THE DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS FOR ROUNDABOUTS IN WISCONSIN

by

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Abstract

Crash occurrences at roadways or intersections are associated with a large variety of factors. The safety performance function (SPF) is a statistical regression model that determines the relation between crash frequency and potential geometric features that lead the crashes at a location. As the funds for safety improvements are limited, it is important to identify the design decisions which will result in the maximum safety benefits. By improving SPFs, engineers can estimate the number of crashes and improve the roadway or intersection safety through applying appropriate safety countermeasures.

The number of roundabouts has increased rapidly throughout the state of Wisconsin in the last several years. There is a strong need to develop an assessment model to evaluate the safety performance of Wisconsin roundabouts. In *2010 Highway Safety Manual* (HSM) published by American Association of State Highway and Transportation Officials (AASHTO), SPFs of roundabouts have been developed. However, the development of the SPFs is based on the data collected from locations across the country, the real condition of local roundabouts, such as geometry design, driver behavior and weather condition, cannot be reflected in these models.

Two types of safety performance functions of roundabouts in Wisconsin are developed in this thesis by using the negative binomial regression models. The first type is the intersection-level SPFs, which considers the crash frequency, traffic volume and geometric features of whole roundabouts. The second type is the single approach-level SPFs, which considers the entering-circulating locations at roundabouts with their crash frequency and geometric features.

The results show that for the intersection-level SPFs, crash frequency has a strong relation with traffic volume (AADT). For the single approach-level SPFs, crash frequency are related to traffic volume, lane width, and entry angle. To evaluate how the Wisconsin roundabouts SPFs perform, a comparison with models developed by National Cooperative Highway Research Program (NCHRP) is provided. The results reveal that Wisconsin roundabouts SPFs tend to have less crash frequency. The potential reasons of these findings are discussed.

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Chapter 1 Introduction

1.1 Background

Research has proved that roundabout, defined as a circulatory intersection, can enhance safety by decreasing the number of crashes, particularly by mitigating the number of accidents that result in fatality and injury (1, 2, 3). A study conducted by the Traffic Operations and Safety Laboratory at the University of Wisconsin-Madison found that 71% of locations decrease in fatal and injury crashes and a 52% decrease in total number of injury crashes after 30 urban and suburban Wisconsin intersections were changed into roundabouts (4). The geometry of the roundabout restricts vehicles to travel in the same direction and reduce the conflict points associated with the left-turn and right-turn maneuvers in traditional intersections (5). Besides its safety advantage, a roundabout also offers lower maintenance costs, less surface area, and better traffic flow. Due to these advantages, the construction of roundabouts as alternatives to signalized intersections has been increasing throughout the country.

Before an intersection is constructed or converted, engineers use a predictive method to estimate the crash frequency associated with known geometric features (6). According to the 2010 Highway Safety Manual (HSM) published by the American Association of State Highway and Transportation Officials (AASHTO), safety performance function (SPF) is a regression model that predicts crash frequency based on independent variables of geometry (7). An appropriate SPF model can help engineers realize the important variables which may be involved in accidents and the relationship between crash frequency and those variables. If engineers do not know which factors lead to accidents, they may waste resources on inefficient designs. Therefore, with knowledge of the variables that lead to higher crash frequency, engineers are able to design intersections that minimize the factors that lead to accidents.

1.2 Problem Statement

The HSM identifies crash modification factors (CMF) for the conversion of signalized intersections to roundabouts and for the conversion of stop-controlled intersections to roundabouts. In general, SPFs models certain configurations and CMFs will be applied to the model as a particular geometric feature is changed when all other conditions remain the same. The roundabout CMFs provided by the HSM that convert signalized and stop-controlled intersections to roundabouts vary on a wide range depending on the terrain type of intersection (7). However, the HSM provides no other factors to model on how the geometry features or other characteristics of roundabouts affect the performance, such as lane width, central island diameter, and entry angle of the roundabout. In addition, the formations of CMFs suggested by HSM are based on United States roundabout data. These CMFs can only represent the general national conditions but cannot express the real condition of geometry features in a specific locality. Hence, when these CMFs are applied in the designs of certain locations, the results may not be accurate.

The state of Wisconsin has 288 roundabouts constructed through 2013. Figure 1 presents the distribution of roundabouts in Wisconsin (8). Due to the increased number of roundabouts, there is a strong need to develop a roundabout safety performance function which incorporates the local geometric characteristics of Wisconsin geometry, geography, weather, and driver behaviors based on the Wisconsin roundabout data. In the future, when analyzing the roundabouts by using the developed safety performance function, the result of the analysis will be appropriate for Wisconsin.

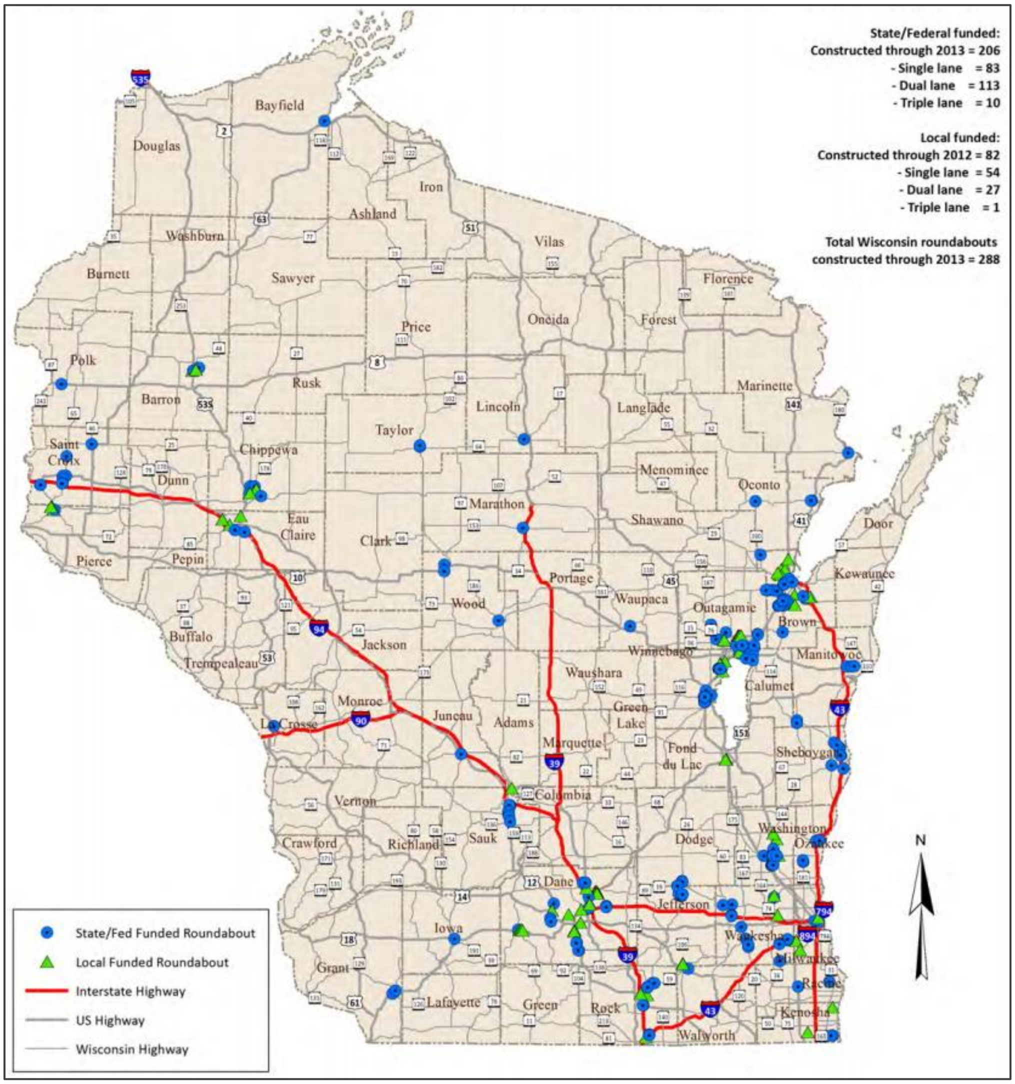

Figure 1 State of Wisconsin Roundabouts (Through Feb 2014) (8)

1.3 Research Objective and Research Scope

The first objective of this research was to develop the safety performance function of roundabouts in the state of Wisconsin. To develop the SPF model, traffic volume will be considered, and also geometric variables also will be input to the regression model to be evaluated. This SPF will define the relationship between the crash frequencies associated with other geometric variables and provide a predictive number of crashes before for a new roundabout is built.

The second objective of this research is to develop the safety performance function for geometric features of a single approach to a Wisconsin roundabout. The methodology will be the same as the first objective, except that instead of viewing roundabout as a whole, the analysis is evaluated by their geometric features of approach. This SPF can evaluate the safety performance of one single approach of a roundabout.

The scope of the research includes:

- Collecting the comprehensive geometric information for 25 roundabouts throughout the state of Wisconsin.
- Collecting all crash data history of these roundabouts. For the analysis of the second objective, the crash history of every approach of the roundabouts will be collected.
- Collecting traffic volume, measured as annual average daily traffic (AADT), for these roundabouts and their approaches
- Developing safety performance function for these roundabouts that presents the crash frequency as a function of AADT and other geometric variables.

1.4 Thesis Organization

This thesis consists of 5 chapters. Chapter 1 introduces how the roundabout SPF will be developed. Chapter 2 provides a literature review including the geometry variables of roundabouts, general introduction of roundabouts, and the developing and application of safety performance functions. Chapter 3 describes the process of data collection and the methodology used for analyzing data. Chapter 4 presents the result of the data analysis and the discussion of the findings. Chapter 5 provides the conclusions and suggests the future works.

Chapter 2 Literature Review

The purpose of this literature review is to provide an overview of the safety performance of roundabouts. The review will define critical geometric features, which are potential factors that may lead to crashes at roundabouts, and analyze existing research related to the processes of development of SPF models for roundabouts.

2.1 Geometric Features of Roundabouts Potentially Related to Crashes

Transportation safety has been a widely-research topic and is the primary goal for all traffic designs. Engineers quantify safety and identify a variety of factors that cause crashes. A common approach to identify the safety performance of an intersection or a segment of roadway is to develop an equation that includes all potential variables. Several studies have proved that crash frequency is not only related to the annual average daily volume (AADT) (9), but is also affected, at least partly, by the geometric features of roundabouts (3, 10, 11).

Some of the roundabout features are depicted in Figure 2.1 and are described in the following sections.

