NCHRP

REPORT 572

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Roundabouts in the United States

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed research provides the most effective approach to the solution of many problems facing highway administrators and engineers. Often, highway problems are of local interest and can best be studied by highway departments individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation develops increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement rather than to substitute for or duplicate other highway research programs.

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FOREWORD

By B. Ray Derr
Staff Officer
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Based on a comprehensive evaluation of roundabouts in the United States, this report presents methods of estimating the safety and operational impacts of roundabouts and updates design criteria for them. The report will be useful to geometric designers and traffic engineers who are considering improvements to an intersection. Presentation materials that may be helpful in public meetings and similar forums are available on the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7086).

Although traffic circles have been used in the United States since 1905, their use has been limited since the 1950s because many were found to work neither efficiently nor safely. The modern roundabout was developed in the United Kingdom in the 1960s to address these problems. Two key characteristics of the modern roundabout are (1) entering traffic that yields to circulating traffic and (2) geometric constraints that slow entering vehicles. Many studies have shown that modern roundabouts (hereafter referred to as roundabouts) are safe and effective, and they are now widely used internationally.

Because roundabout design is relatively new to the United States, there has been some reluctance to use them. Perceived differences in driver behavior raise questions about how appropriate some international research and practices are for the United States. Therefore, additional information on the safety and operation of roundabouts in the United States will be very helpful to planners and designers in determining where roundabouts would reduce intersection crashes and congestion and in refining the design criteria currently being used. These design refinements can be particularly important for bicyclists and pedestrians using the intersection.

Under NCHRP Project 3-65, Kittelson & Associates, Inc. and their subcontractors reviewed existing safety and operational models. After compiling a comprehensive inventory of roundabouts in the United States, they traveled to several representative ones to gather geometric, operational, and safety data. Particular emphasis was placed on collecting data at roundabouts with significant pedestrian and bicycle volumes. They then evaluated the different analytical models to determine how well they replicate U.S. experience. The best models were then refined. During the course of the project, the research team also gathered information on transportation agencies' experiences with different design configurations.

NCHRP Web-Only Document 94 (http://www.trb.org/news/blurb_detail.asp?id=7274) contains the appendixes to this report and includes detailed reviews of the literature on safety performance and operational models, the master inventory of U.S. roundabouts assembled for this project, and the results of the statistical testing of various models.

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AUTHOR ACKNOWLEDGMENTS

Numerous individuals contributed to this effort. Mr. Lee A. Rodegerdts of Kittelson & Associates, Inc. directed the project as Principal Investigator. Mr. Bruce Robinson served as the co-Principal Investigator for the early stages of the project. Many staff members at Kittelson & Associates, Inc. made significant contributions, including Dr. Miranda Blogg, Ms. Elizabeth Wemple, Mr. Edward Myers, Ms. Karen Giese, Mr. Sagar Onta, Mr. Del Huntington, and Mr. Ralph Bentley. Dr. Michael Kyte and Dr. Michael Dixon of the University of Idaho, Dr. George List of North Carolina State University (who was with Rensselaer Polytechnic Institute during the conduct of this project), and Dr. Aimee Flannery of George Mason University led the data collection efforts. The field data collection team consisted of students from three universities: including Mr. Phil Rust and Mr. Yuri Mereszczak from the University of Idaho; Ms. Stacy Eisenman, Mr. Hyunwoo Cho, Ms. Alix Demers, and Ms. Rebecca Brown from Rensselaer Polytechnic Institute; and Mr. William Johnson and Ms. Angie Martin from George Mason University. The operational data extraction team from the University of Idaho included Ms. Christina Hemberry, Mr. Gary Haderlie, Mr. Brent Orton, Ms. Chittemma Potlapati, Ms. JoeAnn Brazill, and Ms. Audra Sherman. Dr. Rod Troutbeck, Dr. Werner Brilon, and Dr. Ning Wu made significant contributions to the operational analysis. Dr. Bhagwant Persaud and Mr. Craig Lyon led the safety analysis, with Dr. Richard Hall of the University of Southampton providing senior review. Mr. David Harkey and Mr. Daniel Carter conducted the pedestrian and bicycle evaluation. Dr. John M. Mason, Jr., of Pennsylvania State University and Mr. Wayne Kittelson of Kittelson & Associates, Inc. provided senior review and guidance.

The authors appreciate the many contributions of data that support the findings of this project. People from agencies all across the United States, too numerous to mention individually, supplied crash data, design plans, and other information, as well as facilitated our field visits during scouting and data collection. The authors also thank Mr. Srinivas Mandavilli of Kansas State University for being available on short notice to assist with data collection in Kansas and Mr. Michael Wallstedt of TranSystems, Inc. and Mr. Leif Ourston of Ourston Roundabout Engineering for providing supplementary video footage.

The authors especially thank the NCHRP 3-65 panel members for long and diligent service in reviewing and guiding this project and greatly appreciate the guidance and patience from the Senior Program Officer of the National Cooperative Highway Research Program.

SUMMARY

Roundabouts in the United States

Based on the findings of this study, roundabouts appear to be successful in a wide variety of environments in the United States. The following sections summarize the major conclusions from this study.

Safety Performance

In general, roundabouts have improved both overall crash rates and, particularly, injury crash rates in a wide range of settings (urban, suburban, and rural) for all previous forms of traffic control except for all-way stop control, for which no statistically significant difference could be found. In addition, single-lane roundabouts have better safety performance than multilane roundabouts. The safety performance of multilane roundabouts appears to be especially sensitive to design details.

This study produced a number of major safety findings:

- Intersection-level crash prediction models for the prediction of the overall safety performance of the intersection. These models relate the crash prediction to the number of lanes, number of legs, and the average annual daily traffic.
- Approach-level crash prediction models that relate common types of crashes (e.g., exiting-circulating crashes) to average annual daily traffic volumes and key geometric parameters that were demonstrated to influence the prediction.
- An updated comparison of the performance of roundabouts to other forms of traffic control, disaggregated to a greater extent than any previous study of U.S. roundabouts.

Operational Performance

Currently, drivers in the United States appear to use roundabouts less efficiently than models suggest is the case in other countries around the world. In addition, geometry in the aggregate sense—number of lanes—has a clear effect on the capacity of a roundabout entry; however, the fine details of geometric design—lane width, for example—appear to be secondary and less significant than variations in driver behavior at a given site and between sites.

The following model is recommended for the entry capacity at single-lane roundabouts:

$$c = 1130 \cdot \exp(-0.0010 \cdot v_c) \quad \text{(S-1)}$$

where

c = entry capacity (passenger car units [pcu]/h)
v_c = conflicting flow (pcu/h)

Because driver behavior appears to be the largest variable affecting roundabout performance, calibration of the models to account for local driver behavior and changes in driver experience over time is highly recommended to produce accurate capacity estimates. The exponential model parameters can be calibrated using locally measured parameters as follows:

$$c = A \cdot \exp(-B \cdot v_c) \tag{S-2}$$

where

c = entry capacity (pcu/h)
$A = 3600/t_f$
$B = (t_c - t_f/2)/3600$
v_c = conflicting flow (pcu/h)
t_f = follow-up headway (s)
t_c = critical headway (s)

The recommended capacity model for the critical lane of a multilane entry into a two-lane circulatory roadway is as follows:

$$c_{crit} = 1130 \cdot \exp(-0.0007 \cdot v_c) \tag{S-3}$$

where

c_{crit} = entry capacity of critical lane (pcu/h)
v_c = conflicting flow (pcu/h)

The recommended control delay model follows:

$$d = \frac{3600}{c} + 900T\left[\frac{v}{c} - 1 + \sqrt{\left(\frac{v}{c} - 1\right)^2 + \frac{\left(\frac{3600}{c}\right)\frac{v}{c}}{450T}}\right] \tag{S-4}$$

where

d = average control delay (s/veh)
c = capacity of subject lane (veh/h)
T = time period (h: $T = 1$ for 1-h analysis, $T = 0.25$ for 15-min analysis)
v = flow in subject lane (veh/h)

The recommended level of service (LOS) criteria are the same as those currently used for unsignalized intersections. The LOS for a roundabout is determined by the computed or measured control delay for each lane. The LOS is not defined for the intersection as a whole.

These models have been incorporated into an initial draft procedure for the *Highway Capacity Manual*, which the TRB Committee on Highway Capacity and Quality of Service will continue to revise until its eventual adoption.

Geometric Design

This study produced a number of major geometric design findings:

- The application of acceleration and deceleration effects appears to significantly improve the ability to predict 85th-percentile speeds entering and exiting a roundabout.
- The combination of the extensive field observations of critical gap and the revised speed predictions may be used to refine the current intersection sight distance procedure presented

in FHWA's *Roundabouts: An Informational Guide*. These findings should be considered interim until a more comprehensive study of sight distance needs at roundabouts can be completed.
- Anecdotal evidence suggests the importance of considering design details in multilane roundabout design, including vehicle path alignment, lane widths, and positive guidance to drivers through the use of lane markings.

Pedestrian and Bicyclist Observations

This study produced a number of findings regarding pedestrian and bicyclist behavior at roundabouts:

- This research did not find any substantial safety problems for non-motorists at roundabouts, as indicated by few crashes being reported in detailed crash reports. In addition, no crashes and a very small number of conflicts were observed from video recordings of interactions between non-motorists and motorists. Because exposure data were not available from before a roundabout was present, it is unknown whether pedestrians have altered their travel patterns because of the presence of a roundabout.
- The ability of pedestrians and bicyclists to use the roundabout may be compromised if use of the roundabout by all modes and their subsequent interactions are greater than studied herein or if such interactions increase over time (i.e., as vehicle traffic and/or pedestrian traffic increases).
- An emphasis needs to be placed on designing exit lanes to improve upon the behaviors of both motorists and pedestrians.
- Multilane roundabouts may require additional measures to improve upon the behaviors of motorists, pedestrians, and bicyclists.

CHAPTER 1

Introduction and Research Approach

This report summarizes the findings of NCHRP 3-65, "Applying Roundabouts in the United States." The intended audience for this report is researchers, practitioners, and policy makers who establish federal, state, and local guidelines for roundabouts. Although the content of this document is directly relevant to practitioners, the document is not organized as a guide for easy practitioner use. Once these findings are incorporated into the next edition of FHWA's *Roundabouts: An Informational Guide* (*1*) and other key guidance documents, they should be more accessible to practitioners.

This introductory chapter presents the problem statement and research objective, the scope of study, research approach, and a summary of literature review conducted for this project.

Problem Statement and Research Objective

Although traffic circles have been used in the United States since 1905, their use has been limited since the 1950s because the designs of that era were found to work neither efficiently nor safely. The modern roundabout was developed in the United Kingdom (UK) in the 1960s to address these problems. Two key characteristics of the modern roundabout include (1) a requirement for entering traffic to yield to circulating traffic and (2) geometric constraints that slow entering vehicles. Many studies have shown that modern roundabouts (hereafter referred to simply as roundabouts) can be safe and effective, and they are now widely used internationally. Use in the United States began in 1990 and has been increasing exponentially since that time.

Due to this increased interest in roundabouts, continued demand exists for more information regarding appropriate physical locations, design parameters, and their performance relative to alternative control schemes, with a particular need for that information to be based on U.S. performance rather than simple continued reliance on international experience. The lack of comprehensive and objective U.S. field data on safety and operational performance and design of roundabouts has contributed to this demand for information, as perceived differences in driver behavior raise questions about how appropriate some international research and practices are for the United States. Therefore, additional information on the safety and operation of roundabouts in the United States will be very helpful to planners and designers in determining where roundabouts would reduce intersection crashes and congestion and in refining the design criteria currently being used.

NCHRP and FHWA have identified the need to develop tools based on actual U.S. roundabout performance, rather than using foreign procedures as surrogates. Hence, the primary objective of this research is to produce a set of operational, safety, and design tools, calibrated to U.S. roundabout field data. These tools will enable a person who is already competent in analysis or geometric design of typical at-grade intersections to be able to specify a roundabout that is safe and performs well.

Scope of Study

The scope of this study includes the development of the following work products:

- An updated site inventory of known roundabouts that is accessible to the transportation profession
- A comprehensive database of safety, operational, and design data of selected existing roundabouts for use in future research
- Planning-level safety prediction models to predict the overall safety performance of roundabouts
- Design-level safety prediction models for individual roundabout approaches
- An expanded comparison of safety performance before and after installation of a roundabout
- An updated operational analysis procedure for the *Highway Capacity Manual* (HCM) (*2*), including capacity,

delay, and queue estimates for single-lane and multilane roundabouts
- New speed prediction tools for use in design development
- A comprehensive study of pedestrian and bicyclist behavior at roundabouts
- Updated design guidance incorporating the results from the various studies identified above.

It became clear during the early stages of this research effort that the proposed scope of work and associated data collection effort would be insufficient to address issues related to the accommodation of visually impaired pedestrians at roundabouts. As a result, issues specifically related to visually impaired pedestrians were removed from this scope and combined with channelized right turns at conventional intersections as part of a new problem statement spawned from this project: NCHRP 3-78, "Crossing Solutions for Visually Impaired Pedestrians at Roundabouts and Channelized Right Turns."

Research Approach

The detailed approaches for each of the major components of this research are described in the following sections.

Summarize Existing Relationships

Existing models in use around the world for roundabout safety and operational analysis were described, analyzed, and critiqued to understand the current state of practice in roundabout safety and operational modeling. This literature review is presented later in this chapter.

Site Inventory and Data Collection

A major element of the study included updating and expanding the inventory of U.S. roundabouts compiled during recent research and volunteer efforts and making the inventory available to transportation professionals. The products of this task include an updated database that includes information and data on as many roundabouts in the United States that the team could locate and retrieve information about, including components that are available on line.

At selected sites, the research team collected and summarized extensive data on operational performance, safety performance, geometric parameters, and speeds. Specific data collection methods included assembly of crash reports, crash summaries, and plans; extensive video recording during peak and off-peak periods; and spot speed measurements using radar guns. These methods are described in detail in subsequent chapters of this report.

