The Effects of Roundabouts on Pedestrian Safety

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Preface

This project examines the safety aspects of modern roundabouts with respect to pedestrians. Since the emergence of modern roundabouts in the US, safety has been recognized as a major concern for the effectiveness of roundabout performance. Pedestrians may be more prone to unsafe crossings at roundabouts due to new geometries, signalization (or lack of it), right of way assignments for pedestrians and vehicles, and visual and auditory cues. This project documents case study, statistical, and simulation analyses regarding pedestrian safety at roundabouts. The results suggest that roundabouts are safe with respect to pedestrians.

This report includes the following topics:

- literature review summarizing international and US experience with roundabouts and pedestrians,
- alternative research approaches,
- case study analysis of a candidate roundabout intersection in Raleigh, NC,
- statistical analysis for pedestrian crashes at the case study intersection, and
- simulation of the case study intersection vehicle and pedestrian movements with the original intersection and with the candidate roundabout.

Copies of the report are available from the Southeastern Transportation Center, University of Tennessee – Knoxville. We hope that the results of this research will continue to prove valuable to the roundabout community.

Acknowledgements

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Abstract

Current international research shows that modern roundabouts improve vehicular and pedestrian safety compared to conventional intersections. However, their effects on pedestrian safety in the U.S. remain unsubstantiated. Complicating this problem is a scarcity of pedestrian accident data at roundabouts, especially at intersection locations that were reconstructed as roundabouts and could potentially provide critical before/after accident statistics. This research seeks to examine the safety issues by summarizing the literature that describes international and U.S. experience with roundabouts and pedestrian safety. The research applies three alternate approaches to assess pedestrian safety at roundabouts: case study analysis, statistical analysis, and simulation analysis to compare pedestrian safety at a conventional signalized intersection to a case study modern roundabout.

The case study focuses on a proposed roundabout location - the Hillsborough-Horne Street intersection at North Carolina State University in Raleigh, NC. It is scheduled for reconstruction as a roundabout as part of a corridor project to improve the “front door” to NCSU, as well as improve pedestrian safety. First, pedestrian accident histories for the intersection, which has the fourth highest frequency of pedestrian accidents in North Carolina, are examined with and without the proposed roundabout. Based on reduced vehicle-pedestrian conflicts and better control of wrong-way movements, the proposed roundabout shows promise. Second, a regression model for pedestrian accidents versus street and intersection characteristics of a one-mile section of Hillsborough Street is developed. If a roundabout were constructed, the model forecasts a reduction in pedestrian accidents. Third, a simulation analysis of the Hillsborough-Horne intersection shows that the planned roundabout would have equivalent pedestrian capacity and potentially better pedestrian safety than the original signalized intersection. In summary, the three independent approaches suggest that a roundabout design will improve pedestrian safety at the case study intersection.

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1. Introduction

Problem Statement

Modern roundabouts (Figure1.1) have captured the attention of contemporary traffic engineers. While roundabouts are relatively common throughout the world, U.S. traffic engineers have only recently turned to them as potentially safe, traffic calming roadway treatments. European, Australian, and U.S. reports document how both slower speeds and fewer conflict points in roundabout traffic patterns improve vehicular safety. However, the literature is less clear on the effects of roundabouts on pedestrian safety, especially in the U.S. where special intersection designs for disabled pedestrians are required and where drivers and pedestrians are unaccustomed with the operating characteristics of roundabouts.

The U.S. situation is also complicated by the interest of architects and planners. Increasingly they propose using roundabouts as the centerpieces of pedestrian-oriented new development and redevelopment of older neighborhoods, business corridors, and urban centers. Such locations typically have both high vehicular and pedestrian volumes, and their interactions at roundabouts require careful consideration. Consequently, the effectiveness of roundabouts cannot be promoted solely on the basis of demonstrated safety improvements for vehicular traffic. Land planners and transportation professionals are eager to learn more about pedestrian safety at roundabouts.

Figure 1.1 Modern Roundabout, Brown County, Wisconsin

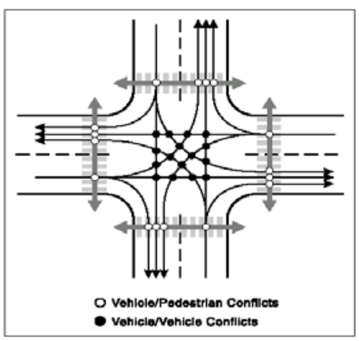
Source: *www.bfw.org/graphics/roundabout.jpg. Contact Cole Runge, Brown County Planning Commission, Green Bay Metropolitan Planning Organization (920.448.3400)*

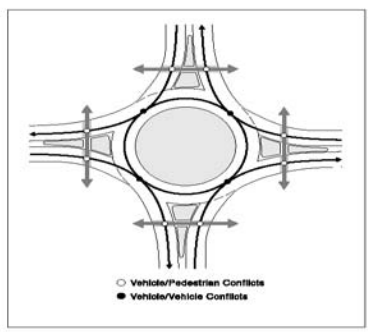
Roundabouts and Vehicular Safety

Roundabouts reduce vehicle speeds, minimize vehicle weaving, automatically establish right-of-way, and reduce conflict points from 32 to 8 (Figure 1.2) according to the FHWA Roundabout Guide[1]. The circulatory vehicle movements at roundabouts eliminate or drastically reduce the critical conflicts resulting from red light running, left-turns against opposing traffic, right-angle conflicts at corners, and rear-end collisions. As a result roundabouts significantly reduce vehicular crashes.

According to Persaud[2], modern roundabouts are safer than other methods of intersection traffic control. After examining 24 intersections that were converted to roundabouts in eight states in a variety of urban, suburban and rural settings, he concluded that roundabouts reduced all vehicular crashes by 39 percent and injury crashes by 76 percent. He estimated reductions in the numbers of fatal and incapacitating injury crashes to be about 90 percent. Other U.S. investigators have found similarly promising results[3, 4]. Vehicular safety improvements are also reported by the international literature[5, 6]. As a result of the documented reductions in vehicle crashes and injuries at roundabouts compared to conventional intersections in similar settings, some professionals strongly promote roundabouts as effective safety treatments for intersections. They predict that "…widespread construction of roundabouts can produce substantial reductions in crash losses associated with motor vehicle use on public roads[2]."

Figure 1.2 Comparing Conflicts





1 *Roundabouts: An Information Guide*, USDOT, FHWA, Pub. No: FHWA-RD-00-067, June 2000.

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

3 Garder, P., The Modern Roundabout: The Sensible Alternative for Maine. Technical Report 96-2. University of Maine, Department of Civil and Environmental Engineering, 1997.

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

5 Elvik, R., A.B. Mysen, and T. Vaa, *Traffic Safety Handbook*, Institute of Transport Economics, Oslo, Norway, 1997.

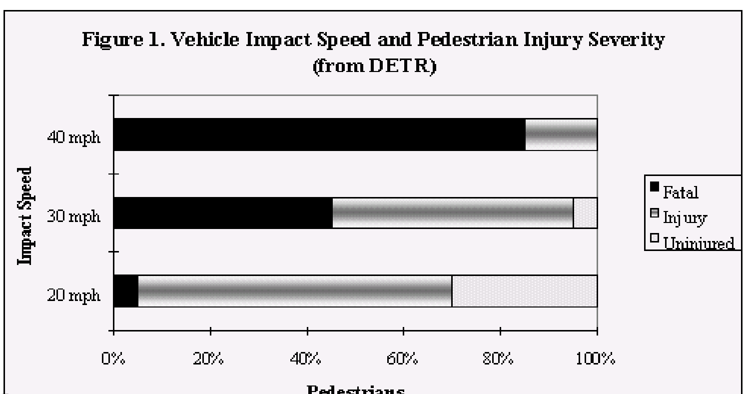
6 Schoon, C. and J. Van Minnen. The Safety of Roundabouts in the Netherlands. *Traffic Engineering and Control*, March 1994.

Roundabouts and Pedestrian Safety

What professional discussions lack, however, are definitive statistics for pedestrian safety at roundabouts. Indeed, the magnitude of the problem remains undefined, though appreciated. Hence, the proposal for this grant was written in mid 1999. Subsequently in mid 2001 NCHRP announced the project *Applying Roundabouts in the United States*[7], a major effort to apply data and results from international sources to U.S. drivers, pedestrians and the highway environment.