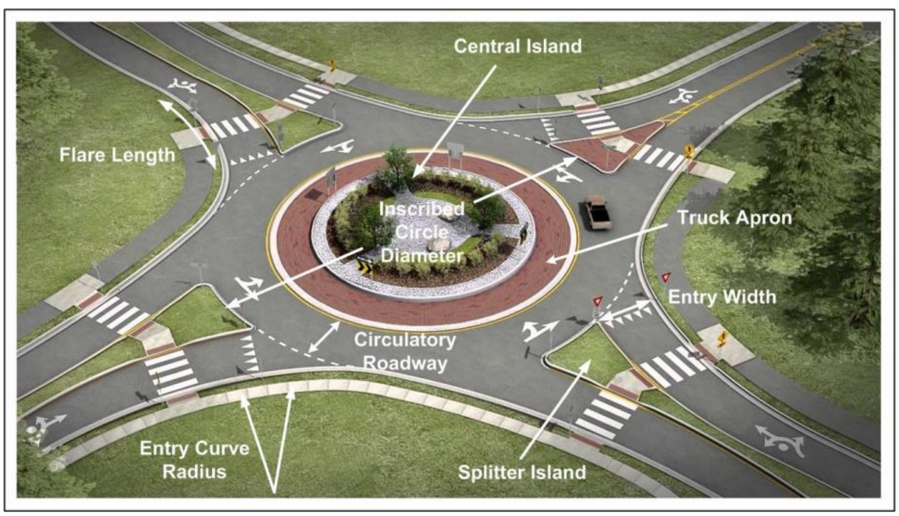

Figure 2 Geometric Features of Roundabout (12)

2.1.1 Inscribed Circle Diameter

The inscribed circle diameter is a measure of the circle corresponding to the outer edge of the circulatory roadway, which is composed of the central island diameter (including truck apron, if applicable) and each side of the circulatory roadway. The size of the inscribed circle for a single-lane roundabout depends on the turning requirements of vehicles and needs to be coordinated with other geometric elements (entry radii, exit radii, and entry width) of roundabouts. The size of the inscribed circle for a multi-lane roundabout must balance the deflection requirements and entry and exit radii. In general, a larger inscribed circle diameter will slow down the speed of approaching vehicles so that the number of crashes between circulating and entering vehicles will be reduced (3, 13, 14, 15).

2.1.2 Central Island

The central island is the raised, non-traversable area inside of the circulating roadway; it determines the shape of the roundabout. The central island may be landscaped for both aesthetic and conspicuity reasons. A raised central island may prevent drivers from seeing through to the other side, thereby eliminating the distraction and reducing the effect of light glare at night from vehicles approaching from the other side.

The diameter of the central island should not be small enough to allow vehicles to turn left in front of the island. The ideal size of a central island generally falls between 50’ and 100’ for a single-lane roundabout and between 65’ and 135’ for a multi-lane roundabout (13, 14, 15).

2.1.3 Entry Curve

An entry curve occurs along the right curb of a roundabout's approach leg. Sometimes multiple curves are necessary to accommodate the surrounding roadways. The design of entry curves affects the speed of approaching vehicles, so they are a large factor for roundabout safety.

Usually larger entry curves will allow faster speeds; therefore crashes between the circulatory and entering lanes are likely to increase. Small or abrupt entry curves may lead vehicles to crash into curbs, traffic signs or other components of roundabouts (13, 14).

2.1.4 Entry Angle

Entry angle can usually be represented as Phi in roundabout geometry. An appropriate entry angle is between 20 and 30 degrees. Narrow entry angles may cause problems with visibility. The entry angle can be measured by two conditions, each of which has its own method of measurement:

- Condition 1 applies for a larger roundabout for which the distance between the left side of the roundabout entry to the next exit is within 100 feet. In Figure 2.2, line a-b is tangential to the median line of the entry lane at the point which intersects with the extension line of the entry splitter island curb, and line c-d is tangential to the median line of the exit lane at the point which intersects the extension line of the exit splitter island curb. In this condition, Phi is half of the angle formed by these two lines.

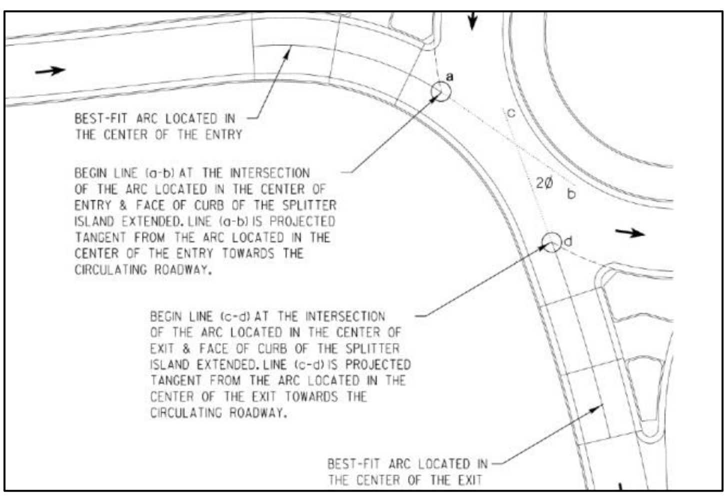

Figure 3 Phi Measurement in Condition 1 (13)

- Condition 2 applies for a smaller roundabout for which the distance between the left side of the entry of roundabout to the next exit is more than 100 feet or there is no adjacent exit existing. In Figure 2.3, line a-b is tangential to the median line of the entry lane in the same way as condition 1 and line c-d is tangential to the median line of the circulatory roadway at the point which intersects with line a-b. In this condition, Phi is the angle formed by these two lines (13, 14).

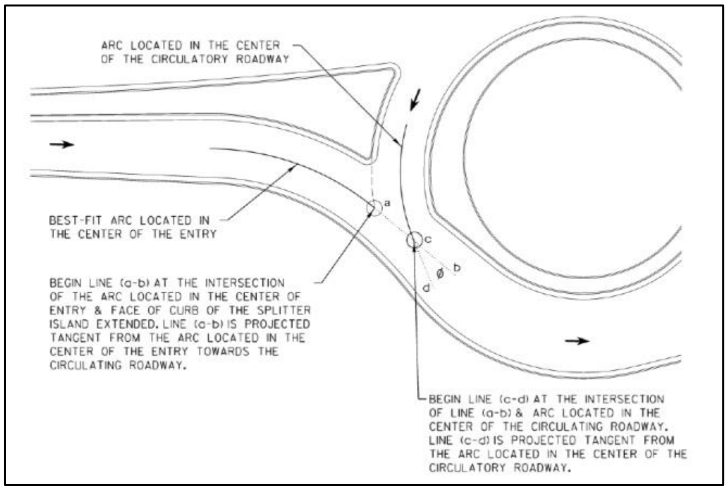

Figure 4 Phi Measurement in Condition 2 (13)

2.1.5 Entry Width

Entry width is the largest measured perpendicular distance between the right edge of the roundabout's approaching leg and the inside edge of the splitter island. The entry width plays an important role in the design of roundabouts because the width determines the capacity for entering vehicles. Larger widths will permit a higher capacity but will also increase the crash rate by promoting higher speeds for approaching vehicles (13, 14, 15).

2.1.6 Entry Flare Length

Entry flaring can be seen at a roundabout's entry lane and can substantially increase capacity when there is insufficient available land. The entry flare length and the entry width can be considered at the same time, since they both affect traffic speed and therefore increase roundabout capacity. The effective flare length is half of the distance between the point at which lane width starts to widen and where the lane reaches entry width (14, 16).

2.1.7 Truck Apron

The truck apron is a traversable area which is part of the central island. The design of the truck apron is based on the needs of larger vehicles, such as trucks and buses, to have adequate space for turning movements when traveling through roundabouts. In general, the truck apron appears distinct from the circulatory roadway to discourage smaller vehicles from traversing through it (13, 15).

2.1.8 Circulatory Roadway Width

The circulatory roadway width is the distance between the central island and the inscribed circle, and is a measure of the space designed for vehicles to cruise through roundabouts. The width of the roadway is determined based on the need of standard vehicles and does not include the truck apron which is considered part of the central island. Circulatory width is an important factor for roundabout capacity and safety (13).

2.2 Roundabout Use and Related Roadway Safety

2.2.1 The Major Benefits of Roundabouts

a. Reducing crashes after the construction of roundabouts

Several studies in the United States have indicated that roundabouts are a helpful means to reduce crashes and the severity of crashes (3, 5, 17). A nationwide survey evaluated 35 roundabouts. The result showed that 28 roundabouts reduced the total number of crashes and 29 roundabouts decreased the number of injury accidents. The number of injury crashes for 15 intersections was reduced to zero after roundabout construction (18). Persaud et al. also reported that converting traditional intersections from stop sign or signal control decreased all crashes by 35 to 72 percent and decreased injury crashes by 74 to 88 percent (19). Another study related to higher-speed rural roundabouts with stop control before the conversion observed a reduction of 67 percent of total crashes and a reduction of 87 percent of injury crashes (20). Multi-lane roundabouts usually have higher design speed and larger capacity than single-lane roundabouts (3). The different geometric features can affect safety performance. After stop control intersections were converted to roundabouts, multi-lane roundabouts tended to have smaller decreases of crashes compared to single-lane roundabouts (18), or even result in an increase in the number of crashes (20). Table 1 shows the reduction in crashes compared to previous intersections in the United States.

Table 1 Comparisons to Previous Intersection in the United States (5)

Control Before	Sites	Setting	Lanes	Estimate of the Percent Reduction in Crashes (and Standard Error)	
				All	Injury + Fatal
All Sites	55	All	All	35.4% (3.4)	75.8% (3.2)
Signalized	9	All	All	47.8% (4.9)	77.7% (6.0)
	4	Suburban	2	66.7% (4.4)	Sample too small to analyze
	5	Urban	All	Effects insignificant	60.1% (11.6)
All-way stop	10	All	All	Effects insignificant	Effects insignificant
Two-way stop	36	All	All	44.2% (3.8)	81.8% (3.2)
	9	Rural	1	71.5% (4.0)	87.3% (3.4)
	17	Urban	All	29.0% (9.0)	81.2% (7.9)
	12		1	39.8% (10.1)	80.3% (10.0)
	5		2	Sample too small to analyze	Sample too small to analyze
	10	Suburban	All	31.8% (6.7)	71.0% (8.3)
	4		1	78.2% (5.7)	77.6% (10.4)
	6		2	19.3% (9.1)	68.0% (11.6)
	27	Urban/ Suburban	All	30.8% (5.5)	74.4% (6.0)
	16		1	56.3% (6.0)	77.7% (7.4)
	11		2	17.9% (8.2)	71.8% (9.3)

b. Improving traffic flow

Conversion of intersections to roundabouts may provide more efficient traffic flow. Russell et al. observed that for intersections converted into roundabouts in Kansas, the Average Intersection Delay, Queue Length and Degree of Saturation decreased significantly by 65 percent, 44 percent and 53 percent, respectively (21). A thorough study in Oxford, Mississippi, also found that constructing a roundabout improved traffic operation by decreasing delays by 24 percent, decreasing idling time by 77 percent, and increasing average speed by up to 67 percent (22).

Poor air quality is frequently observed at both signalized and stop control intersections due to the traffic delays, deceleration and acceleration movements, and queuing of vehicles. By improving traffic flow and decreasing vehicle idling time, roundabouts can also significantly reduce exhaust emissions and fuel consumption (22, 23). Várhelyi used a "car-following" method to register driving patterns from randomly-selected vehicles both before and after construction of roundabouts. The result showed a 29 percent decrease of CO emissions, 21 percent decrease of NO_x emissions and 28 percent decrease of fuel consumption (24). Another study by Höglund found that changing a signalized intersection to a roundabout not only resulted in large reductions of travel time, but also reduced HC and CO emissions by 699 kg/year and 4160 kg/year, respectively (25). Based on the demonstrated facts, roundabouts are beneficial for both the road users and the environment.