Operational Model Development

Operational model development included the following tasks:

- **Evaluation of existing models and software.** This task consisted of comparing the field data collected for each roundabout to the predictions from a wide range of existing roundabout capacity models, plus two major software implementations in use in the United States (RODEL and aaSIDRA). The evaluation focused primarily on the ability of each model to predict capacities, delays, and/or queues under the geometric and traffic flow conditions observed at U.S. roundabouts.
- **Development of two operational models that attempt to best fit the U.S. data and explain the performance of U.S. roundabouts.** The capacity models considered comprise the full range of potential formulations, including empirical regression and analytical formulations (gap acceptance). Delay and queuing models are based on those currently in use in the HCM for predicting performance at other unsignalized intersections.
- **Development of a draft revised HCM procedure that incorporates the findings from this research.**

Safety Model Development

Unlike operational model development in the United States, where the HCM has been a definitive reference for more than 50 years, safety model development in the United States is in its infancy, with the first edition of the *Highway Safety Manual* still in development at the time of this research. Other countries have successfully developed safety models, but it has been unclear if these models are directly transferable to the United States. Using this international experience to guide the selection of variables and model forms, the research team performed a considerable amount of safety model development in this research:

- **Development of intersection-level safety performance functions (SPFs) that can be applied at a planning level for estimating the incidence of crashes.** This development involved testing existing models and (1) recalibrating them if feasible or (2) developing new models if the existing models were determined to be an inadequate fit to U.S. data. This latter step capitalized on insights gained from previous modeling experiences to identify model deficiencies resulting from omitted variables, incorrect functional forms, overfit models, and lack of causal variables.
- **Development and evaluation of approach-level SPFs to explore design relationships and assessment of the**

value of approach-level predictive models. This development involved the same sequence of steps used for the intersection-level model development.

- **Exploration of the potential for speed-based safety models.** The concept of a speed-based model that relates safety performance to absolute speeds and/or relative speeds (speed consistency) was pursued with the hope of providing an intermediate link to both safety and operational performance. The rationale is that speed profiles are a manifestation of the driver's response to a design. The work included testing and calibrating models for linking crashes to the speed profile and the speed profile to roundabout characteristics.
- **Development of an expanded comparison of intersection safety before and after installation of roundabouts.** This comparison between roundabouts and the form of control that preceded their installation was disaggregated as much as possible (e.g., urban versus rural, one lanes versus two lanes) to improve its utility to practitioners.

Motorized Design Criteria

The approach to developing updated design criteria had two major components: speed estimation, and incorporation of safety and operational findings into design criteria. Both efforts were conducted under the premise that the overall design methods currently in use in the United States are sound and that any findings from this study would supplement and augment those procedures, not completely replace them (unless findings suggested otherwise).

The approach used for speed estimation in roundabouts involved collecting and comparing spot speed data in the field for various movements through the roundabout at key points along their paths. These speeds were then compared to current prediction techniques presented in FHWA's *Roundabouts: An Informational Guide* (*1*) to test the overall veracity of the current methods and to propose alterations as needed to improve the fit of the models to the field data.

For overall assessments of the effects of safety and operational findings on design, three approaches were used. First, an overall set of descriptive statistics for the sites in the study were prepared to assess the overall safety performance of each roundabout by its general configuration (e.g., single-lane versus multilane). Second, the safety and operational prediction models developed in their respective modeling efforts were examined for the relevance of various geometric parameters useful in design (e.g., entry width). Third, anecdotal evidence was used where modeling efforts were not sufficient to provide insight on potential relationships between the design of the roundabout and its potential safety and/or operational performance.

Pedestrian and Bicyclist Analysis Approach

The approach to this study was to collect data related to pedestrian, bicyclist, and motorist behaviors from enough locations and for enough pedestrians and bicyclists to answer the questions posed in the introduction of this report. The analysis produced a series of descriptive statistics from the acquired and derived data for each site, which defined the actions and behaviors of pedestrians, bicyclists, and motorists. These behaviors were then compared across sites to determine which locations should be reviewed more closely. Those sites that appeared to produce behaviors substantially different from the mean values for like sites were reviewed to determine if there were geometric or operational features at those locations that may have contributed to the observed behaviors.

In addition to comparing the roundabout sites, the research team also compared the results from the pedestrian analysis in this study to those of a study being conducted for FHWA, titled "Safety Index for Assessing Pedestrian and Bicyclist Safety at Intersections" (*3*). Specifically, the pedestrian time and behavior results from the roundabout approaches in this study were compared to similar data that were collected for two-way-stop–controlled, all-way-stop–controlled, and signalized intersections within the FHWA research study. The goal of this supplemental analysis was to shed light on any differences or similarities among these types of intersections with respect to pedestrian behaviors.

The objectives of the observational analysis were to characterize how pedestrians and bicyclists interact with motor vehicles at roundabouts, assess safety on the basis of these observations, and determine if there is an association between the observed behaviors and the geometric and/or operational characteristics. The following specific questions were addressed for pedestrians:

- How do pedestrians behave when crossing the leg of a roundabout? How do they respond to vehicles when preparing to cross or crossing the street? Do they cross within the crosswalk? Do they cross in one stage or two stages (using the splitter island as a refuge area)?
- What is the yielding behavior of motorists when they encounter a pedestrian who is crossing or waiting to cross?
- Did the behaviors of motorists and pedestrians create unsafe situations? Are there conflicts between motorists and pedestrians, and what are the underlying causes?
- How do the behaviors of pedestrians and motorists at roundabouts, which are yield controlled, compare to the behaviors of pedestrians and motorists at other types of crossings, including those with no control, stop control, or signal control?

- What are the geometric or operational characteristics that tend to cause problems for pedestrians or that tend to result in safer and more accessible designs? Are there differences in behaviors between the entry side and exit side of a leg? Are there differences in behaviors between one-lane and two-lane legs?
- Do any of the characteristics differ by region of the country?

The questions are similar for bicyclists crossing a leg. However, for bicyclists entering the roundabout, additional questions were addressed:

- How do motorists and bicyclists interact on the approach to the roundabout and within the circulating lane? Where do bicyclists position themselves; does the bicyclist "take the lane"?
- Are there conflicts or avoidance maneuvers on the approach or within the circulating lane?
- What types of behaviors do bicyclists exhibit that raise safety concerns (e.g., wrong-way riding, incorrect left turns)?

Marketing Materials

In addition to funding the scope of work, the AASHTO Standing Committee on Research approved additional funding to develop marketing materials for roundabouts. These materials consist of a series of self-guided Microsoft® PowerPoint™ presentations that can be used as is or adapted as needed to assist in communicating roundabout concepts to political and technical decision-makers. These presentations are available from the TRB website (http://www.trb.org/news/blurb_detail.asp?id=7086).

Literature Review

To support the research approach for this project, this report presents an extensive literature review that was conducted to support the two major efforts to model safety and operational performance. In addition, this report includes a brief summary of current design guidance in use in the United States to provide background for the design recommendations. Additional supplemental literature for other components of this study is referenced in their respective discussions of findings.

Safety Prediction Models

To date, most of the research and literature dealing with the safety of roundabouts has focussed on the relative change in safety following the conversion of conventional stop- and/or signal-controlled intersections to roundabouts. The explicit quantification of roundabout safety, measured in terms of expected crash frequency, has thus far not received equal attention. However, for the designer, understanding the relationships between roundabout design features and crash frequency is imperative.

This report reviews, by country of origin, published models that address the relationships between roundabout geometry and other factors, and safety. These models originate from the United Kingdom, Australia, France, and Sweden. Also reviewed are studies on the safety effect of converting conventional intersections to roundabouts.

A summary of the safety models included in the review is provided in Table 1. Appendix A contains a comprehensive review of each source, by country of origin, followed by a summary indicating how useful the insights from this review were in guiding the research effort. (All appendixes have been published as *NCHRP Web-Only Document 94* available on the TRB website [http://www.trb.org/news/blurb_detail.asp?id=7274]).

A summary of the effect of each parameter according to the models from the United Kingdom, Australia, and Sweden is provided in Table 2. The table is broken into common and unique measures for each model. The French model (SETRA), which is not tabulated here, related only one variable (average annual daily traffic [AADT], which had a positive effect) in a single model for all crash types combined. Measures common to two or more of the models are volume, pedestrian volumes, number of lanes on approach, number of circulating lanes, radius of the central island, radius of vehicle path, and approach curvature or deflection. Most factors, with the exception of the radius of the central island, were found to have similar effects on safety (i.e., same positive or negative direction).

The literature review provided insight on how many sites may be needed for direct calibration. For example, models for other intersection types were typically based on samples of 300 to 450 sites. Conversely, the UK model for four-leg roundabouts used only about 80 sites (*4*), but there was quite a large variation in some of the key variables. On this basis, the research team confirmed that the development of safety models for U.S. roundabouts would be a challenging task given the relatively few U.S. installations and the low numbers of crashes at them. Therefore, the research team concluded it would need to consider alternatives to the direct calibration of models relating crashes at roundabouts to all of the geometric and operational characteristics that may affect their safety.

For the direct calibration of models, it was evident from the review that, even if large sample sizes were available, the characteristics of interest would need to vary enough to allow the relationship between crashes and these variables to be modeled. These difficulties appeared to be magnified

Table 1. Summary of safety models.

Country and Author	Sample Size	Constant Features	Variable Features	Model	Input Parameters
United Kingdom: Maycock & Hall (*4*)	84	• Four legs • Single grade • Circular island • No unusual features	• Island size • Speed	Total crashes/ roundabout	• Vehicle AADT
				Total crashes/ crash type	• Vehicle AADT
				Total crashes/ leg/crash type (geometric)	• Vehicle AADT • Pedestrian volume • Entry width • Angle • Sight distance • Approach curve • Gradient • Radius • Percentage of motorcycles
Australia: Arndt (*5, 6*)	100	None	• Number of legs • Number of lanes • Urban/Rural • Island shape • Speed	Total crashes/ leg/crash type	• Vehicle AADT • Number of lanes • Speed variables • Vehicle path radius • Side friction
Sweden: Brüde & Larsson (*7*)	650	N/A	• Number of legs • Number of lanes • Speed limit	Crashes/million of entering vehicles	• Vehicle AADT
France: SETRA (*8*)	N/A	N/A	N/A	Total crashes/ roundabout	• Vehicle AADT

Legend:
AADT = Average annual daily traffic; N/A = Not available

in the modeling of different crash types. However, the various crash types needed to be modeled, as others have done, to guard against the opposite effects of a variable being masked. For example, increased entry deflection might reduce entering-circulating crashes but increase rear-end crashes (though to a lesser degree).

Most important, through the literature review, a wide array of variables for the safety analysis was identified. This list was useful in guiding the data collection and modeling efforts.

Review of Before-After Safety Studies

The research team also reviewed studies on the safety effect of converting conventional intersections to roundabouts and found that the results of these studies are usually reported without indicating whether regression-to-the-mean biases were considered in the analysis. Further, in most cases, the research team was unable to determine if this bias exists. Thus, the reader is cautioned to accept the results summarized here in the spirit in which this section is provided—to provide a flavor for the safety benefits of roundabouts. The decision to report these results in spite of possible reservations was based on a belief that, with the very large reductions that were consistently observed, the benefits of roundabouts would remain substantial if regression-to-the-mean effects were removed and any other methodological limitations were to be overcome. Details on studies of conversions from other forms of intersections can be found in Appendix A.

The one definitive study of U.S. conversions conducted for the Insurance Institute for Highway Safety (IIHS) (*9*), and subsequently updated for the New York State Department of Transportation (NYSDOT) (*10*), was based on a rather small sample size. As such, only limited disaggregate analysis could be done to try to isolate the geometric factors associated with the greatest safety benefits of roundabout construction. While some of these factors have been isolated in evaluations outside of the United States, that knowledge may not be directly transferable. In addition, several of those studies had methodological limitations. The review of the previous studies did provide useful insights for guiding the disaggregated before-after analysis for this study. Useful lessons were learned from the pitfalls and limitations of many of those studies (e.g., small sample sizes, ignoring regression to the mean, and improperly accounting for traffic volume changes over time). These lessons emphasized the need for, and the use to be made of, recent advances in safety estimation methodology aimed at overcoming these limitations.

Capacity Models

Capacity is a required input to delay and queuing models. In terms of existing U.S. capacity methodologies, the HCM

Table 2. Summary of geometric, traffic, and other characteristics affecting safety.

Measure	United Kingdom (Maycock & Hall)					Australia (Arndt)					Sweden (Brüde & Larsson)		
	SV	**APP**	**Ent/C**	**Other**	**Ped**	**SV**	**RE**	**Ent/C**	**Ext/C**	**SS**	**All**	**Cyclist**	**Ped**
Measures Common to All Models[1]													
AADT/volume	+	+	+	+	+	+	+	+	+	+	+		
Pedestrian volumes					+								+
Number of approaching lanes							+				+	+	+
Number of circulating lanes								+			+	+	+
Radius of central island			–					+			See Note 2	–	
Radius of vehicle path	–	–				–							
Approach curvature or deflection	–							–	–				
Measures Specific to the United Kingdom Models (Maycock & Hall) (4)													
Road width at entry	*/+	*/–	+/–										
Percentage of motorcycles			+	+									
Angle to next leg		*	–										
Gradient		+/+%	+/–%										
Sight distance	+	+											
Weaving length between splitter islands		*			*								
Distance to first sight of roundabout					*								
Average flare length		*											
Measures Specific to the Australia Models (Arndt) (5, 6)													
Length of vehicle path						+							
85th percentile speeds						+	+	+	+				
Reduction in 85th percentile speed						+							
Potential side friction										+			
Measures Specific to the Sweden Models (Brüde & Larsson) (7)													
Three legs instead of four legs											–		
Posted speed limit	*				*						+		
Presence of bicycle crossings												–	

Legend:
SV = single vehicle; *APP* = approaching; *Ent/C* = crashes between an entering and a circulating vehicle; *Other* = other non-pedestrian crashes; *Ped* = pedestrian crashes; *RE* = rear-end crashes on approach; *Ext/C* = crashes between an exiting vehicle and a circulating vehicle at multilane roundabouts; *SS* = sideswipe crashes on two-lane segments.
+ = an increase in this measure increases crash frequency
– = an increase in this measure decreases crash frequency
* = the measure had a significant relationship with crash frequency but the relationship was not specified

Notes:
[1] The French model (SETRA) (*8*) is inappropriate to tabulate here because it related only one variable (AADT) in a single model for all crash types combined. AADT had a positive effect.
[2] Optimum 10 m to 25 m

includes a gap acceptance model limited to single-lane roundabouts, and it does not provide any guidance on delay, queues, or level of service. The methods in FHWA's *Roundabouts: An Informational Guide* (*1*) for one- and two-lane roundabout capacities were derived using the UK empirical model with assumed values for the six geometric input parameters. The German empirical capacity relationship was recommended for the operational analysis of an urban compact roundabout. These models were intended to be provisional until further research could be performed on U.S. roundabouts.