For example, a typical roundabout reference like the FHWA Roundabout Design Guide (Chapter 2)[1] gives explicit vehicular crash reduction statistics that are similar to those by Persaud. Yet, the Guide has no such data for pedestrians. The consultant for the Guide relies on the indirect surrogate measure of speed[8]. The consultant presents information showing that at the lower 20-mph speed of most roundabouts, the chance of a pedestrian being killed if hit by a vehicle is 15%. On the other hand, at conventional intersections where the speeds are typically 30 to 40 mph the chances of being killed if hit by a vehicle range from 45% to 85% (Figure1.3). Persaud reports that for his 24 case study intersections the pedestrian crash sample was too small to estimate safety effects[2]. An Australian study[9] and a Scandinavian study[10], however, report that roundabouts are safe for pedestrians. The Swedish Road Administration commissioned VTI (Swedish National Road & Transport Research Institute) to study accident and injury risks at roundabouts with different layouts in different traffic environments.

Figure 1.3 Vehicle Impact Speed and Pedestrian Injury Severity



[7] NCHRP request for proposal, Transportation Research Board, Spring 2001.

[8] Roundabout Basics, Special Roundabout Insert for *Streetwise*, Kittelson & Associates, Inc., November 1999.

[9] Jordan, P.W., Pedestrians and Cyclists at Roundabouts, *Proceedings of the 3rd National Local Government Engineers Conference*, Australia, 1985.

[10] Ulf, B and L. Jorgen, Traffic Safety of Roundabouts for Cyclists and Pedestrians, Swedish National Road and Transport Research Institute, Linkoping, Sweden, 1999.

[9] Jordan, P.W., Pedestrians and Cyclists at Roundabouts, *Proceedings of the 3rdNnational Local Government Engineers Conference*, Australia, 1985.

[10] Ulf, B. and L. Jorgen, Traffic Safety of Roundabouts for Cyclists and Pedestrians, Swedish National Road and Transport Research Institute, Linkoping, Sweden, 1999.

The limited amount of U.S. pedestrian safety data may be explained by the relative infrequency of pedestrian-vehicle crashes compared to vehicle-vehicle crashes. For example, NCDOT studies show that the heavily traveled Hillsborough Street near the campus of North Carolina State University has an average of about seven pedestrian crashes annually compared to about 300 vehicle crashes[11]. The paucity of pedestrian safety data may also be explained by documented intersections being located where little pedestrian activity occurs. Furthermore, unconventional intersections like roundabouts do not have easily identifiable categories in accident reports. Hence, what data that may exist cannot be identified in U.S. accident databases.

But therein lies the quandary. Relatively little pedestrian data exist compared to vehicle crash data; even less pedestrian crash data exist for roundabout treatments. Yet, roundabouts are often proposed for traffic calming in high pedestrian areas like Hillsborough Street, the traditional "front door" of NC State University's campus[12, 13]. Similar high activity, pedestrian-oriented roundabout sites are in Colorado, Oregon, Vermont, Maryland, and Florida[14]. Yet, they are relatively new and there is little or no history of pedestrian accidents. However, some advocates for roundabouts point to the scarcity of pedestrian accident data as evidence of their efficacy as a safety treatment. In any event, there is a need to obtain more information about how roundabouts affect pedestrian safety. By doing so, the intent is to clarify pedestrian safety issues at roundabouts. Subsequently in 2001, TRB similarly recognized the need for more pedestrian safety information at roundabouts[15].

Pedestrian Issues at Roundabouts

According to the FHWA Design Guide (Chapter 2)[2], roundabout splitter islands (Figure 1.2) provide refuge to pedestrians and allow them to cross one direction of traffic at a time. However, the crosswalks are set back from the yield line creating additional walking distance, and they usually occur between the first and second vehicles in the queue. Both situations are unusual for U.S. pedestrians. Indeed, anecdotal evidence leads to concerns that pedestrians may minimize their walk distance by taking short cuts across the central island and cause impatient drivers to challenge pedestrians.

Furthermore, pedestrian – vehicle right of way rules differ at roundabouts compared to traditional intersections. For example, North Carolina State Statute says that vehicles yield to pedestrians at traditional intersections. Roundabouts, which are not recognized by Statute, require pedestrians to yield to the vehicles.

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[11] NCDOT Traffic Accident Analysis System Strip Analysis Reports prepared by J. Jaeger and B. Murphy, May 2000.
[12] A New Vision for Hillsborough Street, Prepared by Walkable Communities, Inc. for the Hillsborough Street Partnership, October 26, 1999
[13] http://www.eos.ncsu.edu/courses/ce/ce400_info/roundabout/index.html
[14] http://www.eos.ncsu.edu/courses/ce/ce400_info/roundabout/links.html

Pedestrian safety is also an issue of perceived vs. real risks. Even though pedestrian safety at roundabouts seems to be high (based on international experience and limited U.S. experience) many pedestrians do not perceive roundabouts to be safe. Yet, compared to intersections controlled by two-way stop signs, roundabouts may improve pedestrian safety, especially for crossing the major street. Approach speeds are lower and unexpected right or left-turning movements do not exist at roundabouts. However, both roundabouts and two-way stop controlled intersections require pedestrians to judge gaps in the major (uncontrolled) stream of traffic. Some professionals believe that pedestrian safety may worsen at roundabouts compared to all-way-stops or sign controlled intersections, though there are not available references to substantiate their opinions. There is little international experience with this comparison because all-way-stops are unusual outside the U.S. All-way stops may be safer for pedestrians with visual impairment because all vehicles are stopped, and pedestrians can hear that before they begin to cross. Furthermore, for several reasons, roundabouts may be more difficult to navigate for pedestrians with physical impairments. The walk distance is longer because crosswalks are set back from the intersection. Traffic is always moving, and visually impaired pedestrians may find it more difficult to judge gaps by sound at roundabouts. On the other hand, signalized intersections offer explicit, positive guidance to pedestrians by way of visual and sometimes audible pedestrian signal indications. Thus, the decision process for visually impaired and other pedestrians may be easier at signalized intersections compared to roundabouts.

In summary, U.S. pedestrian safety at roundabouts has not been studied extensively because of the lack of pedestrian crash data. The potential safety benefits of roundabouts are not assured to pedestrians according to available U.S. research and anecdotal discussions, though more future data may substantiate safety benefits to pedestrians. Pedestrians are found relatively safer only at some types of roundabouts[15]. These issues (Table 1.1) combined with U.S. laws for pedestrian right-of-way justify a study of pedestrian accidents at roundabouts.

Table 1.1 Summary Pedestrian Safety Issues at Roundabouts and Intersections

Issue	Roundabouts	Intersections
Pedestrian Crash Data	Little	Much
Speed	Lower	Higher
Traffic Calming	Enhancing	Inhibiting
Pedestrian Refuge Areas	Yes	No
Walk Distance	Greater	Lower
Pedestrian-Vehicle Conflicts	8	16
Right-of-Way	Vehicle	Pedestrian
Driver/Pedestrian Familiarity	Little	Much
Judging Gaps (Sighted)	Easy (Low Speed)	Hard

[15] Lange, J. " Bicycle and Pedestrian Facilities at Small Roundabouts in Built-up Areas." – 2nd International Symposium on Highway geometric Design, June 2000(598 – 606) Sponsored by Road Transportation Research Association, Germany and AASHTO.

Judging Gaps (Sight Disability)	Difficult (Continuous Traffic)	Easy (Discontinuous Traffic)
Auditory Cues (Sight Disability)	Difficult (Continuous Traffic)	Easy (Discontinuous Traffic)

Scope and Objectives

This research includes reviewing the literature to assess issues regarding the pedestrian safety problem at roundabouts and applying the findings to develop a methodology to analyze a case study intersection that is scheduled for reconstruction as a roundabout. In addition, to substitute for the paucity of before-and-after pedestrian accident data for intersections reconstructed as roundabouts, a simulation of pedestrian-vehicle interactions at the case study intersection is undertaken.

The goal of this project is to evaluate the safety of pedestrian movements at roundabouts. The specific objectives are the following:

- To review literature on modern roundabouts and pedestrian safety.
- To identify methods and their data requirements for assessing pedestrian safety at conventional intersections and roundabouts.
- To compare methods and their data requirements to available roundabout analysis methods and synthesize a research methodology.
- To assess the magnitude of pedestrian safety with respect to a case study roundabout.
- To determine the effectiveness of a case study roundabout compared to a conventional signalized intersection with respect to pedestrian safety.