2.2.2 Types of Crashes at Roundabouts

Even though the safety benefits of roundabouts are remarkable, certain types of crashes still occur. The crashes that do occur are generally less severe because vehicles drive slower than they do at signalized intersections. Due to the geometric design of roundabouts, vehicles can only travel through them in one direction and at a lower speed (5). This geometry can prevent the occurrence of head-on, right-angle, and left-turn collisions, which have higher fatality and injury rates. A safety analysis of 17 roundabouts in five states (Kansas, Maryland, Minnesota, Oregon, and Washington State) found that construction of roundabouts changed the types of crashes that occurred at intersections (26). Angle, head-on, and rear-end crashes significantly decreased after converting intersections to roundabouts. On the other hand, the number of fixed-object and sideswipe crashes increased; such crashes occurred most frequently at roundabouts. In a research study of 39 roundabouts throughout United States, rear-end, exit-circulating and entering-circulating crashes occurred most frequently (3). Single-lane roundabouts had a higher rate of entering-circulating crashes than exit-circulating crashes. At multi-lane roundabouts, a majority of crashes were exit-circulating. A study of crashes in Wisconsin evaluated the different types of crashes of roundabouts (27). There were no head-on crashes reported at any of the sites. Sideswipe crashes occurred most often, accounting for 42 percent of crashes at these roundabouts. Most of the crashes only caused property damage, and no fatal crashes were found during the study period.

In a study conducted on 15 roundabouts in Italy, Montella identified the crash contributory factors at roundabouts by using association rule analysis (28). Crashes that occurred could be attributed to either a single or multiple factors. Among 62 different contributory factors, geometric design was found to be the most frequent factor, occurring in almost 60 percent of total crashes. Markings and pavement were also major contributory factors that led to crashes. The author suggested that the improvement of geometric design might have a high cost while other crash factors, such as markings and signs, might be easier to improve.

2.2.3 International Experiences of Roundabouts

Roundabouts were present in Europe long before they appeared in the United States. There is well-developed research and studies of roundabouts in many countries. Despite different geometry, weather, and driving behaviors, international studies can still provide good information and references for roundabouts in the United States.

Robinson et al. revealed that the number of injury crashes reduced from 45 to 87 percent in Australia, 57 to 78 percent in France, and 25 to 39 percent in the United Kingdom (5). Hydén and Várhelyi found that roundabouts in Sweden improve safety by making crashes less severe and reducing the number of expected injury crashes by 44 percent (29). They also found the implementation of roundabouts helps to reduce accidents involving pedestrians and bicyclists by 80 percent and 60 percent, respectively. Brabander et al. from Belgium observed that injury crashes were reduced by an average of 34 percent (30) after intersections were converted to roundabouts. Roundabouts were more effective in reducing crashes when the former intersections had higher speed limits. Considering all this research in other countries and the United States, the results demonstrate that the construction of roundabouts is beneficial in most situations.

2.3 An Overview of Safety Performance Functions

2.3.1 Statistical Methods for Crash Estimation

When the safety of an intersection or a roadway segment is evaluated, it is very important to understand the factors that may lead to crashes. Many factors or variables may affect the crash frequency. In some scenarios, only one factor significant was found to affect crash frequency, while in other scenarios, combinations of factors were identified. Several factors have been recognized as the main reasons that lead to crashes, such as large traffic volume, unsafe speed, or poor geometric design. However, other factors that may be ignored by road users may also cause serious accidents. Therefore, researchers and engineers have used statistical analysis to develop different predictive models of crash frequency and identify the crash frequency and their associated factors. The reliability of the models is based upon how well the model can fit with the local characteristics and features (7).

A thorough review showed that a large variety of statistical methods for the estimation of crash frequency had been applied over the years (31). Among these methods, one of the most popular and widely-used methods is the Empirical Bayes method. This method was developed by Hauer to estimate the crash frequency by using the concept of weights which depend on the strength of the accident record (32). The Empirical Bayes method can correct the bias made by regression-to-the-mean and improve the estimation of crash frequency (33, 34). The scenario of regression-to-the-mean may introduce a bias into the crash estimation and cause inflated effectiveness at the site with extremely high crash frequency (7, 33). In *2010 Highway Safety Manual* (HSM), the regression models was built with data obtained from several similar sites, and the models can be adjusted to represent the local situation and have a more precise estimation of the crash frequency. The predictive method can be applied to model existing condition, alternatives to existing conditions, or new roadways.

2.3.2 Application of Safety Performance Functions

The safety performance functions (SPFs), which are models built to incorporate traffic volumes, geometric features and operational factors associated with the crash history of a specific location or roadway segment, provide a useful method to estimate average crash frequency (7). In HSM, the SPF was developed based on the situation that traffic volume was the primary input variable. This model contained a base condition which anticipated a particular set of typical geometric features. The crash modified factors (CMFs), which represent the change of crash frequency results from one particular situation, can be multiplied by the original function if the geometric features are different than the base condition (7). A different model considers not only the traffic volume but also considers the geometric features as input variables. This second model requires more geometric information to develop but its results can reflect more local geometric features.

SPFs can be applied for both the intersections and roadway segments (34, 35). Intersections and roadway segments can have different geometric conditions, so the variables for SPFs are also different. Table 2 summarizes the possible factors that describe the characteristics, geometric features, and driver behaviors.

Table 2 Potential Variables that Lead to Crash for Intersections and Roadway Segments

	Intersections (Major and minor road)	Roadway segments
Variables related to the crash frequency	• Number of legs • Median width • Grade of roadway • Number of lanes • Traffic control • Lane width • Annual daily traffic volume (AADT) • Peak hour traffic volume • Turning volumes • Shoulder width • Heavy vehicles percentage	• Terrain type • Segment length • Number of lanes • Lane width • Median width • Shoulder width • Speed limit • Grade of the roadway • Annual daily traffic volume (AADT) • Heavy vehicles percentage

SPFs assume crash frequencies follow the negative binomial distribution. Crash frequency is countable, non-negative data; hence, crash data is commonly modeled via the negative binomial and Poisson distributions. Because the negative binomial distribution can account the effect of overdispersion, which is common for crash data, it is more suitable for modeling the crash frequency (32, 36). Shankar and Mannering used negative binomial models to determine geometric and weather-related variables had a strong relation with crash frequency (37). Mohammed et al. also observed that negative binomial regression analyses had a better fit than Poisson regression models with the effect of cross-section design studies (38). The use of negative binomial regression to model crash frequency has gained prominence over the years to the point that it is now recommended as national guidance in the HSM (7).

Chapter 3 Data Collection and Methodology

To develop safety performance functions for the state of Wisconsin, a considerable amount of data will be assessed and evaluated. This chapter will describe the collecting of data, such as geometric features of roundabouts, crash history and annual average daily traffic (AADT) and the procedures of developing safety performance functions.

3.1 Overview of Roundabouts

Twenty-six roundabouts in the state of Wisconsin are being evaluated in this study. The criteria for selection of the roundabouts are as follows:

- Information on geometric features is available;
- Chosen from every geographic region of Wisconsin (there are five regions in total); and
- Constructed between 2004 and 2008.

All of these roundabouts were once signalized or stop-controlled intersections. The purpose of conversion from conventional intersections to roundabouts varied from site to site. One of the main reasons is a high crash rate with many severe injuries and fatalities in the past. Therefore, roundabouts were built as a safety treatment to improve the roadway safety. Other reasons are reducing delay, improving poor geometry of an intersection, and increasing capacity. A study conducted by the Traffic Operations and Safety Laboratory (TOPS Lab) evaluated 40 roundabouts built in Wisconsin in 2008 or before (39). Twenty-one of the 25 roundabouts which were examined in this study were used as part of the prior research. In order to increase diversity of the dataset, the 25 selected roundabouts in the study include different types of the roundabouts. These roundabouts are four-leg typical roundabouts, three-leg roundabouts, and highway ramps-related roundabouts. These different geometric features were all considered as the selected variables for the SPFs model development.

The speed of the vehicles that approach roundabouts was not included in this roundabout SPFs development. In NCHRP report 572, a speed-based model based on U.S. data was developed in order to evaluate the interrelationship between the speed of vehicles and safety performance (3). The result showed that the model had little effects on the speed variables. None of the previous SPFs model development, either in the U.S or outside the U.S., considered speed limit as a variable (3). The probable reasons for that is because several vehicles stop at the entry of roundabouts to yield the oncoming circulatory vehicles while other vehicles enter the roundabout without stopping at the entry. Therefore, speed limit of roundabout is not recommended as an input variable in the development of roundabout SPFs.

Table 3 shows some characteristics of roundabouts located in Wisconsin. More details concerning roundabouts will be discussed in section 3.2.

Table 3 Characteristics of 25 Roundabouts

Characteristics		**Number**	**Percentage**
Region	NC	1	4%
	NE	12	46%
	NW	5	19%
	SE	4	15%
	SW	4	15%
Area	Urban	18	69%
	Rural	8	31%
Before condition	Signalized	4	15%
	Minor stop	16	62%
	All-way stop	5	19%
	No control	1	4%
Operation date	2004	6	23%
	2005	5	19%
	2006	5	19%
	2007	9	35%
	2008	1	4%
Number of circulatory lanes	1	13	50%
	2	12	46%
	3	1	4%
Number of approaches	3	10	38%
	4	16	62%

3.2 Geometric Features of Roundabouts

The geometric features of roundabouts can be obtained on a project-level scale by examining the construction plans obtained from the Wisconsin Department of Transportation. Some of the features are easily obtained visually or from tables in the plan sets, such as turning radius, inscribed circle diameter, and central island radius; other features need to be measured manually, such us entry angle, entry width, and flare length. Several potential geometric features that may affect crash frequency had been discussed in Section 2.1. Prior to including all of these variables in the regression models, it is difficult to realize which factors are more important for safety than others. However, as past research shows, both turning radius and lane widths are the main geometric features used to control the speed of approaching road users, and thus improve roundabout safety (14). Figure 3.1 is an example of roundabout summary table with all geometric information. Appendix A provides individual roundabout geometric information and Appendix B provides a summary table for all roundabouts geometric features.

Section 1.2 identified two objectives for this study. The first objective was to develop a safety performance functions based on these roundabouts. All 25 roundabouts were evaluated for the first objective. The second objective was to develop the safety performance function for single approaches based on their geometric features, entering traffic volume and circulatory traffic volume. Only 11 roundabouts were evaluated for the second objective because data were not available for the other 15. The way to divide roundabouts into multiple sectors and the way to distinguish the entering volume and the circulatory volume is shown in Figure 3.2. In Figure 3.2, Q_1 equals sector 1, and so on. All the geometric data related to an associated sector will be collected.

Some geometric features were not consistent throughout the whole roundabout. When the numbers of circulatory lanes were collected, several roundabouts had varying number of lanes, such as 2 lanes in some parts, 1 lane in other parts. In this case, the selection criteria were based on the higher number of lanes. Some of the central island and inscribed circle diameters of roundabouts consisted of different radii, which means they were not perfect circles. In this case, largest radius was selected. For the turning radius in the second objective, the approaches with non-right-turning and the approaches with non-exit in roundabouts were not evaluated.