A summary of the international capacity models is shown in Table 3. These models are either gap acceptance or linear/exponential empirical relationships. Except for the UK model, there are few geometric parameters.

Details on the types of capacity models in use, as well as a survey of international practices in estimating capacity, can be found in Appendix B.

Overall Literature Review Summary

The literature review provided the following useful insights that were used to guide the conduct of the NCHRP 3-65 research:

- A wide array of variables for the safety and operational analyses were identified. The list was useful in guiding the data collection and modeling efforts.
- While safety and operational prediction models have been developed successfully in other countries, it was unclear if

Table 3. Summary of operational models.

Country	Author	Type	Applicability	Input Parameters	Comments
Germany	Wu *(11)*	Gap Acceptance	One to three lanes	• Circulating flow • Number of lanes • Critical headway • Follow-up headway • Minimum gap	Recommended model in Germany. Based on Tanner (*12*)
	Brilon et al. (*13*)	Linear Regression	One to three lanes	• Circulating flow	Refined for one lane
	Brilon et al. (*14*)	Linear Regression	One to three lanes	• Circulating flow	No longer applicable for one lane
	Stuwe (*15*)	Exponential Regression	One to three lanes	• Circulating flow • Number of lanes • Number of legs • Diameter • Travel distance	Limited geometric range applicable
Switzerland	Simon (*16*)	Linear Regression	One lane, bus lane	• Circulating flow	Not applicable to two or more lanes
	Lausanne, as reported in Bovy et al. (*17*)	Linear Regression	One to three lanes	• Circulating flow • Entering flow • Conflict length	Three unique formulas; one lane limited to D = 22-32 m
USA	HCM (*2*)	Gap Acceptance	One lane	• Circulating flow • Critical headway • Follow-up headway	Provisional method. Based on Harders (*18*)
	Robinson et al. *(1)*	Linear Relationship	Urban Compact	• Circulating flow	See Brilon et al. (*13*)
		Linear Relationship	One lane, Diameter = 30-40 m	• Circulating flow	See Kimber (*19*)
		Linear Relationship	Two lanes, Diameter = 55-60 m	• Circulating flow	See Kimber (*19*)
UK	Kimber (*19*)	Linear Regression	All	• Circulating flow • Entry width • Approach half-width • Effective flare length • Entry angle • Entry radius • Diameter	Large sample of observed capacities
France	CETE Quest (*20*)	Exponential Regression	All	• Circulating flow • Exiting flow on leg • Entry width • Width of splitter • Width of circulatory lane	Girabase method. Most widely used in France
	Louah (*21*)	Linear Relationship	N/A	• Circulating flow • Exiting flow on leg	
	CETUR (*22*)	Linear Relationship	One lane	• Circulating flow	Adjustments have been developed for different geometric factors

Table 3. (Continued).

Country	Author	Type	Applicability	Input Parameters	Comments
Netherlands	CROW (*23*)	Range from macro to micro models	N/A	N/A	Approximate and calculation methods
	CROW (*23*), Botma (*24*)		One lane	• Circulating flow • Exiting flow on leg • Number of bicycles	
	Arem & Kneepkens (*25*)	Gap Acceptance		• Circulating flow • Exiting flow on leg • Critical headway • Follow-up headway • Minimum gap	Believed to be poorly researched. Based on Tanner (*12*)
Sweden	CAPCAL2 (*26*)	Gap Acceptance	One to two lanes	• Percentage of heavy vehicles • Critical headway • Follow-up headway • Minimum gap • Proportion of random arrivals • Length of weave area • Width of weave area	Guidebook based on Australian methods; Critical headway - based on geometry
Israel	Polus & Shmueli (*27*)	Exponential Regression	One lane	• Number of legs • Number of lanes • Speed limit	Units are not specified
Australia	Troutbeck (*28*)	Gap Acceptance	One to three lanes	• Circulating flow • Turning flow • Entry flow • Number of lanes • Entry width • Diameter • Critical headway • Follow-up headway	Separate equations for left and right lanes. Insufficient sites to develop linear regression equations
Austria	Fischer (*29*)	Linear Regression	One lane, Diameter = 23-40 m	• Circulating flow	Similar to Swiss method

these models were directly transferable to the United States. Therefore, a considerable amount of model testing and subsequent model development was required for this research. However, direct transfer of the models did appear feasible and the experience from elsewhere could be used, at least, to guide the selection of variables and model forms.

- New safety and operational models should be sensitive to the volume and variation of data acquired by past studies, recognizing that the U.S. database is inherently less rich at this stage in U.S. roundabout development.
- Few before-after safety studies of roundabout installations have been methodologically sound. Lessons were learned from the pitfalls and limitations of these studies (e.g., small sample sizes, ignoring regression to the mean, improperly accounting for traffic volume changes over time). Even the later before-after studies that learned some of these lessons suffered from small sample sizes that limited the disaggregate analysis aimed at identifying the factors associated with the safety benefits of roundabouts. However, it is feasible and useful to capitalize on the recent advances in safety estimation methodology and a now rich sample of U.S. conversions to do, as part of NCHRP 3-65, a before-after study that would in a disaggregate analysis identify a larger number of factors associated with the safety benefits of roundabouts than was possible before.

CHAPTER 2

Data Characteristics

This chapter describes the process used to establish an overall inventory of roundabouts in the United States, the selection of sites for data collection, and the various types of data collected at specific sites. This database serves three major purposes:

- It supports the development of United States-based safety and operational models completed as part of this project.
- It provides a foundation for additional research into topics beyond the scope and budget of this project.
- It establishes a baseline of U.S. roundabout performance during 2003, the year during which most field data were collected. Future research will be able to compare conditions at that time with those experienced in 2003 to determine trends in various measures over time.

The following sections discuss the development of this database, including the overall inventory and collection of the various geometric, operational, speed, and safety elements.

Site Inventory

One of the products of this research project is an updated site inventory that contains information on as many roundabouts as possible during its development. Table 4 provides a summary of the database, compiled by the project team, of the 310 known roundabouts that existed in the United States as of 2003; the locations of these roundabouts are shown graphically in Figure 1. This database was initially developed by a team led by Rensselaer Polytechnic Institute (RPI) for a project conducted for the NYSDOT and supplemented by information collected for this research project (*30*). Most (94%) of these roundabouts are located in urban or suburban areas, with more than half located in the western United States. The most common geometric configuration (more than two-thirds of the roundabouts) consists of a one-lane circulating roadway and four legs. Sixty-one percent of the roundabouts were converted from some form of stop control, while nearly a third were newly constructed intersections. Nearly all of these roundabouts were constructed during the past 10 years, with 46% opening between 2000 and 2003. A complete listing and description of the site inventory used for this project is given in Appendix C.

Table 5 lists the subset of known sites used for the analysis in this study. Each of these sites was assigned a unique site identification code consisting of a two-letter state abbreviation and a two-digit identification number (e.g., MD01). This code was used in combination with a cardinal direction designation for a given leg (e.g., MD01-N) and/or a video number (e.g., MD01-N2) to identify specific videos for a given leg.

Safety Data

Safety databases were required for three purposes:

- To develop intersection-level crash prediction models
- To develop approach-level crash prediction models
- To conduct a before-after study of roundabouts converted from signal or stop control

For a roundabout to be eligible for inclusion in the sample used for each of the three purposes outlined above, the data available had to meet minimum inclusion criteria that varied based on the model under consideration. For developing intersection-level prediction models, crash and traffic volume data and basic geometric information such as number of legs and number of lanes had to be available for a period of time after the roundabout was constructed. The same information was required for approach-level models; however, the data needed to be available at the approach level, and more detailed geometric data were required. For the before-after study, it was necessary to have, at a minimum, AADT volumes for either the before or after period, the construction dates,

Table 4. Characteristics of modern roundabouts located in the United States (2003).

Characteristics	Number	Percentage of total
Total number	310	
Setting		
• Urban	103	36%
• Suburban	164	58%
• Rural	16	6%
Number of legs		
• 6	4	1%
• 5	16	5%
• 4	197	68%
• 3	70	24%
• 2	4	1%
Number of circulating lanes		
• 3	5	2%
• 2	72	25%
• 1	213	73%
Previous intersection		
• One-way stop	30	19%
• Two-way stop	49	32%
• All-way stop	16	10%
• Signal	14	9%
• None	46	30%
Year created		
• 2000-2003	70	46%
• 1995-1999	70	46%
• 1994 or earlier	12	8%
Geographic location (zip code)		
• Northeast (0,1)	24	8%
• Mid-Atlantic (2)	45	15%
• South, Southeast (3,7)	32	10%
• Midwest (4,5,6)	39	13%
• Mountain West (8)	94	30%
• Pacific Coast (9)	76	25%

Note: Not all characteristics are available for all sites; this explains why the totals for each characteristic add up to less than 310, the total number of roundabouts in the database. For example, setting data are available for 283 of the 310 roundabouts. The percentages cited for urban, suburban, and rural settings add up to 100% of the sample of sites for which data for this characteristic is available. The number of legs and geographic location data do not add to 100% because of rounding.

Figure 1. Geographic distribution of known roundabouts as of 2003.

Table 5. Subset of sites used for analysis.

Site ID	State	City	County	Intersection	Setting	Legs	Lanes	Safety	Operational	Speed	Pedestrian	Bicyclist
CA06	CA	Davis	Yolo	Anderson Rd/Alvarado Ave	U	4	1	X				X
CA10	CA	Long Beach	Los Angeles	Pac Coast Hwy/Hwy 19/Los Coyotes Diag.	U	4	3	X				
CA11	CA	Modesto	Stanislaus	La Loma/James St./G St.	U	5	1	X				
CA17	CA	Santa Barbara	Santa Barbara	Milpas St/US 101 NB Ramps/Carpinteria St	U	5	2					X
CA23	CA	Modesto	Stanislaus	W Rumble Rd/Carver Rd	U	4	1	X				
CO01	CO	Eagle	Eagle	SH-6/I-70 spur/Eby Creek Rd	R	4	1			X		
CO02	CO	Golden	Jefferson	South Golden Road/Johnson Rd/16th Street	U	4	2			X		
CO03	CO	Golden	Jefferson	South Golden Road/Utah St.	U	4	2			X		
CO04	CO	Aspen	Pitkin	SH 82/Maroon Crk/Castle Crk	S	4	2			X		
CO06	CO	Avon	Eagle	Avon Rd./Beaver Creek Blvd.	U	4	3	X				
CO07	CO	Avon	Eagle	Avon Rd./Benchmark Road	U	4	2	X				
CO08	CO	Avon	Eagle	Avon Rd./I-70 Eastbound Ramp	U	4	2	X				
CO09	CO	Avon	Eagle	Avon Rd./I-70 Westbound Ramp	U	4	2	X				
CO10	CO	Avon	Eagle	Avon Rd./U.S. Hwy 6	U	4	2	X				
CO49	CO	Vail	Eagle	Chamonix Rd/I-70 EB Ramps/S Frontage Rd	S	6	2	X				
CO50	CO	Vail	Eagle	Chamonix Rd/I-70 WB Ramps/N Frntge Rd	S	5	2	X				
CO51	CO	Vail	Eagle	Vail Rd/I-70 EB Ramps/South Frontage Rd	S	5	2	X	X			
CO52	CO	Vail	Eagle	Vail Rd/I-70 WB Ramps/N Frntg/Sprddle Cr.	S	6	3	X				
CT01	CT	Killingworth	Middlesex	Rte 80/Rte 81	R	4	1	X				
CT04	CT	N. Stonington	New London	Rte 2/Rte 184	U	4	1	X				
FL01	FL	Amelia Island	Nassau	SR AIA/Amelia Island Plantation	S	4	1					
FL02	FL	Boca Raton	Palm Beach	Cain Blvd/Boca Raton Dr	S	4	1	X				
FL09	FL	Bradntn Bch	Manatee	SR 789/Bridge St	S	3	1	X				
FL11	FL	Clearwtr Bch	Pinellas	SR 60/Coronado/Mandalay/Poinsettia	U	5	2		X		X	X
FL14	FL	Ft Wltn Bch	Okaloosa	Hollywood Blvd/Doolittle Blvd	U	3	1	X				
FL15	FL	Gainesville	Alachua	SE 7th Street/SE 4th Avenue	U	4	1	X				
KS01	KS	Olathe	Johnson	Sheridan St./Rogers Rd	U	4	2	X				
KS02	KS	Hutchinson	Reno	23rd Ave./Severence St.	U	4	1	X				
KS05	KS	Lawrence	Douglas	Monterey Way/Harvard Rd	S	3	1	X				
KS09	KS	Manhattan	Riley	Candlewood Dr/Gary Avenue	S	4	1	X				
KS10	KS	Manhattan	Riley	Kimball Ave/Grand Mere Parkway	S	3	1	X				
KS15	KS	Overland Park	Johnson	110th St./Lamar Ave.	S	4	2	X				
KS16	KS	Paola	Miami	K-68/Old Kansas City Rd/Hedge Lane	R	5	1	X				
MD01	MD	Bel Air	Harford	Tollgate Rd./Marketplace Dr.	S	3	1	X		X		
MD02	MD	Leeds	Cecil	MD 213/Leeds Rd/Elk Mills Rd (Lanzi Cir.)	R	4	1	X		X		
MD03	MD	Jarrettsville	Harford	MD 24/MD 165	R	4	1	X		X		
MD04	MD	(unincorporated)	Baltimore	MD 139 (Charles St.)/Bellona Ave	U	4	2	X	X	X		
MD05	MD	Towson	Baltimore	MD 45/MD 146/Joppa Rd	U	5	2	X	X		X	
MD06	MD	Lothian	Anne Arundel	MD 2/MD 408/MD 422	R	4	1	X	X	X		
MD07	MD	Taneytown	Carroll	MD 140/MD 832/Antrim Blvd	S	4	1	X	X	X		
MD08	MD	Annapolis	Anne Arundel	MD 450/Spa Rd./Taylor Ave	U	4	2	X				
MD11	MD	(unincorporated)	Baltimore	MD 372/Hilltop Circle (UMBC)	U	4	1	X				
MD12	MD	Bel Air	Harford	MD 7/Holly Oaks Drive	S	3	1	X				
MD13	MD	Brunswick	Frederick	MD 17/A St/B St/Maryland Ave	U	5	1	X				
MD14	MD	Cearfoss	Washington	MD 63/MD 58/Cearfoss Pike	R	4	1	X				
MD15	MD	Ellicott City	Howard	MD 100 EB Ramps/MD 103	S	4	1	X				
MD16	MD	Ellicott City	Howard	MD 100 WB Ramps/MD 103	S	4	1	X				
MD17	MD	Ellicott City	Howard	MD 100 WB Ramps/MD 104	S	4	2	X				
MD18	MD	Ellicott City	Howard	MD 100 WB Ramps/Snowden River Pkwy	S	4	1	X				
MD19	MD	Federalsburg	Caroline	MD 307/MD 313/MD 318	R	4	1	X				
MD25	MD	Lisbon	Howard	MD 94/MD144	R	4	1	X				
MD26	MD	Lisbon	Howard	MD 94/Old Frederick Rd	R	4	1	X				

Table 5. (Continued).