Overview

Subsequent chapters provide an extensive literature review. Based on the literature review, three approaches seem feasible to study pedestrian safety at roundabouts: case study evaluation, statistical analysis, and simulation. These approaches take as a case study the Hillsborough-Horne Street intersection that is the traditional "front door" to NC State University. For many years it has been a signalized intersection, however, it is a candidate for reconstruction as a roundabout.

The next chapter reviews the literature for methods to assess pedestrian safety at the case study intersection. Subsequent chapters apply the above-mentioned methods to the Hillsborough-Horne street intersection near North Carolina State University. Results and conclusions are presented in the final chapter.

2. Literature Review

Introduction

An important part of this research project was a review of the existing literature dealing with pedestrian safety issues at roundabouts. The survey of U.S. and international literature yielded alternative approaches that can be followed to evaluate pedestrian safety at modern roundabouts. The approaches are case study analysis, simulation analysis, and statistical before-and-after evaluation. Each of these approaches has varying requirements for amount and type of data, and each approach yields findings that vary in specificity and generality. Eventually this study applies each of the approaches to the case study intersection.

Case Study Analysis

The basic requirement for a case study is a good location that meets all the research criteria such that the desired results are produced. The type of data required is both quantitative and qualitative. In that generalization from one or a few cases is not statistically warranted, the amount of data required to evaluate a case is not as great as for a statistical before-and-after study.

A convenient existing roundabout to fit the case study criteria was not found, so the case study analysis will be performed on an intersection where roundabout construction is being proposed. The chosen case study location is the Hillsborough – Horne Intersection due to the high pedestrian activity and its candidacy for a roundabout reconstruction. It is on the most accident-prone street near NC State University, and it is the intersection with the fourth most frequent pedestrian accidents in North Carolina. Pedestrian accidents reports and statistics are available for 1990-1998 and a limited "sketch" forensic analysis may be performed for each crash as necessary.

A case study analysis may be applied to an intersection as follows:

- Choose a location that fits the requirements of the study.
- Collect data like traffic volumes, pedestrian volumes, road geometrics, and accident data.
- Perform a forensic analysis of the collected data in order to document the possible causes of pedestrian accidents.
- Perform the accident analysis by hypothetically retrofitting the traditional intersection with the proposed roundabout design.

There are a number of roundabout case studies for vehicle crashes, including crash prediction models for the UK and Australia, that are summarized in the FHWA guide[3]. The Florida DOT conducted a pedestrian and bicycle case study of a few roundabout projects[4]. In the research paper by Elbadrawi et al.[5], the case study approach

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3 *Roundabouts: An Informational Guide*, U.S. DOT, FHWA, Publication No: FHWA-RD-00-067, June 2000.

4 *Bicyclists and Pedestrian Considerations at Roundabouts*, Florida Department of Transportation

was used and the report went on to recommend crossing locations to improve pedestrian safety. These and other international reports show that the case study approach is a valuable evaluation tool.

Conflict analysis is a tool for case study evaluations. Glauz[4] finds that traffic conflicts where vehicle paths cross are indicative of critical operational points of the intersection being observed. The results of Glauz's study show that if there are fewer conflicts, an intersection is safer. In this project traffic conflict analysis measures the comparative operation of roundabouts and conventional intersections. If there are fewer vehicle-pedestrian conflicts (Figure 2.1), the intersection should be safer, all other factors being equal.

In the context of this research project, forensic analysis is a particular kind of case study used to determine causes and effects. It can be described as a crash analysis of pedestrian accident data where data for each crash is individually studied and the cause is identified. Case study and forensic analysis may be performed together when data is scarce and statistical results are not the goal. The methodology for a case study analysis leads into forensic analysis in order to document the probable accident causes and effects.

Such an approach helps overcome the problems of limited data when only one crash site is being considered. However, generalization to all roundabouts in U.S. is not possible due to varying environments, geometrics, regional driving behaviors, and volumes. For other sites with proposed roundabout construction, new case studies have to be conducted to account for these variances. The generality of the results increases with the data and number of locations.

In Kansas, an examination of traffic conflicts was performed at three intersections. Insufficient data was obtained from the conflict study to perform analysis or make conclusions with regard to roundabout conflicts[5].

Statistical Analysis

Statistical analysis in the context of roundabout safety evaluation would ideally have pedestrian crash data before and after an intersection is reconstructed as a roundabout. Better yet, to account for other possible causal factors, it is desirable to have multiple reconstructions sites. Persaud[6] had nearly 30 intersections in his vehicle safety analysis. Yet, as discussed previously, there is very little data for pedestrian accidents.

Statistical analysis involves several closely integrated steps:

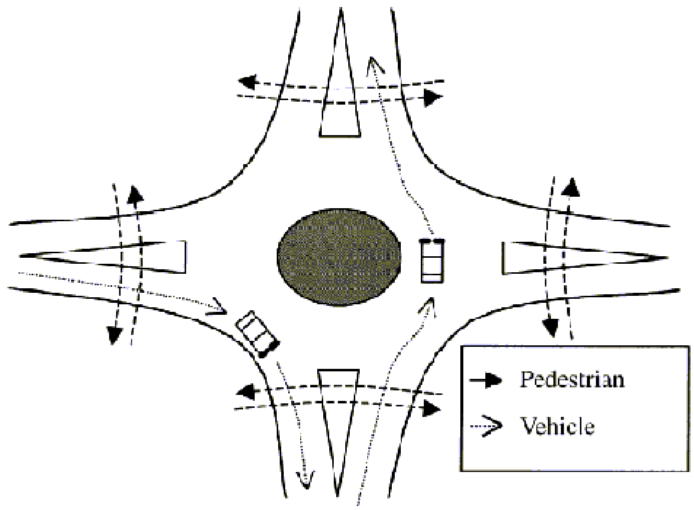
- Define the problem,
- Gather an appropriate amount of data about the problem such that statistical sample size requirements are met,

[5] Elbadrawi, Hesham R. et al. "Pedestrian Crossing Locations at Single Lane Roundabouts." – TRB 79th Annual Meeting, January 2000.

[4] Glauz, W., and Migletz, D., *Application of Traffic Conflict Analysis at Intersections*, National Cooperative Highway Research Program Report 219, TRB, National Research Council, 1980

[5] *Modeling Traffic Flows & Conflicts at Roundabouts*, Mac-Blackwell National Rural Transportation Study Center, February 2000. http://www.cveg.uark.edu/mbtc/research/finals/arc1099/comb1099.html

Figure 2.1 Roundabout Conflicts between Vehicles and Pedestrians



- Apply an appropriate statistical test to the data and interpret the significance of the findings, and
- Document the analysis and findings.

This project presents the problem of characterizing accidents at a specific intersection and determining how roundabout construction at this location will affect the occurrence and severity of these accidents. In the Hillsborough-Horne case a pedestrian accident regression model based on intersection and other characteristics along the Hillsborough corridor is developed. When the proposed reconstruction at the Hillsborough-Horne location changes the intersection characteristics, the model estimates the effects on pedestrian accidents.

Persaud[6] similarly uses a regression model to predict vehicle crashes. In the report published by Kennedy and Hall[7], accident risks at roundabouts were found based on a national stratified sample of 200 three-arm and 100 four-arm urban mini-roundabouts on 30-mph roads. They found that in the accident types reported at both three-arm and four-arm mini-roundabouts, pedestrians formed a small proportion of the accidents. The technique of generalized linear modeling was used to develop relationships between accident frequency and traffic flow, road features, layout, geometry, land use and other variables for different type of accidents.

To test the efficacy of other traffic treatments researchers have used a variety of other statistical tests - point estimates, significance tests and non-parametric tests[8]. A favorite approach employs a "before/after" type of design for such evaluations that implement a preconceived plan like reconstructing an intersection. Before the

[6] Persaud, B.N., R.A. Retting, P.E. Garder, and D. Lord, *Crash Reductions Following Installation of Roundabouts in the United States*, Insurance Institute for Highway Safety, March 2000.
[7] J.V. Kennedy (TRL) and R.D. Hall (University of Southampton) - Accidents at urban mini-roundabouts, TRL Report 281.
[8] The Manual of Transportation Engineering Studies, Chapter 11, Analyzing Accident Data

reconstruction or other improvement accident data is sampled and compared to similar data after the reconstruction.

A 1998 study[9] reports that where roundabouts were installed in the United States, there has been a reduction of 10% to 32 % in the number of vehicle crashes causing only property damage, a reduction in injury crashes of 31% to 73%, and a reduction in fatal crashes of from 29% to 51%. These findings partially support the claim of roundabout advocates[10] that roundabouts are "the safest, most efficient and attractive form of traffic control in the world."