Site#1 STH 54 and Gaynor Street

Source: Google Earth

Basic information				Geometric features		
State	Wisconsin			Number of circulating lanes	1	
Region	NC			Number of approaches	4	
County	Wood			Inscribed circle diameter (ft)	170	
Municipality	Wisconsin Rapids			Center island radius (ft)	55	
Area	Urban			Truck apron width(ft)	20	
Operating date	9/15/2004			Minimum driveway width(ft)	18	
Before roundabout	Minor Stop			Pedestrian crossing	Yes	
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	22	18	16	78	1	1
Q_2	23	20	14	78	1	1
Q_3	24	16	13	78	1	1
Q_4	23	17	15	78	1	1

Figure 5 An Example of Roundabout Geometric Information Summary

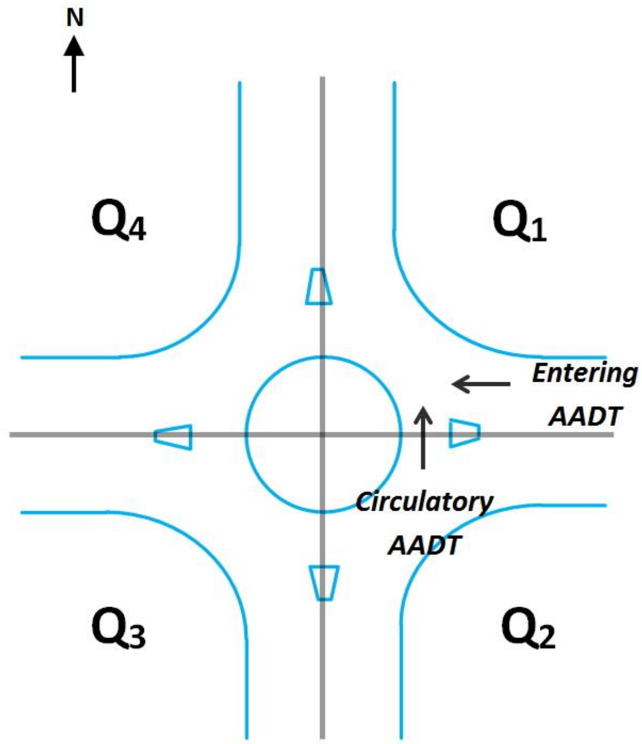

Figure 6 Roundabout divided into four sectors

Table 4 lists the necessary geometric features and corresponding methods of collection according to the first objective and the second objective.

Table 4 Geometric features and their collecting method

Objective	Geometric features	Collecting method
Roundabout SPFs	• Inscribed Circle Diameter • Central Island Radius • Minimum Driveway Width • Number of Circulatory Lanes • Number of Approaches	Construction plan Construction plan Construction plan Observe visually Observe visually
Single approach SPFs	• Entry Angle • Entry Width • Flare Length • Turing Radius • Number of Entry Lanes • Number of Exiting Lanes	Measure manually Measure manually Measure manually Construction plan Observe visually Observe visually

3.3 Crash Data

Crash frequency is defined as the number of crashes that occurred at a certain site (intersection, roadway segment, or network) in a one year period (7). The WisTransPortal contains a comprehensive crash database of WisDOT MV4000 information from 1994 to 2012 (40). The MV4000 form is known as the Motor Vehicle Accident Report and is a crash report used by the police. In this study, crash data were retrieved from WisTransPortal from the year after construction of roundabouts to the year of 2012. Crashes related to the roundabouts were defined to be those that occurred less than 250 feet from the roundabouts. In the WisTransPortal data, there is one column that described whether the crashes occurred in the intersection which could be used to help sort the data. However, each crash report was manually reviewed to ensure the accuracy of the crash data. In this study, four years crash history after the construction of roundabouts will be used.

For the first objective of this study, the number of total crashes that occurred at roundabouts was applied in the SPFs model analysis. Figure 3.1 depicts a roundabout that was divided into four sectors. The crash history of each sector was evaluated along with the sector's geometric features. The crashes in each sector were defined as crashes that occurred at the entry lane and circulatory roadway; the crashes that occurred at the exit lane of the sector were excluded, because those crashes were not related to the geometric features of roundabouts.

3.4 Traffic Volume

Traffic volume is usually measured as annual average daily traffic (AADT), the total volume of traffic on a roadway or an intersection in a year divided by 365 days. The traffic volume capacity varies according to the different categories of roundabouts. In general, the typical maximum average daily traffic volume on four-leg roundabouts is approximately 25,000 for single-lane roundabouts, and is approximately 45,000 for multi-lane roundabouts (5). The multi-lane roundabouts accommodate larger vehicle volume but have less benefit than the single-lane roundabouts. In one individual approach leg of roundabout, the sum of the conflicting volumes and the entering volumes can be evaluated to determine the number of entering lanes required. Traffic volume data were collected using two methods: one was from the Wisconsin Highway Traffic Volume database and the other is from WisDOT traffic count data (41).

The process of collecting AADT data for the entire roundabout was typically simple. The Traffic volume was computed as the sum of the AADT that entered the roundabouts. The proportion of the entering volume in one sector to the total volume of the intersection multiplied by the AADT of the intersection would estimate the entering AADT of one sector. The circulatory volume for a sector is computed by taking the sum of the individual counts that pass through the sector circulatory roadway, and divided by total volume then multiply by the AADT. For collecting AADT data of the second objective, only the circulatory AADT and entering AADT of one sector were considered. In the year of 2010, the TOPS Lab conducted field traffic counts for single approach of 17 roundabouts in Wisconsin. Eleven roundabouts that had crash data were selected to be evaluated in this study. Figure 7 shows an example of traffic counts at one roundabout.

For instance, if the circulatory volume for sector 1 is computed, the movements whose volumes comprise the total circulatory volume are the through, left and U-turn movements in sector 2, the left and U-turn movements in sector 3, and the U-turn movement in sector 4.

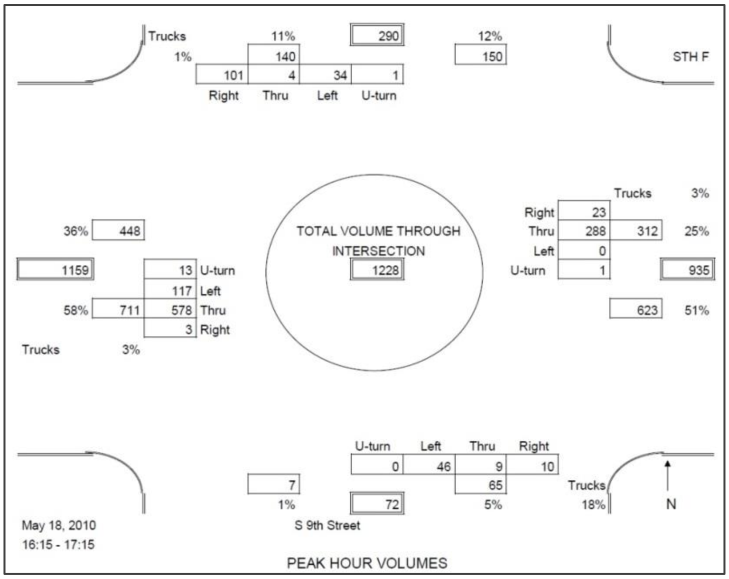

Figure 7 Traffic Counts at a Roundabout

Table 5 and 6 provides a summary of the geometric features used in the Roundabouts modeling and single approach modeling. 25 roundabouts were included in the roundabout dataset and 30 approaches were included in the single approach dataset. These 30 approaches were selected from the 25 roundabouts. As mentioned previously, for an approach to be selected, the following data need to be available: entering and circulatory roadway traffic volume, detail geometric information, and crash records at the site.

Table 5 Summary of Roundabout Geometric Data for First Objective

Total Roundabouts: 25				
Roundabout features	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
AADT	8250	33040	17482	7196.8
Inscribed Circle Diameter (ft)	100	246	149	29.5
Center Island Radius (ft)	29	95	48.7	13.1
Minimum Circulating Lane Width (ft)	13	30	21.4	3.9
Number of Circulating Lanes	1	3	1.5	0.6
Number of Approaches	3	4	3.6	0.5
Crash Frequency(4 years)	1	48	11.8	10.2

Table 6 Summary of Single Approach Geometric Data for Second Objective

Total approaches: 30				
Geometric features	**Minimum**	**Maximum**	**Mean**	**Standard Deviation**
Entry Angle	10	32	20.6	5.3
Entry Width	16	45	25.3	5.7
Flare Length	0	145	43.7	38.9
Turning Radius	42	209	77.5	30.0
Circulatory AADT	388	56547	8085.6	9911.8
Entering AADT	630	39263	7586	6919.2
Crash Frequency (4 years)	0	62	8.2	11.3

3.5 Study Design

This section will apply the traffic and geometric data from the state of Wisconsin to describe the development procedures of intersection-level roundabout SPFs and single approach SPFs of roundabouts. These statistical steps are described as follows:

- *Step 1: Input the data and investigate the data*

  The crash frequency, AADT and other candidate variables are input to the model. Before the data analysis, all the data will be investigated to ensure they are correct and no data are missing.

- *Step 2: Examine the type of regression model*

  The regression model type is selected after checking the accuracy of the data. Previous research shows that the negative binomial regression model is preferred for modeling crash frequency because crash data is usually overdispersed. The negative binomial regression is more appropriate than the Poisson regression model when crash frequency is evaluated and was used in the following data analysis.

- *Step 3: Data analysis – forward step*

The forward step selection method is applied to find the best model with appropriate variables. The model starts with no variables and one variable is added to the model at a time. The selection of the next variable is based on the one that provides the highest likelihood ratio. The likelihood ratio test (LRT) is a statistical method that provides an objective standard for selecting better models. The suggested equation for the likelihood ratio test is shown as follow:

$$LRT = -2\ln\left(\frac{\mathcal{L}_s}{\mathcal{L}_g}\right)$$

Where

$\mathcal{L}_s$: likelihood functions for simpler models

$\mathcal{L}_g$: likelihood functions for more complex models

- *Step 4: Data analysis – Cook's distance leverage*

  The leverage for an observation measures the effect of a data point on the model. If an observation has greater leverage, it has more influence on the model. The Cook's distance leverage is used to measure the effect of removing the data point. If the results are the same with or without the observation, then this observation has little or no influence on the regression model. If the result has a significant difference, the observation is influential to the regression model.

- *Step 5: Additional testing of the models*

  After the significant variables for the model have been determined through the previous steps, this step is to check whether any other findings exist that influence the model. After the testing, the regression model can be finalized.

3.6 Methodology

When all crucial significant variables had been identified, recommend equations for SPFs were formed. More detail information will be discussed in chapter 4. The procedures applied to achieve the study objectives are shown in Figure 8.