Site ID	State	City	County	Intersection	Setting	Legs	Lanes	Safety	Operational	Speed	Pedestrian	Bicycle
MD27	MD	Millington	Kent	US 301 NB Ramps/MD 291	R	4	1	X				
MD28	MD	Millington	Kent	US 301 SB Ramps/MD 291	R	4	1	X				
MD31	MD	Oak Grove	Pr. Georges	MD 193/Oak Grove Rd	U	3	1	X				
MD33	MD	Rosemont	Frederick	MD 17/MD 180	R	4	1	X				
MD38	MD	Stevensville	Queen Annes	MD 18/Castle Marina Rd	S	4	1	X				
MD39	MD	Temple Hills	Pr. Georges	MD 637/Good Hope Ave.	S	4	1	X				
MD40	MD	Temple Hills	Pr. Georges	MD 637/Oxon Run Dr.	S	4	1	X				
ME01	ME	Gorham	Cumberland	US 202/State Route 237	U	4	1	X	X	X		
MI01	MI	Okemos	Ingham	Hamilton Rd/Marsh Rd	S	3	2	X	X	X		
MI03	MI	East Lansing	Ingham	Bogue Street/Shaw Lane	U	4	2	X				
MO01	MO	Columbia	Boone	Business Loop/I-70	S	5	1	X				
MS01	MS	Jackson	Rankin	MS 475/Airport Rd/Old Brandon Rd	S	4	1	X				
NV01	NV	Las Vegas	Clark	Hills Cen. Dr./Vllg. Cen. Cir./Mdw. Hills Dr.	S	4	2	X				
NV02	NV	Las Vegas	Clark	Town Cen. Dr/Hualapai Way/Far Hills Ave.	S	4	3	X		X		
NV03	NV	Las Vegas	Clark	Town Cen. Dr./Village Cen. Cir./Lib. Hills Dr.	S	4	2	X			X	
NV04	NV	Las Vegas	Clark	Town Cen./Cyn. Run Dr/Banburry Cross Dr	S	4	3	X				
NV05	NV	Carson City	Carson City	5th St/Edmonds	R	4	1	X				
NV09	NV	Las Vegas	Clark	Carey Ave/Hamilton St	U	4	2	X				
NV10	NV	Las Vegas	Clark	Carey Ave/Revere St	U	4	2	X				
NV16	NV	Las Vegas	Clark	Lake South/Crystal Water Way	S	4	1	X				
NV18	NV	Las Vegas	Clark	Hills Drive/Longspur	S	3	2	X				
OR01	OR	Bend	Deschutes	Colorado Ave/Simpson Dr	U	4	1	X	X	X		X
OR04	OR	Bend	Deschutes	Century Dr/Colorado Ave/Chandler Ave	U	4	1	X				
OR07	OR	Bend	Deschutes	Mt. Washington Dr/Shevlin Park Rd.	S	4	1	X				
OR09	OR	Bend	Deschutes	Century Dr./14th St./Simpson Ave.	U	4	1	X				
OR15	OR	Eugene	Lane	Barger Dr/Green Hill Rd	S	3	1	X				
SC01	SC	Hilton Head	Beaufort	Whooping Crane Way/Main St	S	4	1	X				
UT02	UT	Orem	Utah	2000 South/Sandhill Rd	U	4	2				X	X
VT01	VT	Manchester	Bennington	Rte 7A/Equinox(Grand Union)	S	4	1			X	X	
VT02	VT	Montpelier	Washington	Main St./Spring St (Keck Circle)	U	3	1	X		X		X
VT03	VT	Brattleboro	Windham	RT 9/RT 5	S	4	2	X	X	X		
WA01	WA	Gig Harbor	Pierce	SR 16 SB Ramp/Borgen Blvd.	S	4	1		X	X		
WA02	WA	Gig Harbor	Pierce	Borgen Blvd/51st	S	4	1			X	X	
WA03	WA	Bainbridge Is.	Kitsap	High School Rd/Madison Ave.	U	4	1	X	X	X	X	X
WA04	WA	Port Orchard	Kitsap	Mile Hill Dr. (Hwy 166)/Bethel Ave	S	3	1	X	X	X		
WA05	WA	Sammamish	King	NE Inglewood Hill/216th Ave NE	S	4	1		X	X		
WA06	WA	Monroe	Snohomish	SR 522 EB Ramps/W. Main St./Tester Rd	S	5	2	X				
WA07	WA	Lacey	Thurston	I-5 NB Ramp/Quinault Dr/Galaxy Dr	S	4	1	X	X	X		
WA08	WA	Kennewick	Benton	27th Ave/Union St/Union Loop Rd	U	4	1	X	X	X		
WA09	WA	Gig Harbor	Pierce	SR 16 NB Ramps/Burnham Dr./Borgen Blvd.	U	6	2		X	X		
WA10	WA	Federal Way	King	Weyerhauser Way/33rd Pl./32nd Dr. S.	S	3	2	X				
WA15	WA	Lacey	Thurston	Marvin Rd/Britton Pkwy./Willamette Drive	S	4	2	X				
WA16	WA	Lacey	Thurston	College St. SE/45th Ave. SE	S	4	2	X				
WA17	WA	Lacey	Thurston	Marvin Rd./Hawk Prairie Rd.	S	4	1	X				
WA22	WA	University Pl.	Pierce	Grandview Dr/56th St W	S	3	1	X				
WA23	WA	University Pl.	Pierce	Grandview Dr/62nd Court W/Park Entrance	S	4	1	X				
WA24	WA	University Pl.	Pierce	Grandview Dr/Bristonwood Dr/48th St W	S	4	1	X				
WA25	WA	University Pl.	Pierce	Grandview Dr/Cirque Dr	S	3	1	X				
WA26	WA	University Pl.	Pierce	Grandview Dr/Olympic Blvd	S	4	1	X				
WA27	WA	University Pl.	Pierce	56th Ave./Alameda Ave. W/Cirque Dr.	S	4	1	X				
WI01	WI	Howard	Brown	Lineville Rd (CTH M)/Cardinal Ln	S	4	1	X				

Legend: U = urban, S = suburban, R = rural. Settings are approximate.
The complete 2003 site inventory can be found in Appendix C.

the control type before construction, and crash data for both the before and after periods.

Crash data at these roundabouts were gathered by three primary means:

- Crash records were gathered from local jurisdictions in the vicinity of all field data collection sites.
- Additional data were gathered via phone calls, e-mail, and traditional mailings to jurisdictions that might have roundabouts with significant crash histories (i.e., roundabouts that had been in operation for more than 1 year).
- Data were extracted from files created by RPI for the NYSDOT project.

The 90 roundabouts in the intersection-level crash dataset were selected based on the availability of crash data (either summaries or detailed crash records), basic geometric information (e.g., number of lanes, number of legs, and diameter), and total entering daily traffic volumes; all components were needed for the site to be included in the dataset. The majority of these 90 roundabouts were single-lane roundabout sites, in urban or suburban environments. In addition, the roundabouts studied have an average AADT of approximately 16,700 entering vehicles/day (low of 2,668 and a high of 58,800). Figure 2 characterizes the sites used in the intersection-level crash dataset. Figure 3 provides a summary of the frequency of crashes at sites in the intersection-level crash dataset. As shown, the majority of the roundabout crashes per year are occurring at urban, multilane roundabouts. Within the dataset, there was little difference in the frequency of crashes per year at the single-lane urban, suburban, and rural roundabouts.

Tables 6 and 7 characterize the approach-level model dataset, which is a subset of the total intersection-level dataset. A total of 139 legs were included in the approach-level dataset. These 139 legs were selected independently from the 90 roundabouts used for the intersection-level dataset based on different data requirements. As noted previously, for a leg to be included in the dataset, all of the following data were needed: detailed crash records (e.g., police reports), detailed geometry (e.g., entry width, entry angle, approach curvature, etc.), and approaching and circulating daily traffic volumes. Table 8 provides a summary of the geometric data used in the approach-level modeling. The geometric data were developed from a manual review and reduction of data from as-built drawings of the roundabouts. Within the approach-level dataset, Figure 4 provides a summary of the types of crashes occurring. As shown, the majority of the crashes in the dataset occurred at multilane roundabouts and were either exiting-circulating or rear-end crashes.

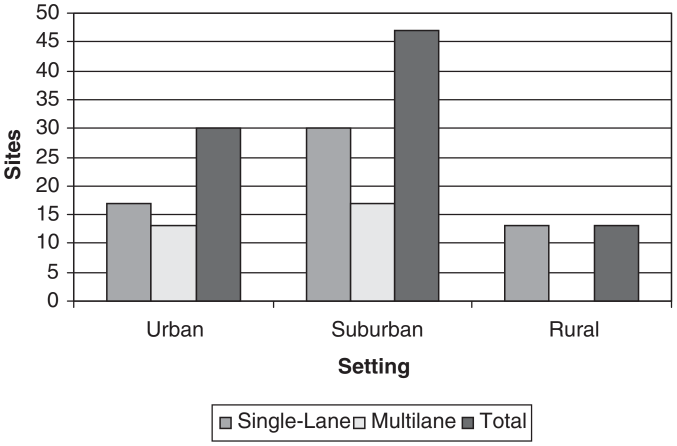

Figure 2. Summary of roundabout characteristics used for intersection-level safety analysis.

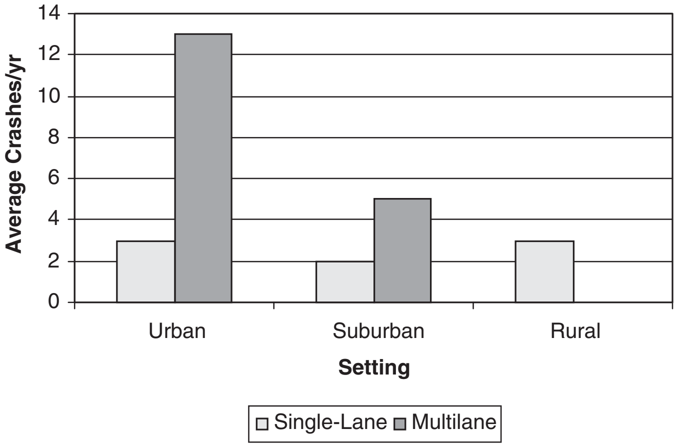

Figure 3. Intersection-level roundabout dataset—average crashes per year.

Fifty-five roundabouts were used for the before-after study, as these were the roundabouts where both before- and after-conversion crash records were available. The two sources for the before-after dataset were the previously conducted before-after study for the IIHS (5) and new data collected for this project. A breakdown of this dataset by jurisdiction, control type before conversion, setting, and number of circulating lanes is shown in Table 9 and Figure 5. At these sites, before roundabout installation, there were 1,159 crashes; after installation, there were 726 crashes. The average length of time of the crash history before roundabout installation was 3.7 years; the average length of time of the crash history after installation of the roundabout was 3.3 years.

Operational Data

The overall inventory of roundabouts provided a rich source from which potential sites for the field data collection could be identified. The following criteria were used to identify these sites:

- An expectation of queuing on one or more of the roundabout approaches, representing capacity conditions

Table 6. Incidence of approach-level crashes by type.

Crash Type	Number of legs = 139 (at 39 roundabouts) Mean length of crash history = 3.8 years					
	All		Single Lane		Multilane	
	Incidence	Percentage	Incidence	Percentage	Incidence	Percentage
Entering-Circulating	141	23%	40	29%	101	22%
Exit-Circulating	187	31%	10	7%	177	38%
Rear-End on Approach	187	31%	42	30%	145	31%
Loss of Control on Approach	77	13%	42	30%	35	7%
Pedestrian	5	1%	1	1%	4	1%
Bicyclist	8	1%	3	2%	5	1%
Sum*	**605**	**100%**	**138**	**99%**	**467**	**100%**

*Percentages may not add to 100 because of rounding.

Table 7. Annual frequency of approach-level crashes by type.