The advantage of statistical analysis is that the results are be very pragmatic and statements about the results of the study can be authoritatively made. This approach gives researchers a chance to generalize the results based on certain correlations. The most obvious disadvantage is the need to collect a large amount of data, which can be costly, time-consuming or impossible. This problem is clearly present in dealing with pedestrian traffic data at U.S. roundabouts and may be continually evident into the future unless appropriate data is collected in advance of and after reconstructions.

Simulation Analysis

A simulation approach is appropriate for projects where evaluation is required despite scarcity of real data. With proper modeling and calibration, a simulation can provide realistic, substitute data in lieu of data collected at an actual intersection. In many cases, computer simulations are more practical than field experiments. The results are obtained quickly and the disruption of traffic operations can be completely avoided.

SIDRA, Corsim, Synchro and Paramics are simulation software products that are popular for the study of pedestrian conflicts and/or accidents**.** The project *Pedestrian and Bicycle Safety at Roundabouts*[2] conducted by the Florida DOT applied SIDRA to evaluate capacity and safety of roundabouts at proposed locations in the state. Since the Florida Roundabout Guide[11] prescribes SIDRA for design of roundabouts, its use for predicting crashes has justifiable veracity.

The City of Fort Collins[12] in Colorado used Paramics, for design and evaluation of safety concerns at a high capacity modern roundabout. Consulting engineers produced a simulation of a proposed, unprecedented, three-lane modern roundabout that was anticipated to handle 8,000 vehicles an hour. The simulation software demonstrated not only how the roundabout would function, but how upstream signalized intersections would generate gaps in the traffic flow approaching the roundabout, and how these gaps would contribute to the operating capacity of the roundabout. The Paramics simulation included trucks and illustrated how traffic flows from proposed driveways at a nearby retail store would be accommodated.

[9] Jacquemart, G., Modern Roundabout Practice in the United States, Synthesis of Highway Practice 264, Washington, D.C., Transportation Research Board, National Research Council, 1998

[10] Wallwork, M., Roundabouts, Information Brief and Design Guide, Alternate Street Design, Inc., Orange Park, Florida, undated.

[11] Roundabout Design Guide, Florida Department of Transportation

[12] http://www.dowlinginc.com/

As part of an urban redevelopment proposal, a preliminary visualization of the traffic operations of a large roundabout was conducted for Petaluma, CA. This particular simulation[12] modeled parking lots.

The showcase project for "walkable communities" in the City of Raleigh is the Hillsborough Street corridor where the case study Hillsborough-Horne intersection is located. In the spring semesters of 2000 and 2001 senior civil engineering students at NC State University class simulated this corridor with and without the proposed roundabouts using Synchro, Corsim and Sidra[13]. The simulation analysis proved to be an effective way to demonstrate the pros and cons of constructing roundabouts for the heavy pedestrian traffic.

Table 2.1 summarizes various simulation software packages and their relevance to pedestrian safety at roundabouts. The Simulation Analysis chapter discusses the pros and cons of each software package in more detail.

Table 2.1. Summary of various Simulation Software Packages

Simulation Software	Pedestrian	Roundabouts	Delay	Safety
CORSIM	X	X	√	X
SYNCHRO	X	√	√	X
SIDRA	X	√	√	X
ARCADY	X	√	√	√
PARAMICS	√	√	√	X
INTEGRATION	X	X	√	X

Legend: X = feature not available, √ = available feature

Summary

The following tables summarize the methods and projects examined by the literature review. Table 2.2 shows requirements and characteristics of each approach considered to be a candidate for this research. As a result of there being no database of before and after pedestrian accident data for even one intersection reconstructed as a roundabout, a blend of the methods will be used in this research as described in the next chapter. Table 2.3 shows what approaches and specific items or interest are addressed by the research project reviewed in this chapter. They serve as valuable guides to the conduct of this research.

[13] NC State University, Department of Civil Engineering, CE 400, www.ncsu.edu/ce_400_info

Table 2.2. Summary Assessment of Methods

Approach	*Input Requirements*				*Output Characteristics*			Cost
	Before/After Data	Quantitative Data	Qualitative Data	Data Required	Descriptive	Generalized	Specific	
Statistical Analysis	√	√	X	≥ 30 samples	X	√	X	**Low**
Case Study Analysis	√	√	√	Not specific	√	X	√	Moderate
Simulation	X	√	X	Not specific	X	X	√	High

Legend: X = feature not available, √ = available feature

Table 2.3. Projects Relevant to Pedestrian Safety at Roundabouts

Research Projects	Case Study Analysis	Simulation Analysis	Statistical Analysis	Pedestrians	Bikes	Vehicles	Conflict Analysis	Safety	Capacity	Geometric
Florida DOT	√	√	X	√	√	X	X	√	X	X
Persaud	X	X	√	X	X	√	X	√	X	X
Elbadrawi	√	√	X	√	X	X	X	X	X	√
City of Fort Collins	√	√	X	X	X	√	X	X	√	√
Hillsborough Street	√	√	X	√	X	√	X	√	√	√
UK	√	X	√	√	√	√	X	√	X	X
California	√	√	X	X	X	√	X	X	√	√
Mac-Blackwell	√	X	√	√	√	X	X	X	√	√
FHWA Report	X	X	x	√	√	√	√	√	√	X

Legend: X = feature not available, √ = available feature

3. Research Approach

The literature review discussed three approaches for assessing the safety impacts of roundabouts on pedestrians. Since the literature review and search for available data revealed no detailed before-and-after data for intersections reconstructed as a roundabout, a single case study will be the focus of the research. By applying a synthesis of case study analysis, regression modeling and simulation the following objectives will be accomplished:

- Estimate the magnitude of pedestrian safety problems at a case study roundabout,
- Determine pedestrian safety impacts for a proposed roundabout and compare results to pedestrian safety at the original signalized intersection,

Methodology

The following methodology describes the research, interim results of the various steps, and the subsequent approach that focuses on a case study intersection.

1. Review and summarize reports and papers that describe international and U.S. experiences with roundabouts and pedestrian safety to provide guidelines for evaluating pedestrian safety at roundabouts.

   Besides finding interesting applications of roundabouts throughout the U.S. and elsewhere, the literature review identified three approaches worthy of consideration depending on the amount of data available: case study and forensic crash analysis, statistical tests and regression analysis, and simulation.

2. Request pedestrian crash information from state departments of transportation.

   Two types of data were sought. The first is before/after pedestrian crash data for intersections retrofitted with roundabouts. The second is accident reports. For each accident case, information regarding the following was desired: level of pedestrian activity; type of nearby development; traffic volumes by movement; pedestrian design treatments; geometric and traffic control treatments; and environmental factors including landscaping, roadway profile, and the like.

   Virtually no cases and accident reports for pedestrian accidents at roundabouts were found after contacting the state and city departments of transportation in North Carolina, Maryland, Florida, Colorado, California, and Oregon. The data search also revealed that compared to vehicle accidents at intersections reconstructed as roundabouts, there are virtually no recorded pedestrian accidents. The paucity of data may be explained by the following: compared to vehicle movements, there is relatively little or no pedestrian activity at the roundabouts documented; roundabouts are relatively new and the databases are still developing; and conventional state and national databases do not adequately distinguish between conventional intersections and roundabouts so that computer searches and police accident report reviews are unproductive. Advocates for roundabouts would also suggest that roundabouts are significantly reducing pedestrian accidents, hence little or no data on such accidents exist.

As a result of the lack of data, the focus of the research shifted to considering a single case study intersection. The case study intersection is the Hillsborough-Horne intersection described as the "front door" to NC State University in earlier sections of this report. Three complementary approaches (case study and forensic crash analysis, regression analysis, and simulation) winnow as much information as possible from the single case to accomplish the research.

3. Quantify the magnitude, frequency and severity of the pedestrian safety problem at roundabouts.

Steps 1 and 2 did not provide the sufficient data for quantifying the magnitude, frequency and severity of pedestrian accidents at roundabouts for the reasons discussed. As a consequence, the methodology shifted to examining accidents at a case study intersection that is under consideration for reconstruction as a roundabout.

4. Conduct crash analyses for a selection of the pedestrian accident cases at roundabouts and intersections. The results can identify probable causes as pedestrian error, driver error, and related factors. This step also provides a contingency strategy for possible sparse data on pedestrian accidents at roundabouts. The information developed by this step will support, augment, or substitute for more complete statistical analyses that follow in Step 5.