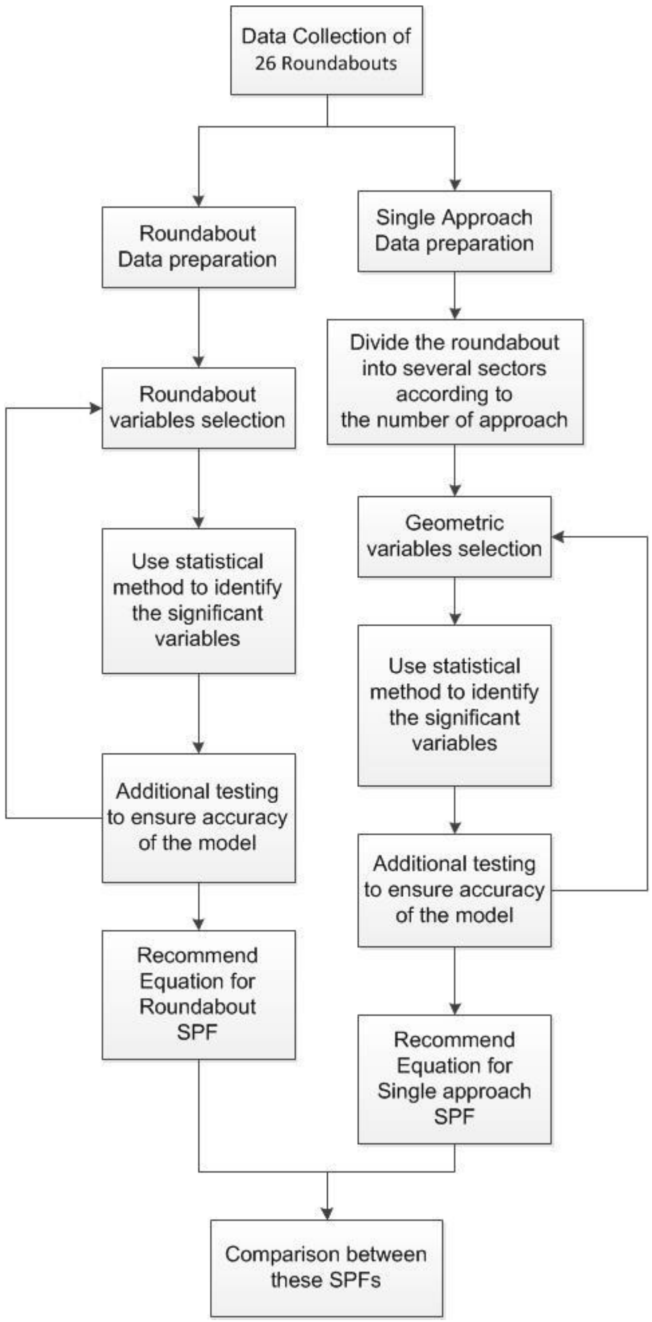

Figure 8 The Methodology of the Study

Chapter 4 Data Analysis and Results

Statistical regression models can be applied to identify the relationship between crash frequency and other geometric features. There are two ways to evaluate the safety performance for one particular location or city. The first way is to calibrate the SPFs models developed by HSM using local conditions represented as CMFs. The second way is to develop SPFs according to local geometric features and conditions. Based on the availability of roundabout data and the number of sites in Wisconsin, the second method is used for developing the models.

4.1 Roundabout Safety Performance Function Model

4.1.1 Development of the Models

In the first objective, the roundabout SPFs models were built as intersection-level, which meant the evaluation was from the view of the whole roundabout. Due to the relatively small number of injury crashes being reported in 25 roundabouts, the SPF models were developed for total crashes only. In order to develop SPFs of roundabouts, the geometric features considered in the model and their abbreviations are described in Table 7.

Table 7 Variables being evaluated in intersection-level and their abbreviations

Variables	**Abbreviation in the program**
Total AADT for roundabouts	AADT
Inscribed circle diameter	inscrbDim
Central island radius	isldDim
Minimum driveway width	minDrvway
Number of circulating lanes	cirLane
Number of approaches	numAprch
Total number of crashes (4 years)	C4

Table 8 shows the results of the Poisson regression model created using the geometric data from Chapter 3. Ultimately, however, the Poisson model was not selected as the final model due to the fact that it was overdispersed (dispersion parameter=6.996336). In cases of overdispersion, negative binomial regression models, such as those used for safety performance functions in the current HSM, are more appropriate. Hence, the final model selected for this analysis was the negative binomial regression model.

Table 8 Analysis by Poisson Regression Model (Intersection-level)

```
Coefficients:
             Estimate Std. Error t value Pr(>|t|)
(Intercept) -13.00309    5.89269  -2.207   0.0406 *
log(AADT)     1.76501    0.67825   2.602   0.0180 *
inscrbDim    -0.01292    0.01405  -0.919   0.3701
isldDim       0.01766    0.02802   0.630   0.5364
minDrvWay    -0.03723    0.03848  -0.968   0.3461
cirLane      -0.14924    0.48848  -0.306   0.7635
numAprch4     0.52105    0.34552   1.508   0.1489
---
Signif. codes:  0 ‘***’ 0.001 ‘**’ 0.01 ‘*’ 0.05 ‘.’ 0.1 ‘ ’ 1

(Dispersion parameter for quasipoisson family taken to be 6.996336)
```

The models were developed to analyze total 4-year crashes at the roundabouts by using negative binomial regression. The form of the model can be seen as follows (3):

$$4\ year\ crashes = \exp(Intercept) \cdot AADT^{b_1} \exp(c_1X_1 + c_2X_2 + \cdots + c_nX_n)$$

Where

$AADT$: annual average daily traffic entering the intersection

$X_1 + \cdots X_n$: other geometric features that affect the crash frequency

$b_1 \ldots b_n, c_1 \ldots c_n$: calibration coefficient

To perform variable selection, it begins by specifying model, which is null model in this study, and the scope of the model which need to be evaluated in this study. The evaluation started with the null model and searched through models ranging between null and full model using forward selection algorithm. Table 9 shows the final result of the analysis. The variable of log(AADT) is found to be significant to the model (with two asterisks in the column "Significance"). Therefore, accoding to this figure, the best model is the one that includes only the variable of log(AADT).

Table 9 Use likelihood Ratio Test to Analyze the Data

Step: AIC = 169.28					
C4 ~ log(AADT)					
	Deviance	**AIC**	**LRT**	**Pr(>chi)**	**Significance**
<none>	26.364	169.28			
+ numAprch	24.650	169.57	1.7145	0.19041	
+ cirLane	24.887	169.81	1.4771	0.22423	
+ inscrbDim	25.416	170.33	0.9488	0.33001	
+ minDrvWay	25.779	170.70	0.5852	0.44428	
+ isldDim	25.871	170.79	0.4935	0.48236	
- log(AADT)	35.228	176.15	8.8631	0.00291	**
Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1					
Call: glm.nb(formula = C4 ~ log(AADT), data = ra, init.theta = 2.357221332, link = log) Coefficients: (Intercept) log(AADT) -8.266 1.099					

The cooks distance leverage test will be applied to examine whether exists observations that influent the models dominantly. An observation is influential if the estimation change substantially when the point is removed. The potential outlier is the roundabout site number 19 with 48 crashes. Figure 9 shows the estimations with (left) and without (right) roundabout site number 19. According to this figure, there was no substantial change found. Therefore, by applying cooks distance leverage test, roundabout number 19 does not appear to be influential to the model. Table 10 shows the final format of the negative binomial regression model and the corresponding coefficient.

Table 10 SPFs of Roundabouts for Total Crashes

	Estimate	**Std. Error**	**z value**	**Pr (>|z|)**	
Intercept	-8.266	3.502	-2.361	0.01825	
Log(AADT)	1.099	0.360	3.052	0.00228	**
Safety Performance Functions of roundabout for total crashes					
Total number of crashes (4 years)	$N_{4\ years} = 2.57112 \times 10^{-4} \times (\text{AADT})^{1.099}$				
Total number of crashes per year	$N = \frac{2.57112 \times 10^{-4} \times (\text{AADT})^{1.099}}{4}$				

The only variable in the model was log(AADT), which represented the actual traffic volume of the roundabout. As the log(AADT) increases at the roundabouts, the crash frequency will most likely increase. This shows the same result with the theory that higher crash volume will have higher crash frequency than lower crash volume. It should be known that the increase of traffic volume refers to the total volume entering the roundabouts, not volume per direction or per approach.

4.1.2 Validation of the Safety Performance Functions

a. Comparison between the SPFs of Wisconsin and the SPFs of the United States

In a report conducted by National Cooperative Highway Research Program (NCHRP), the intersection-level SPFs of 90 roundabouts in the United States were developed (3). The Wisconsin roundabouts SPFs have the similar result to the United States roundabouts SPFs in that AADT was the only variable in the regression models. The number of circulating lanes is one of the potential variables in the regression model and the result shows that it is not significant. The SPFs developed by NCHRP separated the 1 circulating lane and 2 circulating lanes and the SPFs of the United States based on the number of circulating lanes are presented in Table 12.

Table 11 Intersection-level SPF Model for Total Crashes in NCHRP (3)

Number of Circulating Lanes	Safety Performance Functions
1	$0.0023(AADT)^{0.7490}$ [4,000 to 37,000 AADT]
2	$0.0038(AADT)^{0.7490}$[2,000 to 35,000 AADT]

Figure 9 shows the comparisons between the Wisconsin roundabout SPFs and the United States roundabouts SPFs according to the number of circulating lanes, with AADT ranging from 2,000 to 35,000.

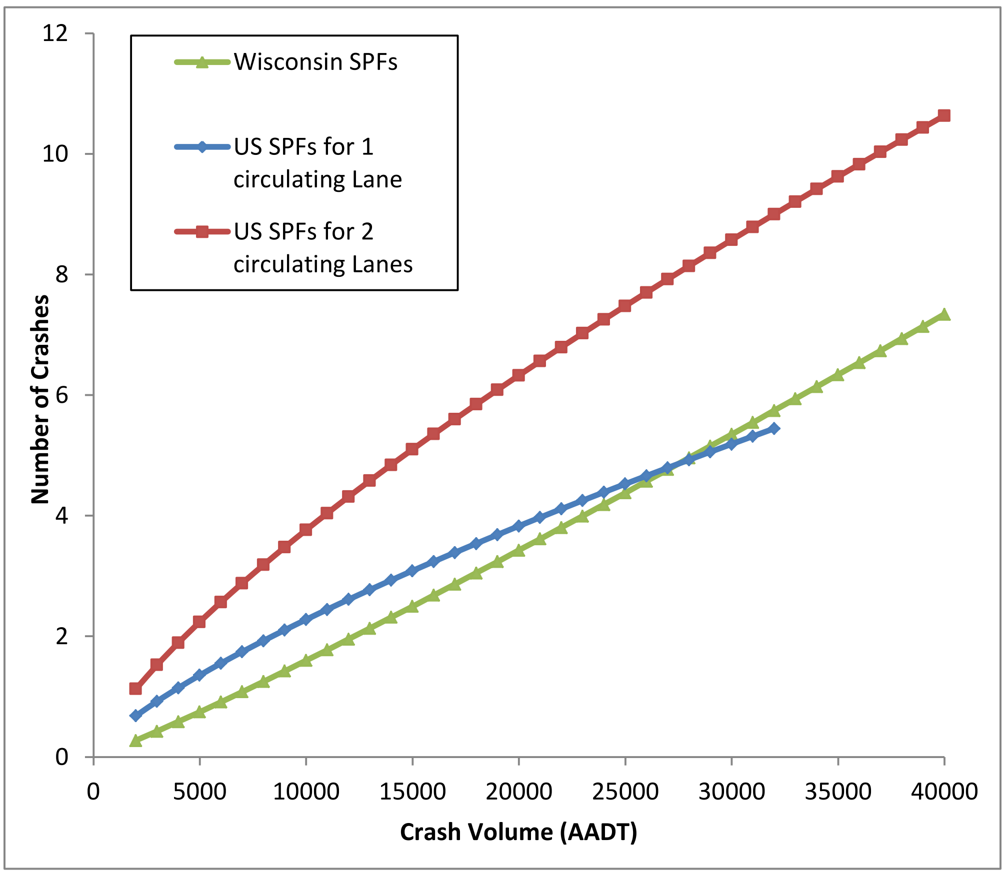

Figure 9 Comparisons between different types of SPFs

From this figure, the regression line of SPFs for Wisconsin is generally under the lines of SPFs for the United States with 1 and 2 circulating lanes. The number of crashes for Wisconsin regression line was partly lower than the US lines with 2 circulating lanes before these two lines intersected at 27,000 AADT. When AADT was higher than 27,000, the Wisconsin SPFs lines fell between the US SPF line with 1 circulating lane and the US SPF line with 2 circulating lanes. From the observations, the figure shows that the expected number of crashes occurred in Wisconsin are less than the crashes in the U.S. Of the particular interest is 25,000 AADT is the threshold for single-lane and multi-lane roundabouts, and 27,000 are closed to this number. The number of lane is one of the geometric features considered in this model. This model is inadequate based on the insufficient dataset. In the future, the Wisconsin roundabout SPFs can be divided according to the number of lanes with a more elaborate dataset. At that time, the comparison between the single-lane and multi-lane of roundabouts in Wisconsin and in the U.S. will be more meaningful.