Crash Type	Number of legs = 139 (at 39 roundabouts) Mean length of crash history = 3.8 years					
	All		Single Lane		Multilane	
	Maximum Crashes Per Year	Mean Crashes Per Year	Maximum Crashes Per Year	Mean Crashes Per Year	Maximum Crashes Per Year	Mean Crashes Per Year
Entering-Circulating	3.03	0.32	3.03	0.22	2.67	0.41
Exit-Circulating	9.09	0.57	9.09	0.57	7.67	0.97
Rear-End on Approach	5.00	0.40	2.00	0.17	5.00	0.64
Loss of Control on Approach	3.03	0.15	3.03	0.18	1.25	0.11
Pedestrian	1.00	0.01	0.14	0.02	1.00	0.03
Bicyclist	3.03	0.05	3.03	0.05	2.00	0.04

Table 8. Summary of approach-level geometric data used for safety analysis.

Variable	Minimum	Maximum	Mean	No. Legs
Inscribed Circle Diameter (ft)	85	300	144.1	139
Entry Width (ft)	12	49	22.2	138
Approach Half-Width (ft)	10	49	20.2	130
Effective Flare Length (ft)	0	308	27.5	134
Entry Radius (ft)	26	282	77.8	131
Entry Angle	0	45	19.2	129
Circulating Width (ft)	12	45	26.1	138
Exit Width (ft)	12	51	23.0	128
Departure Width (ft)	10	50	19.3	123
Exit Radius (ft)	21	285	82.0	115
Central Island Diameter (ft)	20	214	77.7	134
Angle to Next Leg	27	180	89.3	135
1/Entry Path Radius (1/ft)	-0.0100	0.0200	0.0058	123
1/Circulating Path Radius (1/ft)	-0.0300	0.0091	-0.0101	122
1/Exit Path Radius (1/ft)	0.0000	0.0252	0.0053	123
1/Left-Turn Path Radius (1/ft)	-0.0400	0.0244	-0.0184	120
1/Right-Turn Path Radius (1/ft)	0.0000	0.0364	0.0102	121
AADT	220	19,593	4,637	139

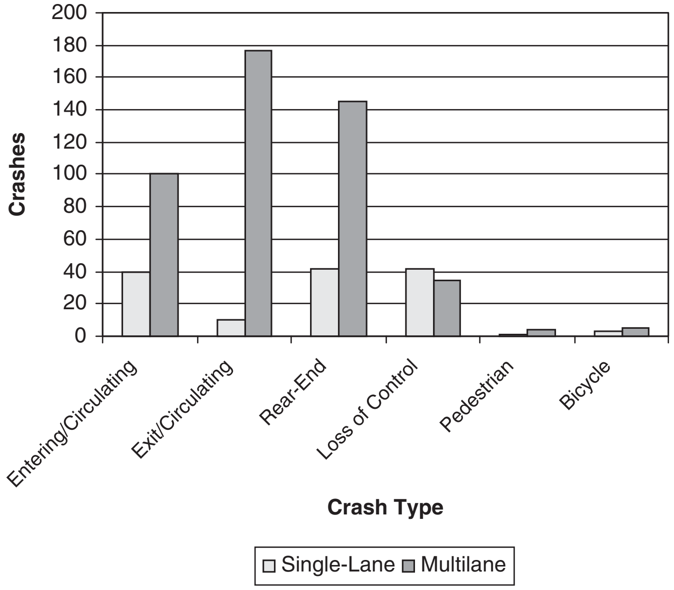

Figure 4. Approach-level crashes by type.

- A balance between single-lane and multilane sites so that operational characteristics of both kinds of sites could be studied
- A range of other geometric conditions so that the effect of these conditions on operations could be studied
- A clustering of sites so that driving time to the sites could be minimized, thus maximizing the number of sites that could be studied

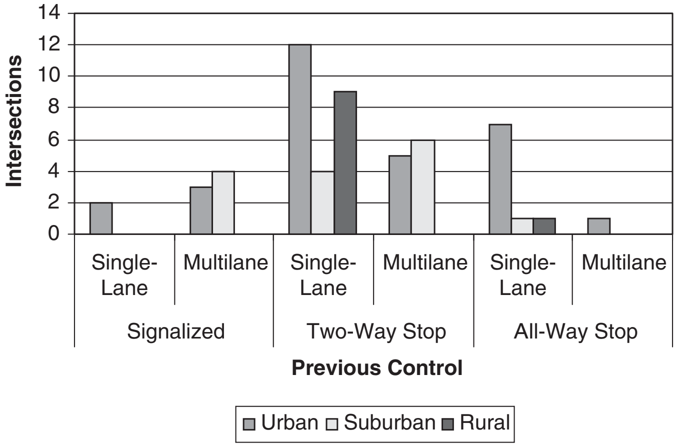

Figure 5. Dataset for before-after study by control type before conversion, setting, and number of circulating lanes.

Table 10 shows a list of the 31 sites at which field video recordings were made during spring and summer 2003. Included in the table are the date of the site visit, the site ID, the intersection name, and the city and state in which the roundabout is located. A total of 34 hours of traffic operations was extracted including the entry flow, conflicting flow, exiting flow, accepted and rejected gaps, turning movement proportions, travel time for different movements, vehicle types, and delay.

A video recording system was designed to allow the team to record the movement of vehicles at the roundabouts selected for the operations study. The recording system included the following components:

- One omni-directional camera that provided a 360-degree view of the roundabout

Table 9. Dataset for before-after study by state, control type before conversion, setting, and number of circulating lanes.

State (Total Sites)	Signalized before						TWSC before						AWSC before					
	U		S		R		U		S		R		U		S		R	
	1L	2L	1L	2L	1L	2L	1L	2L	1L	2L	1L	2L	1L	2L	1L	2L	1L	2L
Colorado (9)				3						6								
Florida (4)	1						2						1					
Kansas (4)							1	1	1		1							
Maryland (17)		2					4	1	2		8							
Maine (1)							1											
Michigan (1)		1																
Mississippi (1)													1					
Missouri (1)													1					
Nevada (3)								1						1			1	
Oregon (4)							1						3					
S. Carolina (1)	1																	
Vermont (2)				1			1											
Washington (6)							1	2	1				1		1			
Wisconsin (1)							1											
TOTALS	2	3	0	4	0	0	12	5	4	6	9	0	7	1	1	0	1	0
	5		4		0		17		10		9		8		1		1	
	9						36						10					

Legend: TWSC = two-way-stop–controlled; AWSC = all-way-stop–controlled; U = urban; S = suburban; R = rural; 1L = one-lane; 2L = two-lane

Table 10. List of field sites for operational and speed data collection.

Date		Site ID	Intersection name	City and State
June	9	NV01	Hills Center Dr./Village Center Cir./Meadow Hills Dr.	Las Vegas, NV
	10	NV02	Town Center Dr./Hualapai Way/Far Hills Ave.	Las Vegas, NV
	11	NV03	Town Center Dr./Village Center Cir./Library Hills Dr.	Las Vegas, NV
	12	NV04	Town Center Dr./Banburry Cross Dr.	Las Vegas, NV
	17	CO01	SH-6/I-70 spur	Eagle, CO
	19	CO02	South Golden Road/Johnson Rd/16th St.	Golden, CO
	20	CO03	South Golden Road/Utah St.	Golden, CO
	30	MD01	Tollgate Rd. /Marketplace Dr.	Bel Air, MD
July	1	MD02	MD213 at Leeds Rd./Elk Mills Rd. (Lanzi Circle)	Leeds, MD
	2	MD03	MD24 at MD 165 (North Harford)	Jarrettsville, MD
	7	MD04	MD139 (Charles St.) at Bellona Ave.	Baltimore Co., MD
	8	MD05	MD45 at MD146/Joppa Rd.	Towson, MD
	9	MD06	MD 2 at MD 408/MD 422	Lothian, MD
	10	MD07	MD 140/MD 832/Antrim Blvd.	Taneytown, MD
	14	VT01	Route 7A/Equinox (Grand Union)	Manchester, VT
	15	VT02	Main St and Spring St. (Keck Circle)	Montpelier, VT
	16	VT03	Route 9/Route 5	Brattleboro, VT
	18	ME01	US 202/State Route 237	Gorham, ME
	23	MI01	Hamilton Rd/Marsh Rd.	Okemos, MI
	25	KS01	Sheridan St./Rogers Rd.	Olathe, KS
	28	CO04	SH 82/ Maroon Creek, Castle Creek	Aspen, CO
	30	UT01	1200 South/400 West	Orem, UT
	31	UT02	1200 South/Sandhill	Orem, UT
August	4	WA01	SR 16 SB Ramp Terminal (near Pioneer at Stinson)	Gig Harbor, WA
	5	WA02	Borgen Blvd/51st	Gig Harbor, WA
	6	WA03	High School Rd/Madison Ave.	Bainbridge Isl., WA
	7	WA04	Mile Hill Dr. (Hwy 166)/Bethel Ave.	Port Orchard, WA
	11	WA05	NE Inglewood Hill/216th Ave. NE	Sammamish, WA
	12	WA06	SR 522 EB Ramps/W. Main St./Tester Rd.	Monroe, WA
	13	WA07	I-5 off-ramp/Quinault Dr/Galaxy Dr.	Lacey, WA
	15	OR01	Colorado/Simpson	Bend, OR

Notes:
1. Other sites were included in the original field list. Bad weather prevented video recording at these sites.
2. The site ID includes the state in which the roundabout is located and the number of that site within a state.

- Three digital video cameras that focused on individual legs at the roundabout
- Two masts, each extendable to 30 ft, to which the video cameras were attached
- Four DVD-R recorders to record the video directly from the digital and omni-directional cameras at the site

Figure 6 shows an omni-directional camera (on the left) and a digital camera (on the right) mounted on the top of the mast. At the beginning of the field data collection, both masts were used, with two cameras located on the top of each mast. However, one mast and two digital cameras were destroyed during an unexpected windstorm in Colorado in late June 2003. Modifications were made to the remaining mast so that one omni-directional camera and three digital cameras could be mounted on that one mast.

Figure 7 shows a typical view of one leg taken by one of the digital cameras. This view shows both circulating vehicles and vehicles queued on the approach. All vehicle movements associated with this leg are clearly visible.

Figure 8 shows a typical view from the omni-directional camera. Vehicles on all four legs are shown, as well as vehicles circulating on the roundabout. This omni-directional view provides an excellent record of all vehicle movements, as well as of the intersection geometry and markings.

Using this video recording system, a total of 262 DVDs were recorded at the 31 sites: 166 DVDs of individual roundabout legs and 96 DVDs recorded of entire intersections using the omni-directional camera. The recordings made for the individual legs included 474 hours of traffic operations. Of the 166 legs recorded, 12 were located at three-lane sites, 58 were at two-lane sites, and 96 were at one-lane sites.

Geometric Data

To support the operational and safety model development, a wide range of geometric data were obtained for each site, as shown in Figure 9. Where possible, these data were collected using definitions consistent with those used for international safety and operational models. In addition, the type of pedestrian crosswalk, presence or absence of striping on the circulating roadway, lane configurations, and type of vertical geometry were noted.

Figure 6. Omni-directional camera and digital camera located at top of mast.

Figure 7. View of one leg from digital camera, Site WA03-S.

Figure 8. View from omni-directional camera, Site WA03.

Speed Data

Currently, speeds are predicted for a roundabout design by measuring speeds along the "fastest path," as defined in FHWA's *Roundabouts: An Informational Guide* (*1*). This path is assumed to be the fastest path traversable by a single *free-flow* vehicle without regard to pavement markings or other traffic. This methodology assumes no acceleration or deceleration between points of measure; as such, the resulting predicted speed represents a reasonable upper limit for the given radius, superelevation, and side friction factor. Appendix G provides details on the specific definitions for defining vehicle paths.

Sixteen single-lane and eleven multilane sites were used for this speed analysis. These sites were chosen to represent a range of geometry, surrounding land use, and volumes found at roundabouts, and the data items collected are summarized in the following paragraphs.

Spot speed data were collected for this project during the summer of 2003 at each location visited by the field data collection team. The speed data were collected using a radar gun, which recorded speeds of free-flow vehicles on each leg to the nearest 1 mph (1.6 km/h) at the following locations:

- At least 200 ft (60 m) upstream of the yield line
- At the yield line
- At the midpoint of the adjacent splitter island
- At the exit point of the roundabout

The number of actual observed data varied by location and leg, depending on the quantity of free-flow observations available and the time constraints of the field data collection team. For some legs, few or no data points were obtained; at other legs, the number of data points exceeded 30. Data points for entering, circulating, and exiting speeds were differentiated by turning movement (i.e., left, through, and right). All data were differentiated by vehicle type (i.e., passenger cars, trucks), and only passenger car data were used for this analysis.

Pedestrian and Bicyclist Data

The sites for the pedestrian and bicyclist observational study were selected from the large number of sites where digital video had originally been recorded as part of the overall field data collection effort. The sites chosen for the analysis were generally those with the greatest number of pedestrians and/or bicyclists. Data were also collected at several additional sites with known high volumes of pedestrians and/or bicyclists, which increased the number of observations and the range of geometric and operational conditions.

Ten specific legs, located at seven roundabouts, were chosen for the pedestrian study. Three of these legs were also used for the analysis of bicyclist movements. A total of 14 legs at seven roundabouts was selected for the study of bicyclists.

