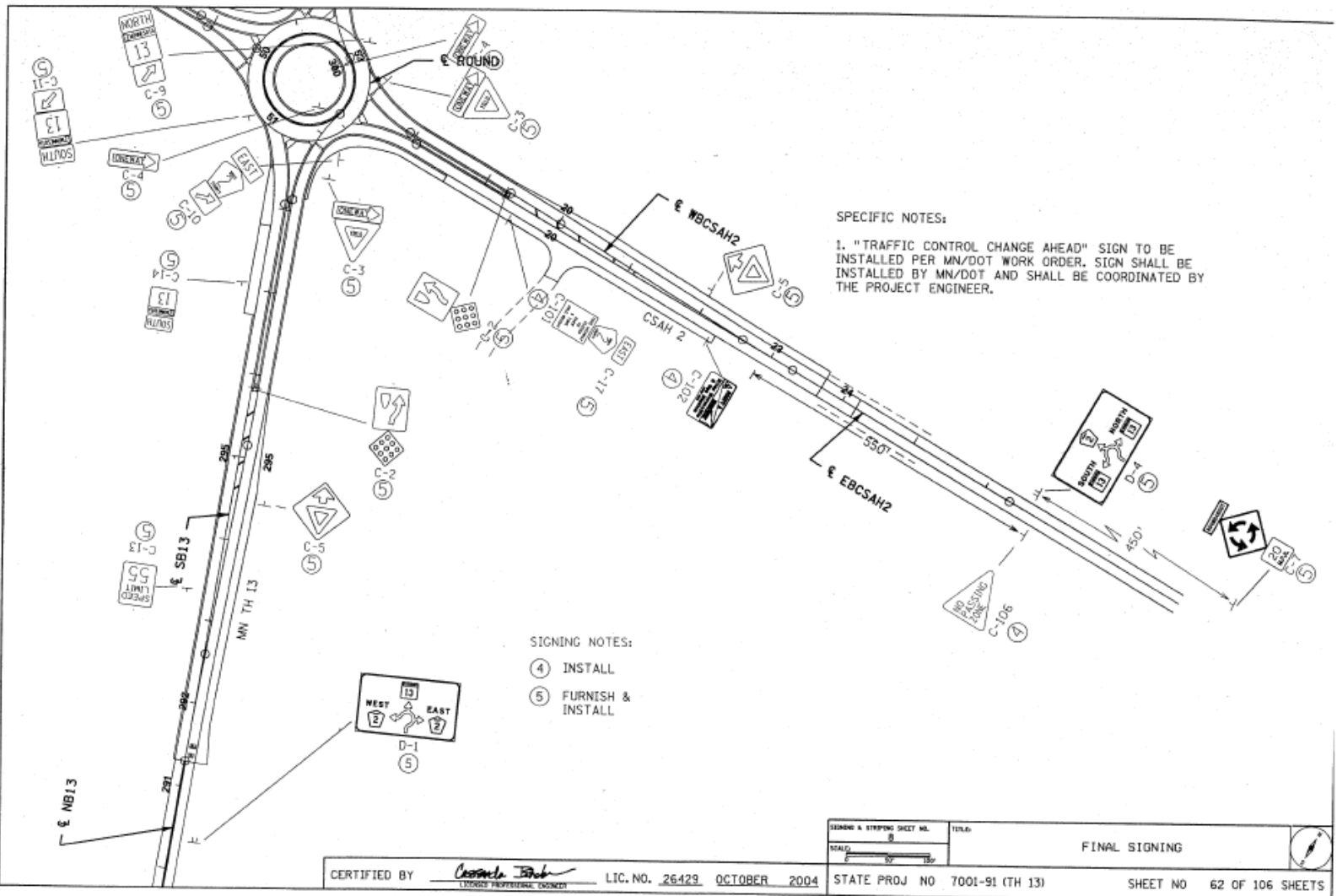
CRASHINJ	Pred	Xbeta	Std
1	3.0458987	1.113796	0.2773055
7	2.9724769	1.0893956	0.3212197
3	1.9184192	0.6515015	0.3060224
0	0.1262659	-2.069365	0.8219098
1	0.1877358	-1.672719	0.6403941
1	0.5704267	-0.561371	0.2936989
2	4.4534051	1.493669	0.2098863
4	4.4595165	1.4950403	0.2390254
1	2.6093755	0.9591109	0.227336
3	0.4121826	-0.886289	0.4564651
1	1.6586296	0.5059917	0.2670427
0	0.8433018	-0.17043	0.4948698
3	2.2974246	0.8317888	0.438581
3	3.6579554	1.2969044	0.2836613
1	0.4906748	-0.711974	0.3423496
0	1.5502561	0.4384202	0.2095015
1	1.1651623	0.1528604	0.2316658
1	1.689396	0.5243711	0.2140672

# APPENDIX G. EXAMPLE ADVANCED SIGNING PLANS





METRO DIVISION - TRAFFIC  
 PLOT NAME: NONE  
 PATH & FILENAME: S:\TRAFFIC\TC Signing\Ar-crivas\013\7001\7001-91\crvas1.v03.dwg  
 PLOTTED: 31-JAN-2005 01:52



SPECIFIC NOTES:  
 1. "TRAFFIC CONTROL CHANGE AHEAD" SIGN TO BE INSTALLED PER MN/DOT WORK ORDER. SIGN SHALL BE INSTALLED BY MN/DOT AND SHALL BE COORDINATED BY THE PROJECT ENGINEER.

SIGNING NOTES:  
 ④ INSTALL  
 ⑤ FURNISH & INSTALL

SIGNING & STOPPING SHEET NO. 8 SCALE: 1" = 100' DATE:	TITLE: FINAL SIGNING	
CERTIFIED BY <u>Cecilia Sobel</u> LIC. NO. 26429 OCTOBER 2004 STATE PROJ NO 7001-91 (TH 13) SHEET NO 62 OF 106 SHEETS		

**APPENDIX H. APPROACH ROAD TUBE LAYOUT PHOTOS**



Rural Paola, KS (Photo Source: © 2011 Isebrands)



Rural Paola, KS (Photo Source: © 2011 Isebrands)



Rural Paola, KS (Photo Source: © 2011 Isebrands)



Rural Paola, KS (Photo Source: © 2011 Isebrands)





Rural Florence, KS (Photo Source: © 2011 Isebrands)



Rural Florence, KS (Photo Source: © 2011 Isebrands)

# APPENDIX I. SPEED PROFILES