The Hillsborough Street corridor near NC State University was selected as the focus of this study. The corridor has high accident rates for both vehicle crashes and pedestrian-vehicle crashes. It is also the subject of community discussion for reconstruction with roundabouts replacing the current signalized intersections.

5. Identify factors that correlate with pedestrian accident causation and safety improvement at roundabouts. Steps 1 through 4 provide the data for the statistical analysis in this task. Factor, correlation, and regression analyses are candidate methods, assuming sufficient data are available. Given sufficient data, Persaud uses an approach adapted from Hauer[1] that accounts for certain crash factors and data issues. The results from this step will indicate the significance (or not) of roundabout design features for improving pedestrian safety.

Accident data for the case study corridor provides the basis for regression analysis of accident data in the Hillsborough corridor. The data and accident reports included 23 conventional four-legged and T-intersections. Over a four-year period from January 1996 to July 1999 there were 879 accidents involving pedestrians, bicycles and vehicles including 25 pedestrian-vehicle crashes (1 fatality), 15 bicycle-vehicle crashes, and 839 vehicle crashes. Available data included police accident reports,

[1] Hauer, E. Observational Before-After Studies in Road Safety. Oxford, England: Pergamon Press, Elsevier Science Ltd., 1997

traffic counts, roadway geometrics, signalization, roadway markings, pedestrian counts at intersections, and vehicle approach speeds. Additional data for the Hillsborough-Horne intersection extends the data base to 1990. Using the data the pedestrian-vehicle crashes were isolated and regressed on pedestrian flows, conflicting vehicle flows, and crossing distance for each approach of each intersection. The resulting regression model is a first step toward a model that can estimate changes in pedestrian accidents if conventional intersections are reconstructed as roundabouts.

6. Develop applicable capacity and simulation analyses to augment the case study and statistical results.

Because pedestrian data are sparse and the success of the regression model of Step 5 is limited, simulation can provide sufficient evidence for conclusions regarding pedestrian safety at roundabouts. Candidate methods for this step include estimating pedestrian level of service with and without roundabout design changes[2,3]. Candidate software packages for the simulation include Corsim, Synchro, Sidra, VSIM and Paramics.

Summary

This chapter outlines the research methodology and gives previews of the outcomes for the steps of the methodology. Subsequent chapters describe the details for the case study forensic analysis, regression accident model, and simulation that are used to compare the proposed roundabout with the existing intersection near NC State University.

[2] Year 2000 Highway Capacity Manual (Draft), NCHRP Project 3-66(6), 1998.

[3] Miller, J.S., J.A. Bigelow, and N.J. Garber, Using 3D Visualization to Calibrate Metrics for Pedestrian Level of Service, Transportation Research Board Paper No. 00-0103, TRB Annual Meeting CD, January 2000.

4. Case Study Analysis

Study Area

Hillsborough Street (Figure 4.1.) is one of the primary arterials connecting downtown Raleigh with Cary, Wake County and the Research Triangle Park. It forms the northern border and traditional "front door" of NC State University. It is a highly traveled corridor consisting of four lanes along most of its length. It serves automobiles, trucks, three bus systems, bicycles, and pedestrians. Hillsborough Street is one of only three major east-west arterials in West Raleigh. Numerous businesses, restaurants and taverns and three educational institutions front the street. Thus, Hillsborough Street sees high pedestrian volumes, making it a highly accident-prone area (Figure 4.2). The intersection at Horne Street is particularly bad (Figures 4.3, 4.4; Tables 4.1a, 4.1b). The pedestrian accident frequency at this site is one of the three or four highest in North Carolina. The reported pedestrian crashes at the Hillsborough-Horne intersection were nine crashes during the period January 1993 to September 1999. These accidents account for approximately 15% of all accidents at the intersection.

While all intersections between Gorman Street and Oberlin Road provide accident and roadway data for the case and regression modeling, the focus area of this research is the Hillsborough–Horne intersection and the roadway within 150 feet of the intersection. The City of Raleigh, NCSU, and the University Neighborhood Association have proposed a roundabout for the intersection (Figures 4.5, 4.6; Table 4.2).

Figure 4.1. Hillsborough Street Corridor

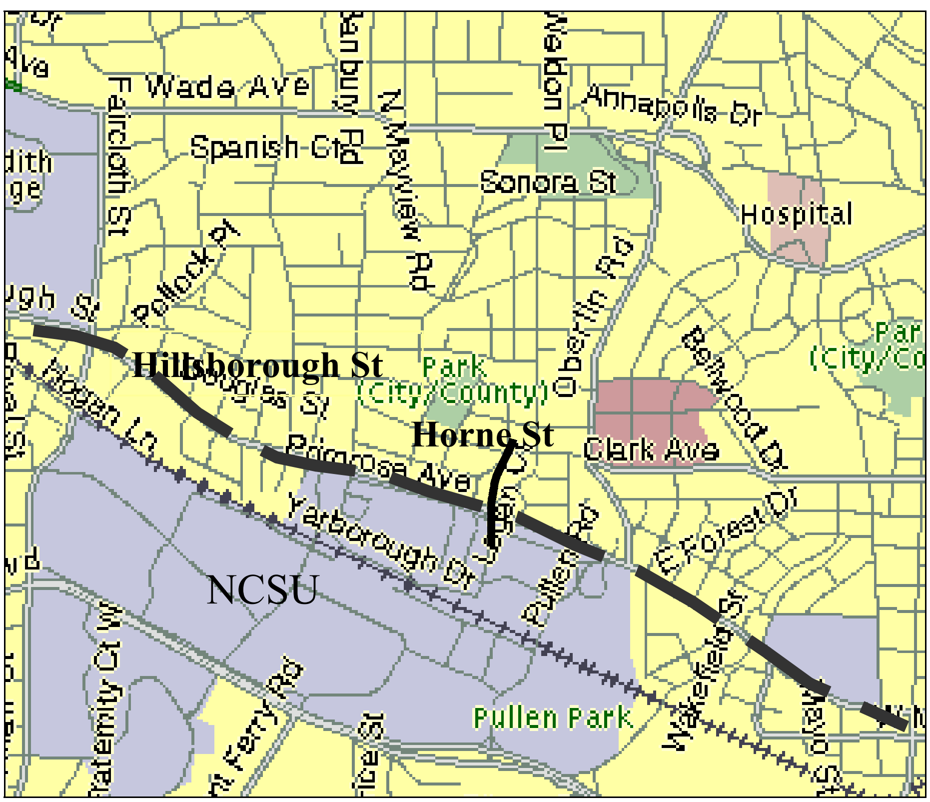


Figure 4.2. Accidents in the Hillsborough Street Corridor (January 1996 - July 1999)