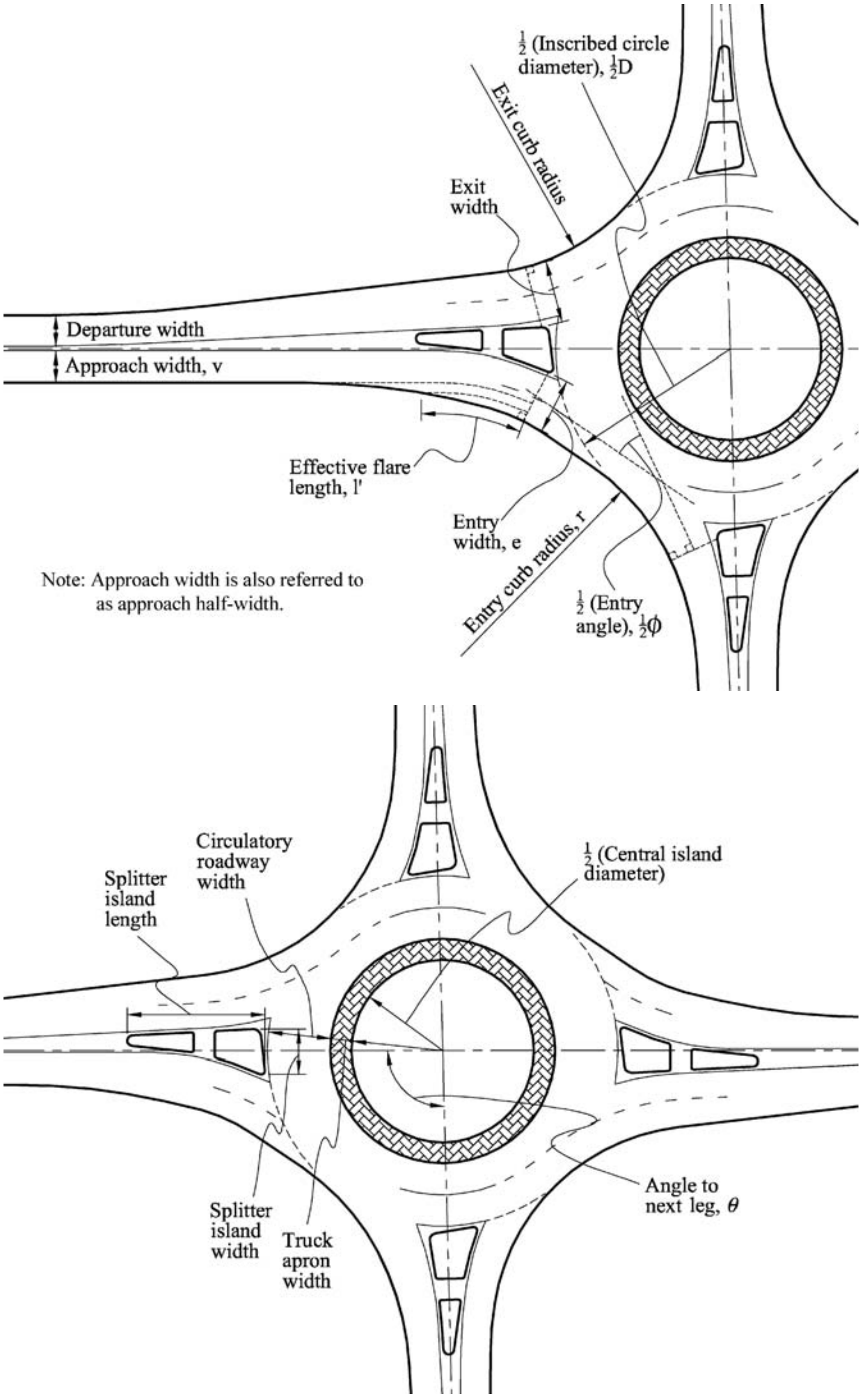

Figure 9. Geometric data obtained for each site.

A summary of all sites used for this analysis is provided in Table 11. A description and image of each leg can be found in Appendix C.

The observational data were acquired from DVDs and videotapes for the sites described previously. The data recorded for each event included the information necessary to attempt to answer the questions previously posed in the introduction. For each pedestrian crossing event, the following information was captured:

- Number of pedestrians crossing (to distinguish individuals from groups)
- Estimated age (adult versus youth)
- Start location (entry side versus exit side)
- Crossing type (within or outside the crosswalk)
- Arrival time (at the curb and prepared to cross)
- Start time (when the crossing was initiated)
- Wait time (difference in start time and arrival time)
- Splitter arrival/departure

Table 11. Summary of pedestrian and bicyclist observation sites.

Location	Intersection	Site/Video ID	Observation Period (min)	Ped. Events	Bike Events
Davis, CA	Anderson Rd/Alvarado Ave	CA06	99	—	89
Santa Barbara, CA	Milpas St/US 101 NB Ramps/Carpinteria St	CA17	120	—	57
Clearwater Beach, FL	SR 60/Gulf Blvd (SR 699)	FL11-E1	120	135	19
Towson, MD	MD 45/MD 146/Joppa Rd	MD05SW-S1	180	89	—
		MD05SW-W1	181	65	—
		MD05SW-NW1	180	38	—
Las Vegas, NV	Town Center Dr/Village Center Cir/Library Hills Dr	NV03-S1	220	22	—
Bend, OR	Colorado Ave/Simpson Dr	OR01-N1/N2	233/233	—	59
		OR01-S1	233	—	27
		OR01-W2	233	—	26
Orem, UT	2000 South/Sandhill Rd	UT02-E1	240	131	12
		UT02-W1	234	35	—
Manchester, VT	Main St (Rte 7A)/Grand Union	VT01-N1/N2	238/142	94	—
Brattleboro, VT	Rte 9/Rte 5	VT02-N1	240	—	39
		VT02-S1	240	—	58
		VT02-W1	240	—	49
Gig Harbor, WA	Borgen Blvd/51st Ave	WA02-E1	158	24	—
Bainbridge Island, WA	High School Rd/Madison Ave	WA03-N2	140	—	29
		WA03-S1/S2/S3	240/140/231	136	112
		WA03-E2/E3	141/231	—	84
		WA03-W1	231	—	30
Totals			**5,118**	**769**	**690**

Legend: Ped. = pedestrian

- Splitter time (difference in splitter departure and arrival times)
- End time (when the crossing was completed)
- Crossing time (difference in end time and start time)
- Rejected gaps (time between arrival time and the next vehicle reaching the crosswalk *and* time between each subsequent pair of vehicles until the pedestrian crosses)
- Accepted gap (time between arrival time and the next vehicle reaching the crosswalk after the pedestrian crosses *or* time between the last rejected gap vehicle and the next vehicle reaching the crosswalk after the pedestrian crosses)
- Pedestrian behaviors during crossing (none, hesitations, stops, retreats, runs)
- Motorist behaviors (yield-slow, yield-stop, does not yield)
- Conflicts (requiring either party to suddenly change course and/or speed)

For bicyclists, the data elements captured had to be expanded. While there were some bicyclists that crossed the leg like a pedestrian, many of the bicyclists captured were approaching the roundabout in the entry lane, departing the roundabout in the exit lane, or traversing the roundabout within the circulating lane. In addition to this basic event type, the following variables were captured for bicyclists:

- Position of bicyclist (within the lane on the leg)
- Motor vehicle presence (passing, trailing, leading, none)
- Entering bicyclist's behaviors (yield, did not yield, safe gap, unsafe gap)
- Exiting bicyclist's behaviors (lane/sidewalk position upon exit)
- Start location for crossing bicyclist (entry side versus exit side)
- Crossing type (within or outside the crosswalk)
- Conflicts (requiring either party to suddenly change course and/or speed)
- Other behaviors (e.g., wrong-way riding)

Appendix D includes more detail about each of the variables captured or derived for pedestrian and bicyclist observations.

Conclusion

The data described in this chapter are the basis for the safety, operational, and design analysis findings from this research. They also are intended to support future research efforts to further understanding of roundabouts in the United States. Discussion of additional research topics to use and expand upon the current database can be found in Chapter 7.

CHAPTER 3

Safety Findings

This chapter describes a number of safety modeling and evaluation tasks. First, the results of the investigation of the ability of non-U.S. prediction models to represent U.S. data are presented—separately for intersection-level and approach-level models. Next are presented the results of the efforts to develop intersection- and approach-level models for U.S. data collected for this project. The last two sections present the results for the modeling of safety as a function of speed and the results of the before-after study.

Ability of Existing Non-U.S. Models to Represent U.S. Data

To test the feasibility of international models, the models were calibrated and used to predict crashes at the U.S. roundabouts in the database. Statistical goodness-of-fit tests were then performed. Appendix E contains a summary of the goodness-of-fit measures and statistical assessments used in this analysis.

Ability of Non-U.S. Intersection-Level Accident Prediction Models to Represent U.S. Data

The general purpose of the intersection-level models is to predict the expected crash performance of an intersection during the planning level of analysis. These models are intended for comparing roundabouts with other forms of intersections and intersection control. As a result, the variables selected for use in the models are deliberately set to be the most basic variables, such as AADT, the number of legs, and the number of circulating lanes.

Existing models were tested with the U.S. data to assess their goodness of fit. The eight intersection-level models came from four sources: four models were based on data from Sweden, three from the United Kingdom, and one from France. These models are designated as follows:

- SWED-TOT1 and SWED-INJ1 (Equations A-10a and A-11a in Appendix A).
- SWED-INJ2 and SWED-INJ3 (Equations A-12a through A-12d in Appendix A).
- UK-INJ1, UK-INJ2, and UK-INJ3 (Equations A-1c through A-1f in Appendix A). The constant parameter for the semi-urban (30–40 mph, or 48–64 km/h) and rural (50–70 mph, or 80–112 km/h) models has been averaged where applicable.
- FR-INJ1 (Equation A-9 in Appendix A).

(Details on these models, including equations, are given in Appendix A.)

Only the first study from Sweden provides a model that predicts total crashes, and the UK models apply only to four-leg roundabouts. For the SWED-TOT1 model, both 70-km/h (44-mph) and 50-km/h (31-mph) speed limits were tested. With the use of a speed limit of 70 km/h [44 mph], testing determined that the model underpredicts crashes (see Table 12). Further testing with the 50-km/h [31-mph] speed limit revealed further underprediction of crashes.

The results of the statistical goodness-of-fit tests, which are also shown in Table 12, indicate that the mean prediction bias per site-year (MPB/site-yr) and mean absolute deviation per site-year (MAD/site-yr) are roughly of the same magnitude, if not greater, than the number of crashes per site-year. This statistic indicates that none of the models fit the data very well.

The existing models include other limitations:

- No model exists for roundabouts with more than four legs or more than two circulating lanes.
- Only one model predicts total crashes, and, by predicting a crash rate independent of traffic volume, it inherently assumes a linear relationship between traffic volumes and crashes.

Table 12. Goodness-of-fit tests of existing intersection-level models to U.S. data.

Model	SWED-TOT1	SWED-INJ1	SWED-INJ2	SWED-INJ3	UK-INJ1	UK-INJ2	UK-INJ3	FR-INJ1
	Total	Injury	Injury	Injury	Injury	Injury	Injury	Injury
No. Sites	78	78	78	78	20	20	61	85
MPB	–3.45	0.49	0.03	0.44	2.77	2.81	2.86	–0.28
MPB/site-yr	–1.18	0.17	0.01	0.15	1.01	1.02	1.00	–0.10
MAD	5.49	1.34	1.09	1.30	3.15	3.17	3.17	1.84
MAD/site-yr	1.88	0.46	0.37	0.44	1.14	1.15	1.11	0.64
MSPE	71.65	4.06	2.83	3.58	23.05	24.85	22.29	13.60
MSPE/site-yr^2	0.11	0.01	<0.01	0.01	0.15	0.16	0.04	0.02
AADT average (range)	15,539 (2,668–37,564)	15,539 (2,668–37,564)	15,539 (2,668–37,564)	15,539 (2,668–37,564)	21,050 (5,322–36,770)	21,050 (5,322–36,770)	16,434 (3,870–37,564)	15,908 (3,870–37,564)
Crashes/site-yr	2.63	0.24	0.24	0.24	0.29	0.29	0.36	0.41
Notes			Only applicable to urban roundabouts		Only applicable to four-leg roundabouts and where major and minor AADTs known separately		Only applicable to four-leg roundabouts	Applicable where entering AADT between 32,000 and 40,000

Legend: MPB = mean prediction bias; MAD = mean absolute deviation; MSPE = mean square prediction error; AADT = average annual daily traffic; yr = year

In light of these limitations and the poor goodness of fit to the U.S. data, the use of existing models to represent the U.S. data is an undesirable option for developing intersection-level prediction models for use in the United States. On this basis, the research team determined that new intersection-level models based on U.S. data needed to be calibrated to have models available for both total crashes and injury crashes at the various site types found in the United States.

Ability of Existing Non-U.S. Approach-Level and Other Disaggregate Safety Prediction Models to Represent U.S. Data

Similarly, to test the possibility of using the UK approach-level models directly on the U.S. database, U.S. data were applied to the existing approach-level and other disaggregate models from the UK to assess their goodness of fit. The UK model form is described in Appendix A.

Initially, the U.S. data developed for this project and crash data used to develop the UK models were compared (Table 13). As shown in the table,

- The U.S. data have a much higher percentage of exiting-circulating crashes;
- The UK data have a much higher percentage of crashes involving loss of control, although this percentage includes crashes in the circulating part of the roundabout, which the U.S. data does not; and
- The U.S. data have a much smaller proportion of pedestrian crashes.

Before testing the UK models, the research team removed from the model any variables for which the necessary data were unavailable by evaluating the estimated parameters at their mean values and adding this value as a multiplicative factor.

Table 14 shows the full UK models (for each crash type) and the mean value of each variable removed. Note that the U.S. data were applied to the more general form of the Maycock and Hall model (*4*). In the final Maycock and Hall model, some variables were omitted (e.g., sight distance and gradient category), and some coefficients were rounded compared to those used here.

Next, the full UK models were recalibrated against the U.S. data by testing them as specified, and then calculating a recalibration term defined as the ratio of observed crashes to predicted crashes. This recalibration term is simply added to the original model as a multiplicative factor. Table 15 describes which UK model was tested against which set of U.S. data for recalibration. Table 16 provides goodness-of-fit statistics for the UK models tested against the U.S. data for entering-circulating, approaching, and single-vehicle crashes.

In light of the limitations imposed by the differences in crash categories between the UK models and the U.S. data, the calibration of the UK models on only fatal and injury

Table 13. Comparison of disaggregated crash data in the U.S. and UK databases.

Crash Type	U.S. Data		Percentage in UK[1]	Notes
	Incidence	Percentage		
Entering-circulating	141	23%	43.3%	
Exiting-circulating	187	31%	14.5% (Defined as “other” in the UK)	Other crashes include exiting-circulating, circulating-circulating, etc.
Rear-end on approach lanes	187	31%	17.0% (Defined as “approach” in the UK)	Most approaching crashes in UK are rear-ends.
Loss of control on approach lanes	77	13%	20.1%	In UK, this type includes single-vehicle crashes on circulating part of roadway.
Pedestrian	5	1%	5.1%	
Bicyclist	8	1%	–	
Total	605	100%	100%	

[1] Only fatal plus injury crashes

Table 14. Approach-level models by crash type at UK roundabouts showing mean values for variables not in the U.S. data.