A variety of reasons may cause different crash experiences at roundabouts in Wisconsin, such as weather conditions, driver behaviors, roadway designs, and speed limits. One possible reason is that snow and ice were more prevalent in Wisconsin than most of the states in the U.S. Drivers in Wisconsin may tend to drive more slowly and carefully than in other places. In addition, the traffic volume in Wisconsin is generally lower than other states, except in the two major cities. However, these facts were not supported by substantial research. There will be more room to explore this topic with future research.

b. Compared with the roundabouts in Wisconsin

The safety performance functions of Wisconsin were developed based on the local geometric features, traffic volume and crash records. This section will use the developed SPFs to evaluate crash frequency of several roundabouts located in Wisconsin. Eight roundabouts were selected based on the availability of the crash data and traffic volumes. Table 13 shows the detailed information of these eight roundabouts. The average number of crashes per year for each roundabout was obtained by dividing the total number of crashes by the total number of years during which these crashes were reported.

Table 12 Summary of Eight Roundabouts Information

Site#	Roundabout	Region	County	AADT	Average Crashes/year
1	CANAL ST and 25THSt	SE	Milwaukee	23300	3.75
2	ELKHORN RD & CLAY ST	SE	Walworth	9200	1.25
3	STH 16 & WALNUT ST	SE	Waukesha	23900	5.33
4	STH 74 & CTH V	SE	Waukesha	17900	0.67
5	STH EE & LAWRENCE DR	NE	Brown	12400	2.67
6	USH 10 & CTH N	NE	Calumet	12000	3.67
7	CTH A & CTH JJ	NE	Outagamie	11700	3.00
8	USH 18 & BENNETT RD	SW	Iowa	12460	3.00

In Figure 10, the SPF is plotted along with eight data points, each of which represents the number of crashes and AADT at a given roundabout. This figure shows that the trend of the observed data (i.e., the eight data points) is similar to the trend of the regression line. To investigate the data further, a statistical method involving the examination of mean absolute error (MAE), is used to valid the regression model. Analysis of MAE is a common method used to measure the goodness of fit between the predictive models and the observational data. The MAE equation is given by:

$$MAE = \frac{1}{n}\sum_{i=1}^{n}|f_i - y_i|$$

Where

f_i: prediction

y_i: true value

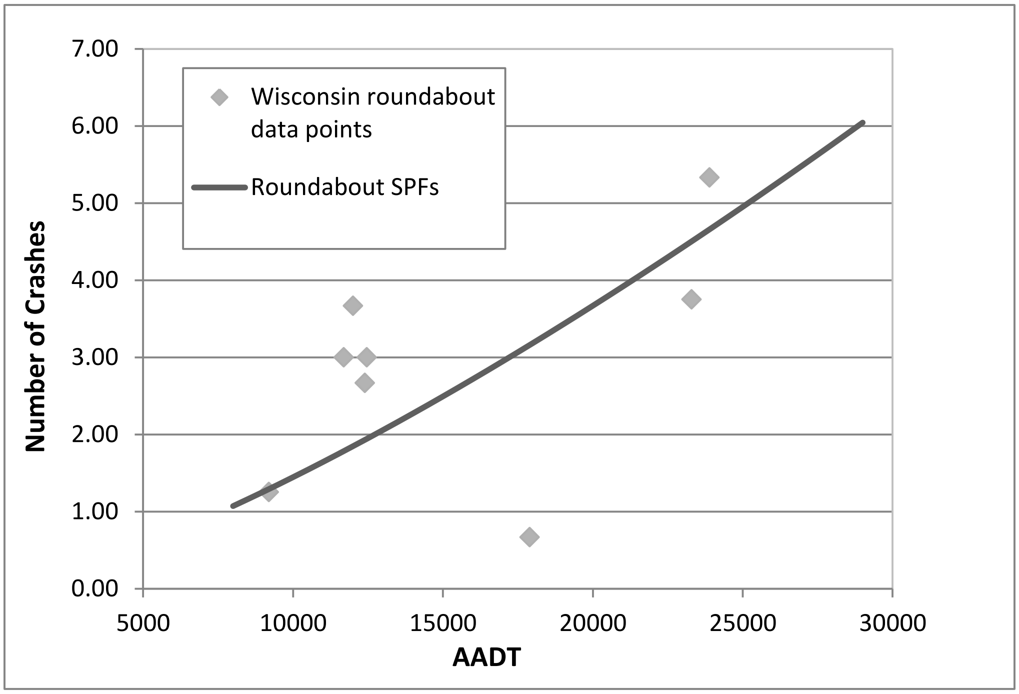

Figure 10 The Roundabout SPFs regression line and 8 Roundabouts

In this study, the value of MAE is calculated as 1.098. This value reveals that the error of the regression model for these eight roundabouts in Wisconsin is within (plus or minus) 1.1 crashes per year of the observed values.

4.3 Single Approach Safety Performance Functions Model

4.3.1 Development of the Models

In the second objective, the SPFs were built for the single approach of the roundabouts and were built for total crashes only. Thirty-one approaches were selected from 25 roundabouts in Wisconsin based on the availability of the detailed geometric data, crash records by sectors, and traffic volume of entering and circulating. The geometric features of roundabouts that being evaluated in the single approach SPFs are shown in Table 14.

Table 13 Geometric features being evaluated in single approach and their abbreviations

Geometric features	**Abbreviation in the program**
Entry Angle	entAng
Entry Width	entWid
Flare Length	cenIslRad
Turning Radius	trkApn
Number of circulating lanes	nCirLan
Number of Entering Lanes	nEntLan
Number of Exiting Lanes	nExtLan
Crash Frequency	C4
Circulatory AADT	log(cirAADT)
Entering AADT	log(entAADT)

As the same procedure as developing intersection level roundabout SPFs, the first step is to estimate the type of the regression model. Figure 11 presents the result of the Poisson Regression model analysis. This model is not applicable due to the large deviance number (132.2). Thus, the negative binomial regression model will be used in the study. The reason was explained in the previous section.

```
> summary(mod)
Generalized linear mixed model fit by maximum likelihood (Laplace
  Approximation) [glmerMod]
 Family: poisson ( log )
Formula: C4 ~ entAng + entWid + flrLen + trnRad + nCirLan + nEntLan +
    nExtLan + cirAADT + extAADT + (1 | site)
   Data: rq

     AIC      BIC   logLik deviance df.resid
   154.2    170.0    -66.1    132.2       20

Scaled residuals:
    Min      1Q  Median      3Q     Max
-1.4765 -0.7061 -0.0338  0.6024  3.1875
```

Figure 11 Analysis by Poisson Regression Model (Single Approach)

The models were developed to analyze total crashes at the single approach of roundabouts by using negative binomial regression. The form of the model was described in the previous section. The likelihood ratio test is also applied to discover the most significant variables to the model. The variables with the higher value of likelihood ratio test remained in the model. Due to the large amount of variables, the evaluation started with full model and eliminated the least value of likelihood ratio using backward algorithm. The final format of the regression model for single approach is shown in Table 15. Additional testing should apply to the equation to ensure no data dominates the regression model.

Table 14 SPFs of Single Approach for Total Crashes

	Estimate	**Std. Error**	**t value**	**Pr (>|z|)**	
Intercept	1.31257	0.72427	2.034	0.041944	
entWid	-0.08646	0.03154	-2.741	0.006122	**
nEntLan	0.89389	0.26391	3.387	0.000707	***
nExtLan	0.54502	0.18902	2.883	0.003934	**
Safety Performance Functions of roundabout for total crashes					
Total number of crashes (4 years)	$N_{4\ years} = 3.715711 \times \exp(-0.08646E + 0.89389nE + 0.54502nX)$				
Total number of crashes per year	$N = \frac{3.715711 \times \exp(-0.08646E + 0.89389nE + 0.54502nX)}{4}$				
entWid: Entry Width; nE: Number of Entering Lane; nX: Number of Exiting Lane					

The single approach models are used to evaluate safety performance of specific approaches of existing roundabouts or to estimate the expected safety changes before converting intersections to roundabouts. In this model, the coefficient of entering width (entWid) is less than zero so that it affects the intercept of the model. As the entry width wider, the crash frequency decreases. In contrast, as the number of entering lane and the number of exiting lane increase, the crash frequency increases. The required number of lanes is determined by traffic volume. Larger traffic volume would need more lanes to accommodate the need and result in the increase of the expected crash frequency.

4.3.2 Validation of the Safety Performance Functions

This section will use the developed single approach SPFs to evaluate crash frequency of several approaches of roundabouts located in Wisconsin. Eight approaches of roundabouts built in 2008 were selected based on the availability of the crash data and traffic volumes. Table 16 shows the detailed information of these eight approaches. The average number of crashes per year for each roundabout was obtained by dividing the total number of crashes by the total number of years during which these crashes were reported.

Table 15 Summary of Eight Approaches of Roundabouts Information

Site#	Roundabout	County	Sector	Land Width	Num. of Entering Lane	Num. of Exiting Lane	Average Crashes/year	Crashes from SPFs
1	STH 53 & Old Town Hall	Eau Clair	1	40	2	2	0.50	1.68
2			2	30	2	1	0.50	0.77
3			3	19	1	2	0.75	0.93
4	CTH 16 & Walnut St	Waukesha	2	21	2	2	0.50	3.43
5			3	20	2	1	0.25	2.03
6			4	20	2	2	1.75	3.71
7	USH 10 & CTH N	Calumet	1	21	1	1	1.00	0.78
8			3	19	1	1	1.50	0.91

To investigate the data further, examination of mean absolute error (MAE) is used to valid the regression model. The MAE equation was presented in the previous section. In this study, the value of MAE is calculated as 0.83. This value reveals that the error of the regression model for these eight roundabouts in Wisconsin is within (plus or minus) 0.83 crashes per year of the observed values. Compare the MAE value of intersection-level roundabouts and of single approach roundabouts, single approach roundabouts have better estimation (0.83<1.10).

The significant variables of the SPFs for single approach are entering width, number of entering lanes, and number of exiting lanes. Although the variables of entering traffic volume and circulating volume apparently are not significant to the regression model, both entering lane width and number of entering lanes have a strong relationship with the entering AADT. The SPFs model developed by NCHRP for single approach has the following form (3):

$$Crashes/year = \exp(-7.2158)(AADT_E)^{0.7018} \cdot (AADT_C)^{0.1321} \cdot \exp(0.0511E - 0.0276\theta)$$

Where

$AADT_E$: entering AADT

$AADT_C$: circulating AADT conflicting with the subject entry

E: entering lane width

θ: angle to the next leg (degree)

In the above equation, AADT is the major variables in the regression models. It is assume that traffic volume is the major factor that influences the crash frequency. However, the SPFs of single approach developed in Wisconsin do not contain the variables of AADT. It is interested to explore the reason that causes two regression models have different result. For the study in Wisconsin, several roundabouts with large traffic volume have small amount of crashes. For instance, approach site number 12 has more than 16,000 AADT but has only one crash in last four years. When the sample size is relatively small, two or three extreme values may change the whole model. More roundabouts data are expected to be collected in the future for a better evaluation of safety performance of roundabouts in Wisconsin.