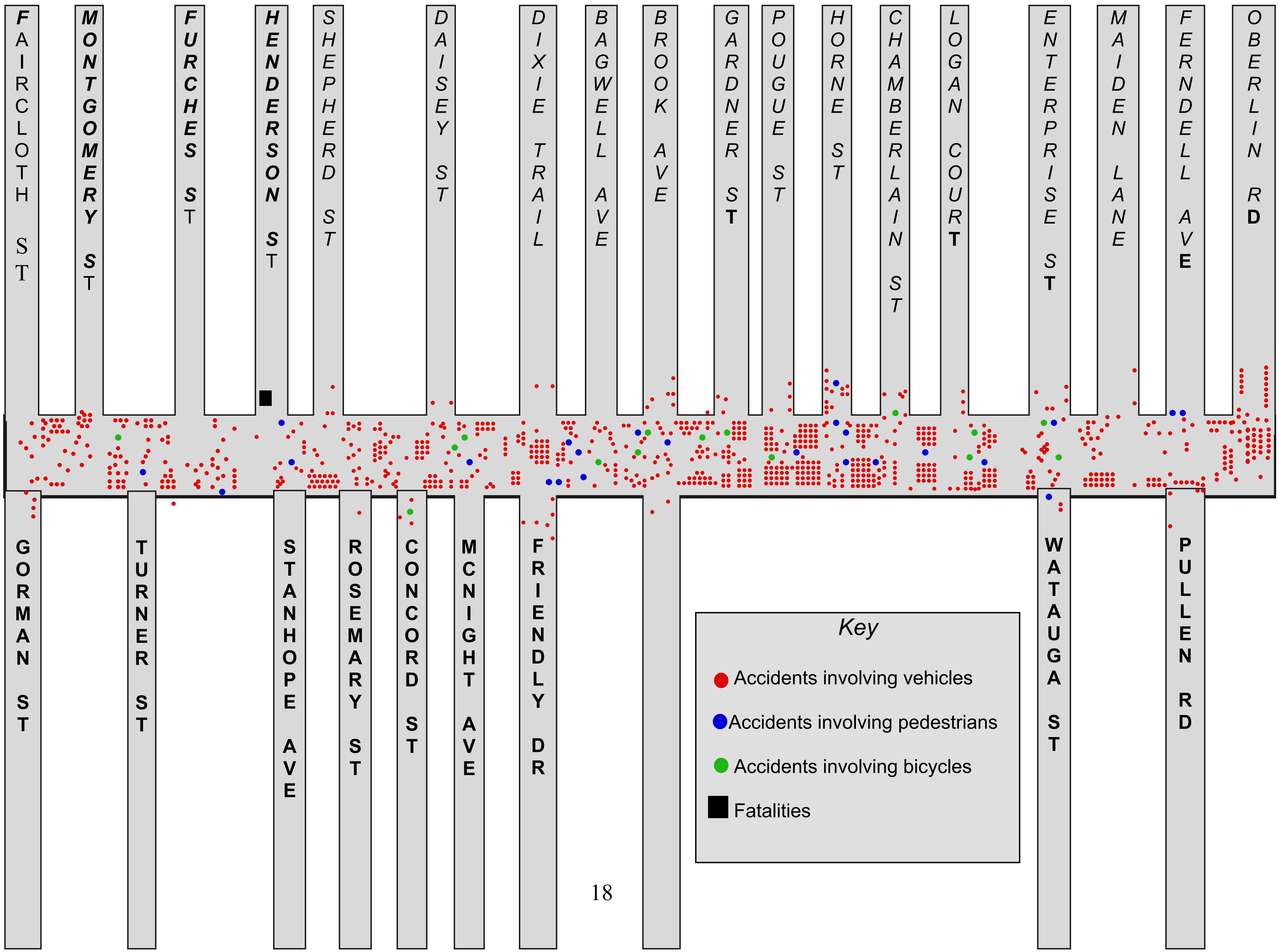


Figure 4.3. Hillsborough-Horne Intersection Pedestrian Crash Locations

Figure 4.4. Existing Intersection at Hillsborough and Horne Streets

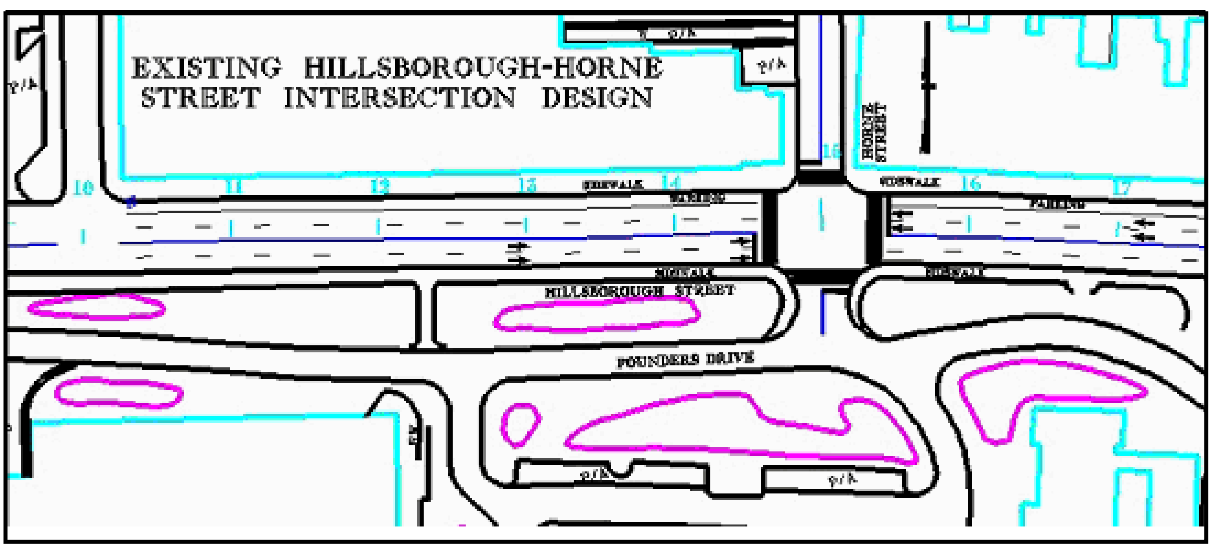


Figure 4.5. Proposed Roundabout for the Hillsborough-Horne Intersection

Figure 4.6. Proposed Roundabout Design for the Hillsborough-Horne Intersection

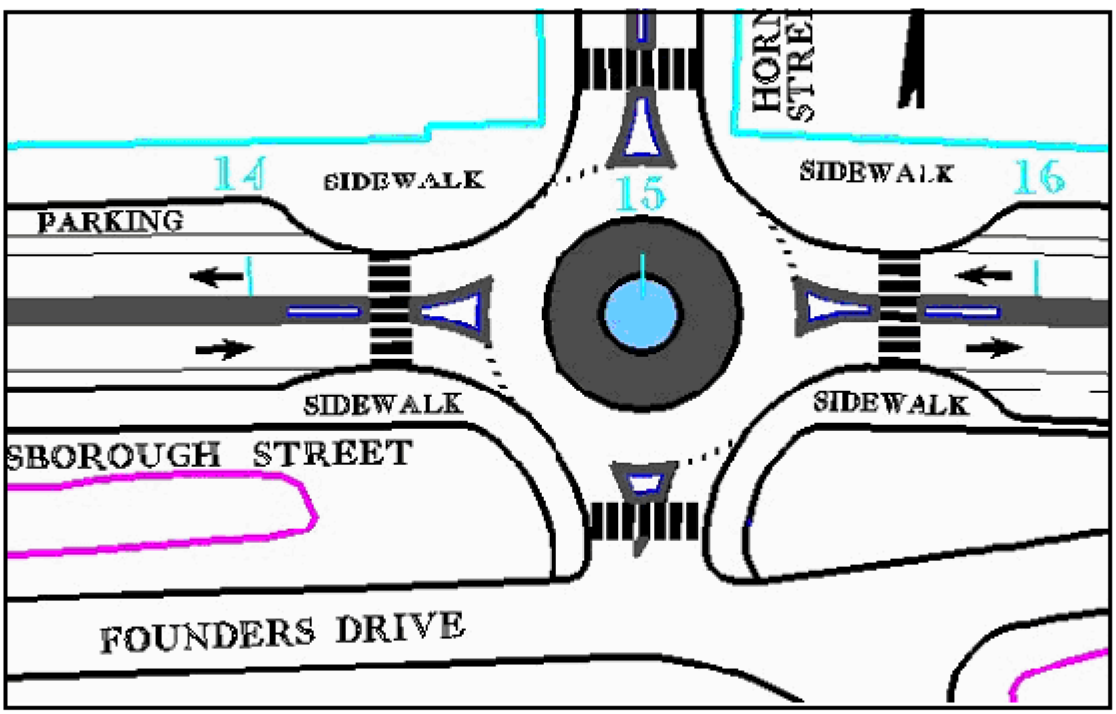


Table 4.1a. Pedestrian Crash Records at the Hillsborough-Horne Intersection

	ID	Date	Time	Vehicle Speed	Crash Location (feet from intersection)	Driving Direction
1	94143511	8-19-1994	23:12	35 mph	Hillsboro St (23)	West
2	94202069	11-11-1994	20:27	35 mph	Hillsboro St (32)	East
3	95038390	2-28-1995	11:15	35 mph	Horne St (5)	North
4	96149963	8-10-1996	2:57	35 mph	Horne St (10)	North
5	96219666	11-11-1996	15:11	35 mph	Horne St (37)	South
6	98007519	1-12-1998	11:41	30 mph	Hillsboro St (4)	East
7	98090881	4-9-1998	15:08	35 mph	Hillsboro St (0)	West
8	98223088	11-16-1998	17:16	15 mph	Horne St (63)	North
9	90125037	8-26-1990	12:51	25 mph	Horne St (0)	South
10	93169886	11-21-1993	14:32	35 mph	Hillsboro St (150)	East
11	94015999	1-26-1994	12:11	35 mph	Hillsboro St (10)	East