Crash Type	Model Term	Parameter Value	Mean Value	Term at Mean Value
Entering-Circulating Crashes (Crashes involving an entering and a circulating vehicle)				
L(constant)	Lk	-3.09		
L(entering flow)	LQ_e	0.65		
L(circulating flow)	LQ_c	0.36		
Entry path curvature	C_e	-40.3		
Entry width	e	0.16		
Approach width correction	ev	-0.009		
Ratio factor	RF	-1.0		
Percentage of motorcycles	Pm	0.21	2.24	1.60
Angle to next leg	A	-0.008		
Gradient category	g	0.09	-0.11	0.99
Approaching Crashes (Crashes between vehicles approaching the roundabout—mostly rear-ends)				
L(constant)	Lk	-4.71		
L(entering flow)	LQ_e	1.76		
Entry path curvature	C_e	20.7		
Reciprocal sight distance	$1/V_r$	-43.9	0.015	0.52
Entry width	e	-0.093		
Gradient category	g	-0.13	-0.11	1.01
Single-Vehicle Crashes (Crashes involving single vehicle anywhere in intersection)				
L(constant)	Lk	-4.71		
L(entering flow)	LQ_e	0.82		
Approach half-width	v	0.21		
Entry path curvature	C_e	23.7		
Approach curvature category	C_a	-0.17	0.05	0.99
Reciprocal sight distance	$1/V_r$	-33.0		
Other (non-pedestrian) Crashes (includes exiting-circulating, exiting-exiting, circulating, etc.)				
L(constant)	Lk	-5.69		
L(entering × circulating flow)	LQ_{ec}	0.73		
Percentage of motorcycles	Pm	0.21	2.24	1.60
Pedestrian Crashes				
L(constant)	Lk	-3.59		
L((entering + exiting vehicle flow) × pedestrian flow)	LQ_{exp}	0.53		

Source: Maycock and Hall (*4*)

Table 15. UK models matched with U.S. data for recalibration of approach-level and other disaggregate models.

UK Model Based on Fatal and Injury Crashes	U.S. Crashes Applied to Model
Entering-circulating: Crashes involving an entering and a circulating vehicle.	Entering-circulating: Crashes involving an entering and a circulating vehicle.
Approaching: Crashes between vehicles on the approach. Mostly rear-ends.	Rear-ends on approach lanes
Single Vehicle: Crashes involving single vehicle anywhere in junction.	Loss of control on approach lanes
Other (non-pedestrian): Crashes include exiting-circulating, exiting-exiting, circulating, etc.	Not attempted because this category is not compatible with U.S. data collected
Pedestrian	Not attempted because pedestrian flows unknown and only 5 total pedestrian crashes in database
Bicyclist – No UK Model	No model

crashes, and the relatively poor goodness of fit to the U.S. data as evidenced by the relatively high values of MAD/site-year (compared to the crashes/site-year) and the relatively high calibration factors, using the existing models to represent the U.S. data is not a desirable option for developing approach-level prediction models for use in the United States. On this basis, new approach-level models need to be calibrated based on U.S. data.

Models Calibrated for U.S. Data

This section presents the development of U.S. intersection-level and approach-level models. These new models are directly calibrated using the data assembled for this project and model forms that others have found successful for roundabout and general intersection modeling. See Appendix E for definitions of statistical terms.

Intersection-Level Prediction Models

Intersection-level safety prediction models were calibrated for total and injury crashes; the latter includes fatal and definite injury crashes and excludes possible injury and property damage only (PDO) crashes. To develop the models, a variety of variable sets were tested:

- AADT entering the intersection only
- AADT, number of legs, and number of lanes
- AADT, number of legs, number of lanes, and the ratio of central island diameter to inscribed circle diameter
- AADT, number of legs, number of lanes, and inscribed circle diameter
- AADT, number of legs, number of lanes, and central island diameter

Generalized linear modeling was used to estimate model coefficients using the software package SAS and an assumed negative binomial error distribution, all consistent with the state of research in developing these models.

Consistent with common practice, the models calibrated are of the following very general and flexible form:

$$Crashes/year = \exp(Intercept) \cdot AADT^{b_1} \exp(X_1 + \cdots + X_n) \qquad (3\text{-}1)$$

where

$AADT$ = average annual daily traffic entering the intersection
$X_1 \cdots X_n$ = independent variables other than AADT in the model equation
b_1 = calibration parameter

Table 16. Goodness-of-fit tests of the ability of UK entering-circulating, approaching, and single-vehicle models to represent U.S. data.

Measure	Crash Type		
	Entering-Circulating	Approaching	Single Vehicle
	UK	UK	UK
Number of legs	81	110	107
Calibration factor (observed/predicted)	1.82	3.83	1.29
MAD/site-yr	0.14	0.36	0.16
MSPE/site-yr^2	0.0004	0.0035	0.0006
Crashes/site-yr	0.32	0.57	0.55

Legend: MAD = mean absolute deviation; MSPE = mean square prediction error
Notes: The *number of legs* is the number of roundabout legs the data were recalibrated against. The *calibration factor* is the recalibration factor for the UK models calculated by dividing the sum of observed crashes by the sum of predicted crashes.

In selecting the recommended intersection-level models for total and injury crashes, the research team looked for low values of the dispersion parameter and statistical significance of the estimated variable coefficients. Tables 17 and 18 summarize these major considerations. The recommended models are the ones that achieve the lowest dispersion parameter values while having all variables significant at a level of at least 10 percent.

The analyses indicate that a model including AADT, number of legs, and number of lanes has the best fit to the data available for calibration. The research team also believes that, at the planning level, the inclusion of central island diameter and inscribed circle diameter was not appropriate, as a practitioner assuming values for these dimensions may introduce artificial error in the prediction. The final calibrated models are shown in Tables 19 and 20. SAS output including detailed statistics, such as standard errors of the estimated parameters, are presented in Appendix F.

It is important to reiterate that these models have been calibrated to the data available to this project. When using the models for a particular jurisdiction, they should be recalibrated using data for a sample of roundabouts in the jurisdiction. To do this, the local jurisdiction dataset is applied to the model provided in Equation 3-1. A calibration factor is calculated as the ratio of the sum of crashes actually recorded in the sample to the sum of the model predictions for individual roundabouts in the sample. The individual local jurisdiction calibration factor is then applied to Equation 3-1. At a minimum, data for at least 10 roundabouts with at least 60 crashes are needed to complete this calibration.

Approach-Level Crash Prediction Models

The general purpose of the approach-level models is to understand the impacts of geometric design decisions on various crash types. For example, as the designer evaluates different design options (e.g. entry width, entry radius, or central island diameter), he/she can assess the direction, if not the magnitude, of the safety consequence of the selection. These models are not intended as predictive models in the same sense that the intersection-level models are. However, if they are used for this purpose, it is stressed that a multiplier should be calibrated, as for the intersection-level models, to reflect local conditions.

Table 17. Comparison of intersection-level model results for total crashes.

Model	Variables	Significance of Variable Coefficients (10% level)	Dispersion Parameter
1	AADT	AADT significant.	1.4986
2	AADT, number of legs and number of lanes	All variables significant.	0.8986
3	AADT, number of legs, number of lanes, and ratio of central island diameter to inscribed circle diameter	Central island diameter/ inscribed circle diameter ratio is not significant; other variables are.	0.8348
4	AADT, number of legs, number of lanes, and inscribed circle diameter	Inscribed circle diameter is not significant; other variables are.	0.7792
5	AADT, number of legs, number of lanes, and central island diameter	Central island diameter is not significant; other variables are.	0.8408

Table 18. Comparison of intersection-level model results for fatal and injury crashes.

Model	Variables	Significance of Variable Coefficients (10% level)	Dispersion Parameter
1	AADT	AADT significant.	1.7262
2	AADT, number of legs, and number of lanes	All variables significant.	0.9459
3	AADT, number of legs, number of lanes, and ratio of central island diameter to inscribed circle diameter	AADT and central island diameter/inscribed circle diameter ratio are not significant; other variables are.	0.8714
4	AADT, number of legs, number of lanes, and inscribed circle diameter	AADT and inscribed circle diameter are not significant; other variables are.	0.6891
5	AADT, number of legs, number of lanes, and central island diameter	AADT and central island diameter are not significant; other variables are.	0.8894

Table 19. Intersection-level safety prediction model for total crashes.

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

Table 20. Intersection-level safety prediction model for injury crashes.

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

The approach-level safety performance functions (SPFs) were developed for specific crash types: entering-circulating, exiting-circulating, and approaching. Due to the relatively small number of crashes being modeled, the SPFs were developed for total crashes only. Generalized linear modeling was applied to estimate model coefficients using the software package SAS and an assumed negative binomial error distribution, all consistent with the state of research in developing these models. These models are of the following form:

$$Crashes/year = \exp(Intercept) \cdot AADT_1^{b_1} \cdots\cdots AADT_m^{b_m} \cdot \exp(c_1 X_1 + \cdots + c_n X_n) \qquad (3\text{-}2)$$

where

$AADT_1 \cdots AADT_m$ = average annual daily traffic
$X_1 \cdots X_n$ = independent variables other than AADT in the model equation
$b_1 \cdots b_m$, $c_1 \cdots c_n$ = calibration parameters

The variables tested include entry radius, entry width, central island diameter, approach half-width (referred to as approach width on Figure 9), circulating width, and others.

Tables 21, 22, and 23 present the candidate models for entering-circulating, exiting-circulating, and approaching crashes, respectively. These tables can be interpreted by applying the values in the tables to the model form given above. For example, Model 6 in Table 21 has the following equation form:

$$Crashes/year = \exp(-7.2158) \cdot (AADT_E)^{0.7018} \cdot (AADT_C)^{0.1321} \cdot \exp(0.0511e - 0.0276\theta) \qquad (3\text{-}3)$$

where

$AADT_E$ = entering AADT for the subject entry
$AADT_C$ = circulating AADT conflicting with the subject entry
e = entry width (ft)
θ = angle to next leg (degrees)

Table 21. Entering-circulating crash candidate models for total crashes.

Model No.	Dispersion	Intercept	Entering AADT	Circulating AADT	Entry Radius (ft)	Entry Width (ft)	Central Island Diameter (ft)	Angle to Next Leg (deg.)	1/Entry Path Radius (1/ft)
1	1.665	-13.2495	1.0585	0.3672					
2	1.664	-13.0434	0.9771	0.3088	0.0099				
3	1.495	-12.2601	0.9217	0.2900		0.0582	-0.0076		
4	1.514	-13.0579	1.0048	0.3142	0.0103		-0.0046		
5	1.302	-8.7613	0.9499	0.2687	0.0105			-0.0425	
6*	1.080	-7.2158	0.7018	0.1321		0.0511		-0.0276	
7	2.032	-8.9686	0.8322	0.1370					-138.096

*Recommended model

Table 22. Exiting-circulating crash candidate models for total crashes.

Model No.	Dispersion	Intercept	Exiting AADT	Circulating AADT	Inscribed Circle Diameter (ft)	Central Island Diameter (ft)	Circulating Width (ft)	1/ Circulating Path Radius (1/ft)	1/Exit Path Radius (1/ft)
1	6.131	-7.7145	0.3413	0.5172					
2*	2.769	-11.6805	0.2801	0.2530	0.0222		0.1107		
3	3.015	-11.2447	0.3227	0.3242		0.0137	0.1458		
4	3.317	-3.8095	0.2413	0.5626				372.8710	
5	4.430	-9.8334	0.6005	0.7471					-387.729

*Recommended model

Because of correlations among the variables in the individual candidate models and the small sample size of crashes, calibration of a model with more than a few variables was not possible. The candidate models presented for each crash type are quite close statistically. They all tend to contain logical variables with estimated effects in the expected direction. Appendix H contains the SAS output for each of these models.

To recommend the models with the best predictive power, the research team looked for the models with the lowest dispersion parameters while ensuring that the variables in the selected models and the direction of the indicated effects were logical. These recommended models are marked with an asterisk and shaded in Tables 21 through 23. On the basis of the dispersion parameter, models with AADT as the only explanatory variable, clearly, do not have the predictive power of models that contain at least one geometric variable. These AADT-only models are nevertheless presented in Tables 21 through 23 because they are intended for consideration for *Highway Safety Manual* (HSM)-type predictions that are discussed in Chapter 6.

The recommended models do not incorporate the wide array of geometric design features that engineers will be working with as the roundabout design is being developed. However, consistent with current prototype HSM procedures, the analysis does allow for the estimated coefficients for geometric features in recommended and other models to be considered in developing crash modification factors (CMFs) for use in the HSM. For example, the designer can use the AADT-only models (Model No. 1 given in Tables 21 through 23) and then identify the effect of a design change by applying the appropriate CMF (shown in Table 24). For example, to determine the effect of a unit change in entry width on entering-circulating crashes, the designer would first determine a base level of entering-circulating crashes using Model No. 1 given in Table 21 as follows:

$$Crashes/year = \exp(-13.2495) \cdot AADT_E^{1.0585} \cdot AADT_C^{0.3672} \qquad (3\text{-}4)$$

The designer would then apply the implied CMF from Table 24 that relates a unit change in entry width to entering-circulating crashes: 1.0524. Caution is advised, however, because many of the variables are correlated, resulting in model-implied effects that may not reflect reality. Therefore, the correlations should be considered when determining which CMFs might be used in the HSM. To this end, a correlation matrix is provided as Table 25.

Although the number of entering-circulating, exiting-circulating, and approaching crashes predicted with the approach-level models can be added together to estimate the total number of crashes at a roundabout, the designer is advised to use the intersection-level model for the purposes of estimating the number of crashes at a roundabout. The intersection-level model is better for this purpose because (1) recalibrating the approach-level models for local conditions is more difficult than recalibrating the intersection-level models, and (2) the intersection-level models were developed specifically for such prediction while the approach-level models were developed to assess designs.