Different states have different features of weather, geometry and driving behavior of local residents. If Wisconsin SPFs are applied in other states, crash modification factor, a factor used to compute the expected number of crashes after a specific countermeasure was implemented, need to be multiplied by the SPFs to obtain the local expected crash frequency.

Chapter 5 Conclusions and Future Development

5.1 Conclusions

Having better understandings of the relationship between the crash frequency and the geometric features of roundabouts in Wisconsin can improve the design of the roadway and enhance traffic safety. In order to achieve this goal, the safety performance functions were developed based upon data, such as crash history and geometric features, from 25 roundabouts and 33 single approaches of roundabouts in Wisconsin.

The roundabout SPFs for Wisconsin were successfully developed by using negative binomial regression modelling. The first objective, development of intersection-level SPFs, proves that the crash frequency has a strong relation with traffic volumes (AADT). This regression equation was compared with the model developed by Rodegerts et al. in NCHRP Report 572, and these two models have similar trends. Predicted values of crash frequency from the SPF developed in this research were also compared with crash frequencies from eight roundabouts in Wisconsin. The result show the average predicted number of crashes per year is within (plus or minus) one crash per year from the real data. The model for roundabout SPFs of Wisconsin is presented as follow:

$$N = \frac{2.57112 \times 10^{-4} \times (\text{AADT})^{1.099}}{4}$$

The second objective is to develop an SPF for single approaches of roundabouts based on every sector's geometric features, traffic volume and crash history. The regression model reveals the number of crashes is related to entry lane width, number of entry lanes and number of exiting lanes. Traffic volume was not found to be a significant predictor in the final model, although factors such as lane width and the number of entry lanes are often directly related to volume.

Predicted values of crash frequency from the SPF developed in this research were also compared with crash frequencies from eight approaches of roundabouts in Wisconsin. The result show the average predicted number of crashes per year is within (plus or minus) 0.83 crash per year from the real data. The final model for single approach SPFs of Wisconsin is presented as follow:

$$N = \frac{3.715711 \times \exp(-0.08646E + 0.89389nE + 0.54502nX)}{4}$$

where “E” refers to entry lane width, “nE” refers to the number of entering lane, and “nX” refers to the number of exiting lane.

The development of the SPFs could likely be improved by performing the regression analyses with larger datasets. Ultimately, this study presents the procedure for development of an SPF through negative binomial regression. One key issue in the SPF development was the limited amount of data available from which to develop the models. Although the models developed within this research provide a good starting point for safety analyses at roundabouts in Wisconsin, future models based upon more data could be used to more accurately estimate crash frequencies. The accuracy to which crash frequency is estimated is of the utmost importance as knowledge of it can be used by engineers in their decision-making processes to determine the most effective safety treatment to apply at a given location.

5.2 Future Development

A number of problems were raised when the Wisconsin roundabout SPFs model was developed. These problems suggested several directions for future research that can improve the SPFs regression models.

One direction would be to investigate more roundabouts in Wisconsin and include them in the research database. Larger dataset of the regression models may increase more varieties of the roundabouts so that may improve the accuracy of the estimation. More roundabouts can also even out the bias and extreme values resulted from several special cases.

Another direction would be to develop specific roundabout SPFs based on the different types, such as the number of circulating lanes and the number of approaches of roundabout. When the similar types of roundabouts were evaluated together, there is no need to exclusively consider the exceptions or other underlying factors. The accuracy of the model would be improved and the time for development can be reduced. Again, this practice requires larger database and detailed information of roundabouts.

One task not implemented in this study is to develop SPFs for fatal and injury crashes due to more than 90 percent of roundabouts have less than average one fatal and injury crashes per year. In the future research, more of the roundabouts that have higher number of fatal and injury crashes may account in the dataset for the development of fatal and injury SPFs in Wisconsin.

In addition, as noted previously in Chapter 4, the discrepancy between the expressions of the models can depend on many factors. The traffic volumes, roadway surface, even the crash reporting rate, all can affect the performance of the SPFs. By understanding the reasons behind the difference can help engineers realize the advantages and the disadvantages of the local places when comparing to other localities.

Finally, all the variables used in the regression models were able to be observed visually. However, several factors which cannot be quantified, such as driving behavior and climatic condition, can also affect the crash frequency significantly. This direction could be a new area to explore in the future.

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Appendix A: Roundabout Inventory

Site#1 STH 54 and Gaynor Street

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NC	Number of approaches	4
County	Wood	Inscribed circle diameter (ft)	170
Municipality	Wisconsin Rapids	Center island radius (ft)	55
Area	Urban	Truck apron width(ft)	20
Operating date	9/15/2004	Minimum driveway width(ft)	18
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	22	18	16	78	1	1
Q_2	23	20	14	78	1	1
Q_3	24	16	13	78	1	1
Q_4	23	17	15	78	1	1

Site#2 CTH F and Nine Street

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NE	Number of approaches	4
County	Brown	Inscribed circle diameter (ft)	120
Municipality	De Pere	Center island radius (ft)	35
Area	Urban	Truck apron width(ft)	20
Operating date	11/1/2004	Minimum driveway width(ft)	25
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	22	18	16	78	1	1
Q_2	23	20	14	78	1	1
Q_3	24	16	13	78	1	1
Q_4	23	17	15	78	1	1

Site#3 CTH F and Suburban

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NE	Number of approaches	4
County	Brown	Inscribed circle diameter (ft)	110
Municipality	De Pere	Center island radius (ft)	32
Area	Urban	Truck apron width(ft)	15
Operating date	11/1/2004	Minimum driveway width(ft)	23
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	20	14	15	78	1	1
Q_2	21	16	17	78	1	1
Q_3	25	14	15	78	1	1
Q_4	21	13	15	78	1	1

Site#4 CTH 141 and Allouez Avenue

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NE	Number of approaches	4
County	Brown	Inscribed circle diameter (ft)	160
Municipality	Bellevue	Center island radius (ft)	58
Area	Rural	Truck apron width(ft)	13
Operating date	10/1/2007	Minimum driveway width(ft)	22
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors

Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	10	19.7	22	75	1	1
Q_2	16	19.7	0	71	1	1
Q_3	3	19.2	24	82	1	1
Q_4	20	21.7	0	75	1	1

Site#5 STH 55 and CTH KK

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		1
Region		NE		Number of approaches		4
County		Calumet		Inscribed circle diameter (ft)		171
Municipality		Harrison		Center island radius (ft)		63
Area		Rural		Truck apron width(ft)		7
Operating date		8/3/2006		Minimum driveway width(ft)		20
Before roundabout		Minor Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	24	20	43	60	1	1
Q_2	3	16.6	34	133	1	1
Q_3	22	18.1	33	70	1	1
Q_4	14	17.5	27	88	1	1

Site#6 Lake Park and Plank

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		1
Region		NE		Number of approaches		4
County		Brown		Inscribed circle diameter (ft)		152
Municipality		Appleton		Center island radius (ft)		54
Area		Urban		Truck apron width(ft)		13
Operating date		10/1/2007		Minimum driveway width(ft)		22
Before roundabout		Minor Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	23	22	35	60	1	1
Q_2	19	27	100	120	2	1
Q_3	26	20	28	60	1	1
Q_4	12	21	22	196	1	1

Site#7 STH 28 and STH 32

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NE	Number of approaches	4
County	Sheboygan	Inscribed circle diameter (ft)	138
Municipality	Sheboygan Falls	Center island radius (ft)	49
Area	Rural	Truck apron width(ft)	13
Operating date	9/1/2006	Minimum driveway width(ft)	20
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q1	10	18	34	86	1	1
Q2	25	22	23	43	1	1
Q3	14	18	21	78	1	1
Q4	24	18	27	58	1	1

Site#8 CTH O and Wilgus

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NE	Number of approaches	4
County	Sheboygan	Inscribed circle diameter (ft)	110
Municipality	Sheboygan	Center island radius (ft)	35
Area	Rural	Truck apron width(ft)	15
Operating date	11/1/2007	Minimum driveway width(ft)	20
Before roundabout	All Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	21	16	12	65	1	1
Q_2	20	26	54	45	1	1
Q_3	15	16	19	65	1	1
Q_4	19	28	75	53	1	1

Site#9 Breezewood and Tullar

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		1
Region		NE		Number of approaches		4
County		Winnebago		Inscribed circle diameter (ft)		100
Municipality		Neenah		Center island radius (ft)		29
Area		Urban		Truck apron width(ft)		16
Operating date		9/15/2005		Minimum driveway width(ft)		21
Before roundabout		No Control		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	21	16	25	75	1	1
Q_2	24	17	34	50	1	1
Q_3	24	19	11	56.2	1	1
Q_4	16	20	25	80.4	1	1

Site#10 USH 53 and CTH O Ramp (West)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NW	Number of approaches	3
County	Baron	Inscribed circle diameter (ft)	126
Municipality	Rice Lake	Center island radius (ft)	46
Area	Urban	Truck apron width(ft)	21
Operating date	6/1/2006	Minimum driveway width(ft)	17
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	32	14	27	100	1	0
Q_2	N/A	N/A	N/A	N/A	0	1
Q_3	11	14	25	67	1	1
Q_4	22	18	0	52	1	1

Site#11 USH 53 and CTH O Ramp (East)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NW	Number of approaches	3
County	Baron	Inscribed circle diameter (ft)	126
Municipality	Rice Lake	Center island radius (ft)	46
Area	Urban	Truck apron width(ft)	21
Operating date	6/1/2006	Minimum driveway width(ft)	17
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	7	14	33	124	1	1
Q_2	22	18	0	48	1	1
Q_3	24	14	34	100	1	0
Q_4	N/A	N/A	N/A	N/A	0	1

Site#12 STH 124 and CTH S

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	NW	Number of approaches	4
County	Chippewa	Inscribed circle diameter (ft)	160
Municipality	Eagle Point	Center island radius (ft)	57
Area	Rural	Truck apron width(ft)	6
Operating date	10/15/2005	Minimum driveway width(ft)	22
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	10	25	35	84	1	1
Q_2	26	22	26	60	1	1
Q_3	22	28	35	124	1	1
Q_4	26	25	25	76	1	1

Site#13 STH 35 and Hanley (West)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	2
Region	NW	Number of approaches	3
County	St Croix	Inscribed circle diameter (ft)	152
Municipality	Hudson	Center island radius (ft)	47.5
Area	Urban	Truck apron width(ft)	7
Operating date	10/21/2005	Minimum driveway width(ft)	21
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	37	31	45	77	2	0
Q_2	N/A	N/A	N/A	N/A	0	2
Q_3	18	33	70	152	2	1
Q_4	17	18	45	82	1	1

Site#14 STH 35 and Hanley (East)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	2
Region	NW	Number of approaches	3
County	St Croix	Inscribed circle diameter (ft)	152
Municipality	Hudson	Center island radius (ft)	47.5
Area	Urban	Truck apron width(ft)	7
Operating date	10/21/2005	Minimum driveway width(ft)	21
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	17	30	29	82	2	1
Q_2	19	26	0	131	2	1
Q_3	18	30	37	77	2	0
Q_4	N/A	N/A	N/A	N/A	0	2

Site#15 STH 38 and CTH K

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		1
Region		SE		Number of approaches		3
County		Racine		Inscribed circle diameter (ft)		144
Municipality		Caledonia		Center island radius (ft)		49
Area		Urban		Truck apron width(ft)		11
Operating date		11/15/2007		Minimum driveway width(ft)		23
Before roundabout		Minor Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	20	30	48	98	2	1
Q_2	7	15	35	129	1	1
Q_3	23	20	65	110	2	1