Table 4.1b. Pedestrian Crash Records at the Hillsborough-Horne ntersection

	ID	Driver Gender & Race	Driver Age	Pedestrian Age	Pedestrian Gender & Race	Comments
1	94143511	Male, white	20	40	Male, white	None
2	94202069	Hit and Run	n/a	21	Male, white	Hit and run
3	95038390	Male, white	49	21	Male, white	Hit and run
4	96149963	Hit and Run	n/a	23	Male, white	Safe move violation
5	96219666	Male, white	20	28	Male, white	None
6	98007519	Female, white	22	34	Female, white	Unable to determine
7	98090881	Male, white	40	19	Female, black	Stop sign
8	98223088	Hit and Run	n/a	58	Male, n/a	Safe move violation
9	90125037	Female, white	20	22	Female, white	Yield
10	93169886	Male, white	22	42	Male, black	None
11	94015999	Female, white	41	28	Male, white	Yield traffic signal

Table 4.2. Hillsborough-Horne Intersection and Proposed Roundabout Design

Design Parameter	Existing	Proposed Roundabout
Intersection Type	Signalized	Roundabout
Speed Limit	35 mph	20 mph
Number of E/W through lanes	4	2
Traffic Volumes	2400 vph	1800 vph (est. 25 % reduction)
Medians	None	Yes
Though Lane Widths	10 feet	12 feet
Bike Lane Width	0 feet	12 feet
Parking	North Side	North and South Sides
Horne (2 lanes)	SB approach 1-way, NB appraoch 2-way	Two-way NB & SB
Pedestrian-Vehicle Conflicts	12 (Horne 1-way SB & H'boro no LT WB)	8

Crash Analysis

Determination of crash types, contributory factors, and pedestrian-driver behaviors are key elements of a forensic crash analysis. Tasks include reviewing the crash report, reviewing the reporting officer's diagram and narrative, and hypothetically reconstructing the crash and its causes such as:

- Apparent fault or responsibility for the crashes
- Identification of the pedestrians and their age
- Determination of specific and general problems leading to the crash
- Classification of crashes by type
- Identification of specific contributory factors

By comparing the accident locations with the existing intersection and proposed intersection improvements additional information may be evaluated:

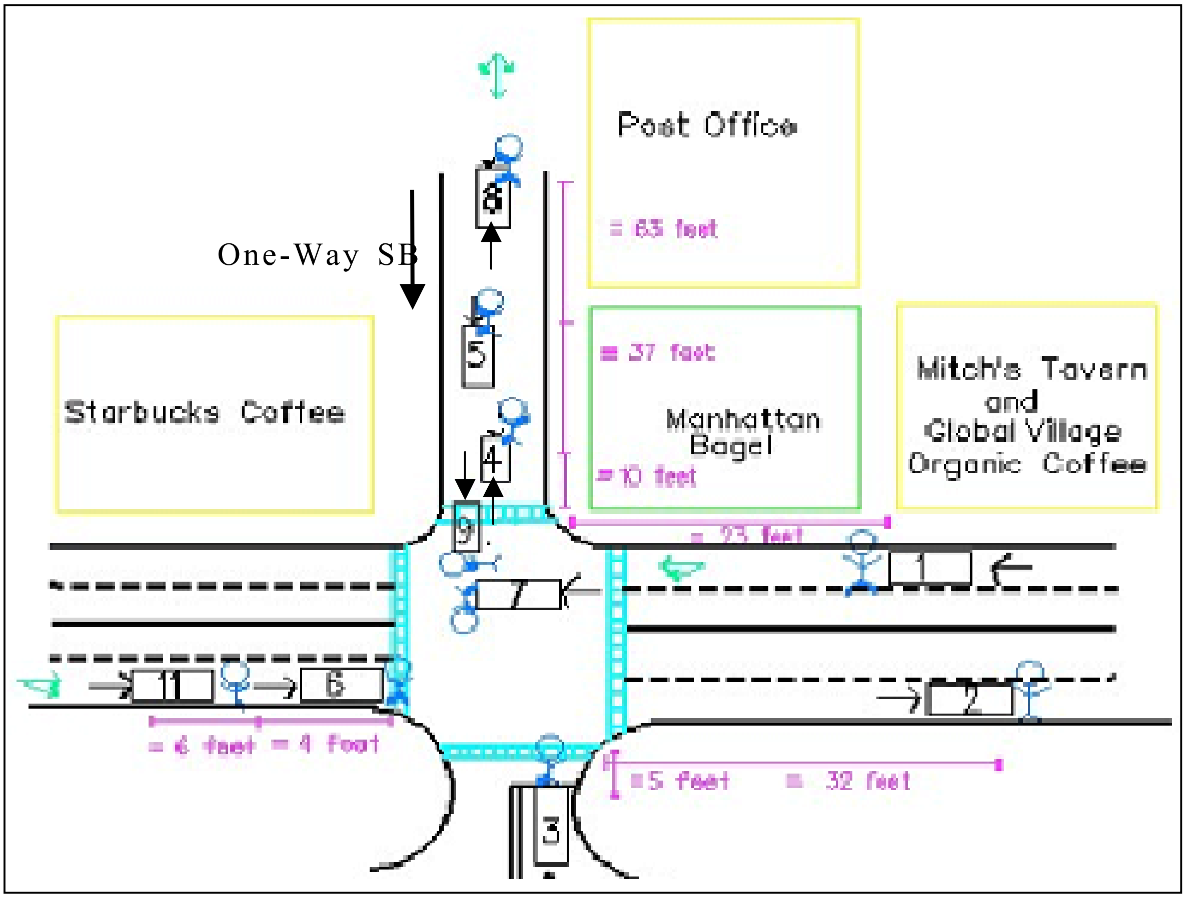
- Increase or decrease in conflict points at the intersection
- Recommendation of countermeasures
- Evaluation of countermeasures to examine their potential effectiveness

Crash Reconstruction

Tables 4.1a and 4.1b summarize police accident reports for eleven pedestrian-vehicle crashes that occurred near the intersection in the period 1990-1998.

Figure 4.7 shows the relative locations of the crashes at the Hillsborough-Horne intersection. It shows three pedestrian-vehicle crashes in the crosswalks (#3, 6, 9), one in the intersection (#7), and six in the approaches to the intersection (#1, 4, 5, 8, 11). Crashes 2 and 10 occurred 32 and150 feet east of the intersection in the eastbound lane. All but three of the crashes occurred outside the confines of the crosswalk area as

Figure 4.7. Hillsborough-Horne Pedestrian Accidents and Locations 1990 - 1998



pedestrians apparently jay walked to shorten crossing distances. Crashes 4 and 8 occurred when cars were traveling the wrong way on a one-way street. Additional details of the crashes are listed in Tables 4.1a and 4.1b.

The following additional factors could potentially contribute to the pedestrian crashes, however, the factors are not obvious from the accident reports and will not be considered in this study.

- Confusion of pedestrian-vehicle right-of-way
- Failure to observe traffic control devices
- Intoxication of driver or pedestrian by alcohol, medication, or illegal substances
- Lack of pedestrian conspicuity (visible, contrasting clothing at night)
- Disobeying traffic control devices and other vehicle ordinances or statutes

Certain changes in design and in pedestrian behavior are also ignored while comparing the safety between the existing and proposed Hillsborough designs.

- The two-lane design of Hillsborough with the proposed roundabout will result in lower traffic volumes and lower traffic speeds. Volume reductions lead to reduced accident exposure, and lower crash speeds lower the severity of accidents.