Table 23. Approaching crash candidate models for total crashes.

Model No.	Dispersion	Intercept	Entering AADT	Approach Half-Width (ft)
1	1.330	-5.6561	0.6036	
2*	1.289	-5.1527	0.4613	0.0301

*Recommended model

Development of Speed-Based Prediction Models Using U.S. Data

The concept of a speed-based model that relates safety performance to absolute speeds and/or relative speeds (speed consistency) was pursued with the hope of providing an intermediate link to both safety and operational performance. The rationale is that speed profiles are a manifestation of the driver's response to a design. Speed profiles are

Table 24. CMFs implied from candidate approach-level models for unit change in variable.

Variable	Entering-Circulating	Exiting-Circulating	Approaching
Entry Radius (ft)	0.9901 to 0.9896	–	–
Entry Width (ft)	1.0524 *	–	–
Approach Half-Width (ft)	–	–	1.0306 *
Inscribed Circle Diameter (ft)	–	1.0224 *	–
Central Island Diameter (ft)	0.9924 to 0.9954	1.0138	–
Circulating Width (ft)	–	1.1171 *	–
Angle to Next Leg (deg.)	0.9728 *	–	–

*CMF was derived from the recommended model.

Table 25. Correlation analysis of approach-level independent variables.

Parameter	Statistic	Inscribed circle diameter	Entry width	Approach half-width	Entry radius	Circulating width	Central island diameter	Angle to next leg	Entering AADT	Circulating AADT	Exiting AADT
Inscribed circle diameter	Pearson Correlation	1.000	0.653	0.611	0.399	0.689	0.946	-0.169	0.245	0.131	0.085
	Sig. (2-tailed)	.	0.000	0.000	0.000	0.000	0.000	0.050	0.005	0.193	0.394
	N	139	138	132	131	138	134	135	130	100	102
Entry width	Pearson Correlation	0.653	1.000	0.818	0.455	0.827	0.629	-0.219	0.416	0.136	0.300
	Sig. (2-tailed)	0.000	.	0.000	0.000	0.000	0.000	0.011	0.000	0.178	0.002
	N	138	138	131	130	138	133	134	129	100	102
Approach half-width	Pearson Correlation	0.611	0.818	1.000	0.187	0.698	0.597	-0.213	0.392	0.186	0.185
	Sig. (2-tailed)	0.000	0.000	.	0.037	0.000	0.000	0.014	0.000	0.073	0.073
	N	132	131	132	125	131	127	132	123	93	95
Entry radius	Pearson Correlation	0.399	0.455	0.187	1.000	0.327	0.336	0.150	-0.004	0.023	0.023
	Sig. (2-tailed)	0.000	0.000	0.037	.	0.000	0.000	0.093	0.969	0.821	0.821
	N	131	130	125	131	130	126	127	122	97	99
Circulating width	Pearson Correlation	0.689	0.827	0.698	0.327	1.000	0.658	-0.194	0.599	0.203	0.281
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	.	0.000	0.025	0.000	0.042	0.004
	N	138	138	131	130	138	133	134	129	100	102
Central island diameter	Pearson Correlation	0.946	0.629	0.597	0.336	0.658	1.000	-0.234	0.310	0.072	0.021
	Sig. (2-tailed)	0.000	0.000	0.000	0.000	0.000	.	0.007	0.000	0.477	0.833
	N	134	133	127	126	133	134	130	125	100	102
Angle to next leg	Pearson Correlation	-0.169	-0.219	-0.213	0.150	-0.194	-0.234	1.000	-0.316	-0.124	-0.001
	Sig. (2-tailed)	0.050	0.011	0.014	0.093	0.025	0.007	.	0.000	0.228	0.991
	N	135	134	132	127	134	130	135	126	96	98
Entering AADT	Pearson Correlation	0.245	0.416	0.392	-0.004	0.599	0.310	-0.316	1.000	0.647	0.596
	Sig. (2-tailed)	0.005	0.000	0.000	0.969	0.000	0.000	0.000	.	0.000	0.000
	N	130	129	123	122	129	125	126	130	98	98
Circulating AADT	Pearson Correlation	0.131	0.136	0.186	0.023	0.203	0.072	-0.124	0.647	1.000	0.220
	Sig. (2-tailed)	0.193	0.178	0.073	0.821	0.042	0.477	0.228	0.000	.	0.028
	N	100	100	93	97	100	100	96	98	100	100
Exiting AADT	Pearson Correlation	0.085	0.300	0.185	0.023	0.281	0.021	-0.001	0.596	0.220	1.000
	Sig. (2-tailed)	0.394	0.002	0.073	0.821	0.004	0.833	0.991	0.000	0.028	.
	N	102	102	95	99	102	102	98	98	100	102

especially relevant to roundabouts for which it is widely believed that speed management is the key to how safe a roundabout is.

The models are of the following form:

$$Crashes/year = \exp(Intercept) \cdot AADT^{b} \cdot \exp(cX) \qquad (3\text{-}5)$$

where
$AADT$ = average annual daily traffic
X = independent speed-related variable
b, c = calibration parameters

Crashes were modeled with AADT and the observed speeds at various locations through the roundabout as independent variables. Speeds were measured upstream of the entry, at the entry point, at the exit point, and in front of the splitter islands at the entry and exit points. With the available data, only models for crashes between vehicles approaching the roundabout showed any distinct relationship to speed. Thirty-six legs had speed data and volume data suitable to calibrating a model for approaching crashes. Table 26 shows the results of this analysis. Appendix I presents the statistical results of the various models that were tested.

The models, on the whole, were deemed inadequate on the basis of the weak effects of the speed variables. However, the Australian experience (*5*, *6*) and the one relatively successful model shown here indicate that a speed-based model approach is promising and that, with a more elaborate dataset, more can be made of it. At the moment, however, this approach is not recommended.

Before-After Analysis

The objective of the before-after analysis was to conduct a statistically defensible before-after study to estimate the safety benefits of installing roundabouts. While such studies have previously been done using U.S. data (*9*, *10*), the goal was to build on those studies using a database that was richer in number of intersections and number of years of data, thus providing the ability to further disaggregate the results. In so doing, the hope was that insights could be gained into conditions that favor roundabout installation from a safety perspective by examining how the safety effect estimates vary with the following factors:

- Traffic volumes
- Type of control before (signal or stop)
- Crash history
- Number of legs
- Single-lane or multilane designs
- Setting (urban versus rural)

The empirical Bayes before-after procedure (*31*) was employed to properly account for regression-to-the-mean while normalizing, where possible, for differences in traffic volume between the before and after periods. The change in safety at a converted intersection for a given crash type is given by

$$\text{Change in safety} = B - A \qquad (3\text{-}6)$$

where
B = the expected number of crashes that would have occurred in the after period without the conversion
A = the number of reported crashes in the after period

B was estimated using the empirical Bayes procedure in which an SPF for the intersection type before roundabout conversion is used to first estimate the annual number of crashes (P) that would be expected at intersections with traffic volumes and other characteristics similar to the one being evaluated. The SPF crash estimate is then combined with the count of crashes (x) in the n years before conversion to obtain a site-specific estimate of the expected *annual* number of crashes (m) at the intersection before conversion. This estimate of m uses weights estimated from the mean and variance of the regression estimate as follows:

$$m = w_1 x + w_2 P \qquad (3\text{-}7)$$

where
m = expected site-specific annual number of crashes before conversion

Table 26. Speed-based approach candidate models.

Model No.	Overdispersion parameter	Intercept	Entering AADT	Speed Differential (mph)	Approach Speed (mph)
1	1.3683	-9.0059	0.8255	0.0622	
2*	1.3346	-9.9951	0.8609		0.0521

Legend: Speed Differential = difference between the speed of vehicles approaching the roundabout and the speed of entering vehicles
*Recommended model

$$w_1 = \frac{P}{\frac{1}{k} + nP}$$

x = count of crashes in the n years before conversion

$$w_2 = \frac{\frac{1}{k}}{\frac{1}{k} + nP}$$

P = prediction of annual number of crashes using SPF for intersection with similar characteristics
k = dispersion parameter for a given model, estimated from the SPF calibration process with the use of a maximum likelihood procedure

Factors then are applied to account for the length of the after period and differences in traffic volumes between the before and after periods. The result is an estimate of B. The procedure also produces an estimate of the variance of B. The significance of the difference $(B-A)$ is established from this estimate of the variance of B and assuming, based on a Poisson distribution of counts, that

$$Var(A) = A \tag{3-8}$$

In the estimation of changes in crashes, the estimate of B is summed over all intersections in the converted group of interest (to obtain B_{sum}) and compared with the count of crashes during the after period in that group (A_{sum}). The variance of B is also summed over all conversions. The variance of the after period counts, A, assuming that these are Poisson distributed, is equal to the sum of the counts.

The estimate of safety effect, the Index of Effectiveness (θ), is estimated as

$$\theta = \frac{A_{sum} / B_{sum}}{1 + Var(B_{sum}) / B_{sum}^2} \tag{3-9}$$

The percentage change in crashes is equal to $100(1 - \theta)$; thus, a value of $\theta = 0.70$ indicates a 30% reduction in crashes.

The variance of θ is given by

$$Var(\theta) = \theta^2 \frac{\frac{Var(A_{sum})}{A_{sum}^2} + \frac{Var(B_{sum})}{B_{sum}^2}}{\left(1 + \frac{Var(B_{sum})}{B_{sum}^2}\right)^2} \tag{3-10}$$

Table 27 lists the base SPFs used as described previously. These data were taken from a variety of reliable sources because data were not collected for this purpose in this project. These base SPFs were recalibrated for use in the specific jurisdictions using data for the sample of roundabout conversions for the period immediately before conversion. Only the data in the 1 year immediately prior to roundabout construction were used for this purpose to guard against the possibility that a randomly high crash count in earlier years may have prompted the decision to install the roundabout and therefore provide functions that would overestimate safety performance. Examination of annual crash trends in the before periods indicated that this decision was justified.

The composite results are shown in Table 28, both in terms of percentage reduction in crashes and the index of effectiveness, θ. Injury crashes are defined as those involving definite injury or fatality. In other words, PDOs and possible injury are excluded. Results are shown separately for various logical groups for which sample sizes were large enough to facilitate a disaggregate analysis. The aggregate results for all sites are reasonably consistent with those from the IIHS and NYSDOT studies. The following conclusions can be drawn:

- **Control type before.** There are large and highly significant safety benefits of converting signalized and two-way-stop–controlled intersections to roundabouts. The benefits are larger for injury crashes than for all crash types combined. For the conversions from all-way-stop–controlled intersections, there was no apparent safety effect.
- **Number of lanes.** Disaggregation by number of lanes was possible for urban and suburban roundabouts that were controlled by two-way stops before conversion. The safety benefit was larger for single-lane roundabouts than for two-lane designs, for both urban and suburban settings. All rural roundabouts were single lane.
- **Setting.** The safety benefits for rural installations, which were all single lane, were larger than for urban and suburban single-lane roundabouts.
- **Additional insights.** Further disaggregate analysis provided the following insights:
  - The safety benefits appear to decrease with increasing AADT, irrespective of control type before conversion, number of lanes, and setting.
  - For various combinations of settings, control type before conversion, and number of lanes for which there were sufficiently large samples, there was no apparent relationship to inscribed or central island diameter.

Conclusion

The safety analysis described in this chapter results in a set of intersection-level prediction tools, approach-level prediction tools, and the most extensive disaggregation to date of U.S. crash performance before and after conversion to a roundabout. Further discussion of the significance and applicability of these findings can be found in Chapter 6.

Table 27. Base safety performance functions used in the empirical Bayes before-after analysis.

Setting	Previous Control	Number of Legs	Source of SPF Data	Model
Urban	Signal	4	Howard and Montgomery Counties, MD	Acc/yr = exp(-9.00)(AADT)$^{1.029}$, k = 0.20 InjAcc/yr = exp(-10.43)(AADT)$^{1.029}$, k = 0.20
Urban	Two-way stop	4	Howard and Montgomery Counties, MD	Acc/yr = exp(-1.62)(AADT)$^{0.220}$, k = 0.45 InjAcc/yr = exp(-3.04)(AADT)$^{0.220}$, k = 0.45
Urban	All-way stop	4	Minnesota – rural sites used due to lack of urban data	Acc/yr = exp(-12.972)(AADT)$^{1.465}$, k = 0.50 InjAcc/yr = exp(-15.032)(AADT)$^{1.493}$, k=1.67
Urban	Signal	3	California	Acc/yr = exp(-5.24)(AADT)$^{0.580}$, k = 0.18 InjAcc/yr = exp(-6.51)(AADT)$^{0.580}$, k = 0.18
Urban	Two-way stop	3	Howard and Montgomery Counties, MD	Acc/yr = exp(-2.22)(AADT)$^{0.254}$, k = 0.36 InjAcc/yr = exp(-3.69)(AADT)$^{0.254}$, k = 0.36
Urban	All-way stop	3	Minnesota – rural sites used due to lack of urban data	Acc/yr = exp(-12.972)(AADT)$^{1.465}$, k = 0.50 InjAcc/yr = exp(-15.032)(AADT)$^{1.493}$, k=1.67
Rural	Two-way stop	4	Minnesota	Acc/yr = exp(-8.6267)(AADT)$^{0.952}$, k = 0.77 InjAcc/yr = exp(-8.733)(AADT)$^{0.795}$, k = 1.25
Rural	All-way stop	4	Minnesota	Acc/yr = exp(-12.972)(AADT)$^{1.465}$, k = 0.50 InjAcc/yr = exp(-15.032)(AADT)$^{1.493}$, k=1.67

Legend: SPF = safety performance function; Acc/yr = total crashes per year; InjAcc/yr = fatal and injury crashes per year); AADT = average annual daily traffic entering the intersection; k = dispersion factor

Table 28. Results for before-after analysis by logical group.

Control Before	Sites	Setting	Lanes	Crashes recorded in after period		EB estimate of crashes expected without roundabouts		Index of Effectiveness θ (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%