Site#16 STH 43 and Mooreland Road (North)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	3
Region	SE	Number of approaches	3
County	Waukesha	Inscribed circle diameter (ft)	246
Municipality	New Berlin	Center island radius (ft)	95
Area	Urban	Truck apron width(ft)	8
Operating date	9/15/2007	Minimum driveway width(ft)	27
Before roundabout	Signalized	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	25	37	145	70	2	2
Q_2	15	27	38	N/A	2	0
Q_3	N/A	N/A	N/A	N/A	0	3
Q_4	13	45	124	77	3	1

Site#17 STH 43 and Mooreland Road (South)

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		SE		Number of approaches		4
County		Waukesha		Inscribed circle diameter (ft)		180
Municipality		New Berlin		Center island radius (ft)		62
Area		Urban		Truck apron width(ft)		10
Operating date		11/15/2008		Minimum driveway width(ft)		28
Before roundabout		Signalized		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	28	20	0	68	1	2
Q_2	14	34	75	60	2	1
Q_3	22	31	23	50	2	2
Q_4	16	26	32	N/A	2	0

Site#18 Springdale and 8th Street

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		SW		Number of approaches		4
County		Dane		Inscribed circle diameter (ft)		124
Municipality		Mount Horeb		Center island radius (ft)		33
Area		Urban		Truck apron width(ft)		11
Operating date		4/27/2004		Minimum driveway width(ft)		29
Before roundabout		Signalized		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	19	24	47	44	2	1
Q_2	28	17	14	100	1	1
Q_3	32	24	18	75	1	1
Q_4	17	26	49	209	2	1

Site#19 Thompson and STH 30 (North)

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		SW		Number of approaches		4
County		Dane		Inscribed circle diameter (ft)		160
Municipality		Madison		Center island radius (ft)		50
Area		Urban		Truck apron width(ft)		7
Operating date		10/18/2004		Minimum driveway width(ft)		22
Before roundabout		All Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	25	24	0	62	2	2
Q_2	23	24	52	62	1	1
Q_3	22	24	19	67	1	1
Q_4	22	24	44	62	2	1

Site#20 Thompson and STH 30 (South)

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	1
Region	SW	Number of approaches	3
County	Dane	Inscribed circle diameter (ft)	136
Municipality	Madison	Center island radius (ft)	40
Area	Urban	Truck apron width(ft)	5
Operating date	11/15/2008	Minimum driveway width(ft)	16
Before roundabout	All Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	N/A	N/A	N/A	N/A	0	1
Q_2	20	24	25	77	2	0
Q_3	20	24	0	102	2	2
Q_4	34	20	35	77	1	0

Site#21 USH 12 Ramp and Parmenter

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	2
Region	SW	Number of approaches	4
County	Dane	Inscribed circle diameter (ft)	130
Municipality	Middleton	Center island radius (ft)	45
Area	Urban	Truck apron width(ft)	10
Operating date	10/15/2006	Minimum driveway width(ft)	13
Before roundabout	All Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	27	25	106	67.5	2	2
Q_2	17	28	105	125	2	1
Q_3	18	17	75	110	1	0
Q_4	21	25	25	50	2	1

Site#22 Canal Street and 25th Avenue

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		SE		Number of approaches		3
County		Milwaukee		Inscribed circle diameter (ft)		170
Municipality		Milwaukee		Center island radius (ft)		55
Area		Urban		Truck apron width(ft)		0
Operating date		9/15/2005		Minimum driveway width(ft)		30
Before roundabout		Signalized		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	10	28	30	75	2	1
Q_2	20	27	25	N/A	2	2
Q_3	25	23	32	50	1	2

Site#23 CTH 42 and I-43 Ramps (West)

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		NE		Number of approaches		3
County		Sheboygan		Inscribed circle diameter (ft)		150
Municipality		Sheboygan		Center island radius (ft)		50
Area		Rural		Truck apron width(ft)		12
Operating date		11/2/2007		Minimum driveway width(ft)		20
Before roundabout		Minor Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	20	24	20	N/A	2	0
Q_2	N/A	N/A	N/A	N/A	0	2
Q_3	16	25	22	88	2	1
Q_4	15	26	0	50	2	2

Site#24 CTH 42 and I-43 Ramps (East)

Source: Google Earth

Basic information				Geometric features		
State		Wisconsin		Number of circulating lanes		2
Region		NE		Number of approaches		3
County		Sheboygan		Inscribed circle diameter (ft)		148
Municipality		Sheboygan		Center island radius (ft)		45
Area		Rural		Truck apron width(ft)		10
Operating date		11/2/2007		Minimum driveway width(ft)		22
Before roundabout		Minor Stop		Pedestrian crossing		Yes
Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	26	24	25	75	2	1
Q_2	21	25	20	60	2	2
Q_3	10	26	20	N/A	2	0
Q_4	N/A	N/A	N/A	N/A	0	2

Site#25 CTH 42 and Vanguard

Source: Google Earth

Basic information		Geometric features	
State	Wisconsin	Number of circulating lanes	2
Region	NE	Number of approaches	4
County	Sheboygan	Inscribed circle diameter (ft)	180
Municipality	Sheboygan	Center island radius (ft)	40
Area	Rural	Truck apron width(ft)	14
Operating date	11/3/2007	Minimum driveway width(ft)	20
Before roundabout	Minor Stop	Pedestrian crossing	Yes

Geometric features by sectors						
Sector	Entry angle (degree)	Entry width (ft)	Flare length (ft)	Turning radius (ft)	Number of entering lanes	Number of exiting lanes
Q_1	14	30	130	92	2	1
Q_2	21	18	105	98	1	2
Q_3	18	30	95	57	2	1
Q_4	11	24	30	42	1	2

Appendix B

B-1 Roundabout Summary for Inventory

Site #	Roundabout Location	AADT	Inscribed Circle Diameter D, ft	Center Island Radius r, ft	Minimum Driveway Width W , ft	Number of Circulating Lanes n_C	Number of Approaches n_A	Last 4 years crash	Total crash	Number of years for total crash
1	17/2ND & GAYNOR	18100	170	55	18	2	4	23	23	4
2	MATTHEW & NINTH & CTH F	11900	120	35	25	1	4	5	9	8
3	SUBURBAN & CTH F	8250	110	32	23	1	4	2	4	8
4	USH 141 & ALLOUEZ AVE	13600	160	58	22	1	4	14	16	5
5	STH 55 & CTH KK	12600	171	63	20	1	4	2	4	6
6	CTH LP/LAKE PARK & CTH P/PLANK	11750	152	54	22	1	4	5	8	5
7	STH 28 & STH 32	9050	138	49	20	1	4	13	23	6
8	CTH O (SUPERIOR) & WILGUS/40	9700	110	35	20	1	4	5	5	4
9	BREEZEWOOD & TULLAR	16150	100	29	21	1	4	9	18	7
10	USH 53 & CTH O RAMPS (west)	11069	126	46	17	1	3	6	8	6
11	USH 53 & CTH O RAMPS (east)	17200	126	46	17	1	3	5	11	6
12	STH 124 & CTH S	10700	160	57	22	1	4	8	14	7
13	STH 35 & HANLEY (west)	12600	152	48	21	2	3	1	1	7
14	STH 35 & HANLEY (east)	12700	152	48	21	2	3	1	6	7
15	STH 38 & CTH K(NORTHWESTERN)	13120	144	49	23	1	3	22	22	4
16	STH 43 & MOORELAND RD (North)	30140	246	95	27	3	3	3	3	4
17	STH 43 & MOORELAND RD (South)	33040	180	62	28	2	4	20	20	4
18	8TH & SPRINGDALE ST	24050	124	33	29	2	4	24	24	4
19	THOMPSON & STH 30 (north)	25100	160	50	18	2	4	48	48	4
20	THOMPSON & STH 30 (south)	16875	136	40	16	1	3	12	20	8
21	USH 12 RAMP & PARMENTER	14950	130	45	13	2	4	12	12	4
22	Canal Sreet & 25th Avenue	23300	170	55	30	2	3	13	16	7
23	STH42 & I-43 ramps (West)	26000	150	50	20	2	3	16	19	5
24	STH42 & I-43 ramps (East)	28100	148	45	22	2	3	18	27	5
25	STH42 & Vanguard	27000	180	40	20	2	4	8	13	5

B-2 Roundabout summary for single approach

Standard Site #	Roundabout Location	Site #	Sector	Entry Angle Phi, degree	Entry Width E, ft	Flare Length L, ft	Turning Radius R, ft	Number of Circulating Lanes n_C	Number of Entering Lanes n_E	Number of Exiting Lanes n_X	Last 4 years crash	Total crash	Number of years for total crash	Circulatory AADT	Entering AADT
2	MATTHEW & 9TH & CTH F	1	1	22	18	16	78	1	1	1	0	0	8	1802	3023
		2	2	23	20	14	78	1	1	1	0	1	8	7210	630
		3	3	24	16	13	78	1	1	1	3	5	8	388	6890
		4	4	23	17	15	78	1	1	1	2	3	8	3372	1357
13	STH 124 & CTH S	5	1	10	25	35	84	1	1	1	4	4	7	1552	2604
		6	2	26	22	26	60	1	1	1	1	2	7	2591	1552
		7	3	22	28	35	124	1	1	1	2	5	7	2928	2739
		8	4	26	25	25	76	1	1	1	1	3	7	2928	3805
17	STH 43 & MOORELAND RD (North)	9	1	25	37	145	70	2	2	2	2	2	4	8134	5729
		10	4	13	45	124	77	1	3	1	1	1	4	3625	16295
18	STH 43 & MOORELAND RD (South)	11	1	28	20	0	68	2	1	2	6	6	4	15833	1096
		12	2	14	34	75	60	2	2	1	2	2	4	4094	13974
		13	3	22	31	23	50	2	2	2	10	10	4	14862	3261
19	STH 92/8TH & STH 92/SPRINGDALE	14	1	19	24	47	44	1	2	1	9	9	4	3705	8494
		15	2	28	17	14	100	1	1	1	6	6	4	5912	3585
		16	3	32	24	18	75	1	1	1	7	7	4	5110	4842
		17	4	17	26	49	209	2	2	1	2	2	4	8400	7129
20	THOMPSON & STH 30 (north)	18	1	25	24	0	62	2	2	2	21	21	4	8233	4108
		19	2	23	24	52	62	2	1	1	7	7	4	1241	10977
		20	3	22	24	19	67	2	1	1	4	4	4	4545	2045
		21	4	22	24	44	62	2	2	1	16	16	4	5593	7970
23	Canal Sreet & 25th Avenue	22	1	10	28	30	75	1	2	1	6	7	7	572	14143
		23	3	25	23	32	50	2	1	2	6	8	7	9517	5865
24	STH42 & I-43 ramps (West)	24	3	16	25	22	88	1	2	1	7	8	5	5820	8769
		25	4	15	26	0	50	2	2	2	7	9	5	5514	3006
25	STH42 & I-43 ramps (East)	26	1	26	24	25	75	1	2	1	5	8	5	4782	11649
		27	2	21	25	20	60	2	2	2	12	17	5	8397	8072
26	STH42 & Vanguard	28	1	14	30	130	92	1	2	1	1	2	5	10980	3583
		29	2	21	18	105	98	2	1	2	4	5	5	1935	12801
		30	3	18	30	95	57	1	2	1	2	4	5	8374	3603
		31	4	11	24	30	42	2	1	2	1	2	5	4982	7013