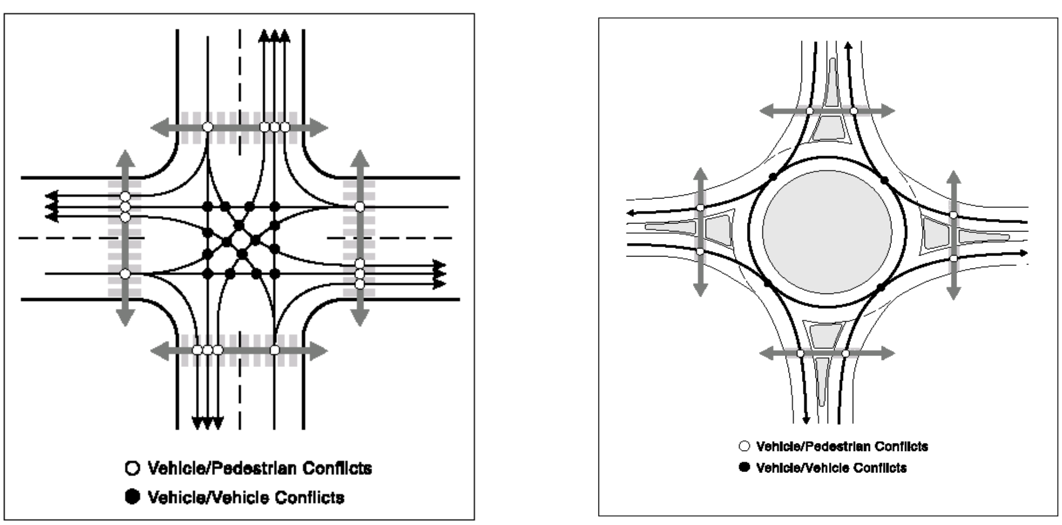
- The existing intersection and the proposed roundabout lie just beyond the crest of a vertical curve, hence, sight distance may have contributed to the original crashes.
- Pedestrians are generally not familiar with roundabouts need to be educated on right-of-way considerations at roundabouts versus conventional intersections. Pedestrians in conventional intersections usually have the right-of-way, while vehicles in roundabouts have the right-of-way.

For this study the main forensic issue to be considered is whether or not the pedestrian-vehicle accident occurred at a conflict Hillsborough-Horne point that could be eliminated by reconstructing the intersection as a roundabout. If the conflict point of the original intersection is eliminated, it is assumed that the accident could be avoided. A secondary consideration is whether or not the overall design of the proposed roundabout including its splitter island with pedestrian refuges and controlled circulatory traffic could have prevented an accident. The number of avoided accidents is assumed to be a measure of improved safety as a result of the roundabout.

In order to compare the safety of the conventional Hillsborough-Horne intersection and the proposed roundabout, the conflict diagrams for each are considered (Figure 4.8). Ideally a roundabout can reduce the number of vehicle–pedestrian conflicts from 16 to 8, however, the one-way southbound Horne approach and no-left turn restriction on Hillsborough reduce the original conflicts to 12 (Table 4.2).

By overlaying roundabout design of Figure 4.6 on the locations of the pedestrian-vehicle crashes of Figure 4.7 and by considering the conflict locations of Figure 4.8, potential improvements in pedestrian safety can be estimated by counting the pedestrian-vehicle accidents that occurred at or near conventional intersection conflict points that are eliminated by the roundabout design.

Figure 4.8. Conflict Points: Intersection vs. Modern Roundabout



Crashes 3, 6, 9 and 11 occurred at or near pedestrian crosswalks that are traditional conflict point locations. Since these conflict points exist for both designs, it may be argued that the accidents might not be avoided in either design. Roundabout advocates would point out, however, that the approach speed would be slower and if the accident occurred, it would likely be less severe.

Crash 7 happened in the north center of the intersection, an area that would be prohibited for pedestrians and vehicles for a roundabout design. It would not likely have happened in the roundabout case.

Crashes 4 and 8 resulted when cars traveled northbound on Horne - a southbound one-way street. The roundabout design would have prevented a left turning eastbound Hillsborough vehicle from making the wrong turn. Furthermore, the roundabout design will have two-way traffic on Horne and pedestrians would expect vehicles traveling northbound.

Crashes 1, 2, 5, and 10 occurred beyond the crosswalk areas and traditional conflict areas of both intersection designs. Thus, the crashes might occur in either case. Note, however, that Hillsborough with the roundabout design would have a two-lane cross-section, that parking would be allowed, and that a bike lane would exist. The crashes happened in the outside lane next to the sidewalk, and the proposed new cross-section would provide a safe buffer area thereby possibly reducing the chances for such crashes.

Table 4.4 summarizes the possible safety effects of the roundabout design at the Hillsborough-Horne intersection. Three of the 11 crashes would likely have been avoided.

Summary

This chapter presented a “sketch” forensic analysis of 11 pedestrian-vehicle crashes at the Hillsborough-Horne intersection near NC State University. Characteristics of the crashes were discussed with respect to whether or not such accidents might be avoided if a roundabout replaces the conventional signalized intersection. Eight of the 11 accidents would still likely occur because they were far enough away that few conditions would be altered by the presence of a roundabout. The three accidents that might have been avoided were directly affected by the roundabout design and control of traffic.

For the accidents that might have occurred, their severity would be less because of decreased speeds dictated by a roundabout. Additional safety enhancements might occur because of the pedestrian refuge offered by the splitter islands, the reduced cross-section from four lanes to two lanes, and the pedestrian buffer offered by parked cars and bike lanes in the roundabout design.

Possible negative effects on pedestrian safety from the roundabout design might occur from right-of-way confusion and uncertain cues for sight impaired pedestrians.

Table 4.3. Safety Effects of the Proposed Roundabout Design

	ID	Would accident happen with a roundabout?	Comments
1	94143511	Yes	Too far from proposed roundabout
2	94202069	Yes	Too far from proposed roundabout
3	95038390	Yes	Unavoidable conflict point
4	96149963	**No**	Wrong way approach avoided
5	96219666	Yes	Too far from proposed roundabout
6	98007519	Yes	Unavoidable conflict point
7	98090881	**No**	Central no-traffic area
8	98223088	**No**	Wrong way approach avoided
9	90125037	Yes	Unavoidable conflict point
10	93169886	Yes	Too far from proposed roundabout
11	94015999	Yes	Unavoidable conflict point

5. Statistical Analysis

Introduction

As discussed in the literature review chapter, before/after statistical tests can be used to gauge the effect of roundabout design on intersection safety compared to conventional signalized intersections. However, these tests require a valid sample of data for one or more of intersections reconstructed as roundabouts. An alternative to a statistical test is a regression model relating design parameters between intersections and roundabouts. By changing the design parameters of the conventional intersection to the expected design parameters of a proposed roundabout, an indication of any safety improvements may be estimated. The regression approach applied to a hypothetical change compared to the statistical test of an actual before and after change is a less desirable, weaker indication of the safety potential of a roundabout. However, the lack of local and national data for reconstructed roundabouts compels the regression approach. This chapter applies it to the Hillsborough-Horne case using the data for pedestrian accidents, vehicle traffic and intersection designs of neighboring intersections in the Hillsborough corridor.

Methodology and Results

Collecting pedestrian accident data from the Hillsborough corridor began the task to develop the pedestrian crash model. According to Figure 4.2 there are 24 pedestrian crashes in the 1996 – 1999 time period. Table 5.1 shows summary statistics of 43 pedestrian accidents for the 1990 – 1998 time period including the 11 documented pedestrian accidents at the Hillsborough-Horne intersection (Chapter 4).

For the roundabout alternative, a change in cross section along Hillsborough Street from four lanes to two lanes occurs at the Hillsborough – Horne intersection. This change suggests that the model be disaggregated to predict the number of collisions per year on each leg of the intersection, and not just on the intersection as a whole. This process yields more data points on which a regression analysis can be performed, but smaller accident frequencies to use in the regression for each location. The data (Table 5.1) formed the basis for a traditional regression analysis to predict pedestrian accidents versus traffic data and intersection designs in the corridor. The resulting model for the proposed design for the Hillsborough-Horne roundabout estimated the safety impacts on pedestrians.

The available data provided six factors related to geometrics and traffic that may be correlated to the number of collisions for the intersections and proposed roundabout. Those six factors are: pedestrian volumes, conflicting traffic flows, crossing distances, lane widths, number of lanes, and the presence of on-street parking. An initial regression analysis relating each factor individually to pedestrian-vehicle crashes showed that the first three factors from the above list had the highest correlation to collisions. Further step-wise regression of the three most correlative factors to pedestrian crashes (Table 5.2) yielded a composite model of the following form:

$$C = (4.56 \text{ Peds} + 2.00 \text{ VPH} - 3.00 \text{ Dist}) \times 10^{-4}$$

where,

C = predicted annual pedestrian-vehicle crashes
Peds = pedestrian flows on one leg of the intersection in the peak hour
VPH = conflicting vehicle flows in the peak hour
Dist = maximum street crossing distance

This model allowed the prediction of pedestrian crashes at the Hillsborough-Horne intersection given changes resulting from the proposed roundabout design. The estimated impacts of the roundabout design are shown in Table 5.3.

Table 5.1. Summary Pedestrian Accident Data 1990 - 1998

Location	Pedestrian Collisions	Time Period	Collisions per year	Pedestrian Flows	Conflicting Traffic (VPH)	Maximum Crossing (ft)	Lane Width(min)	Number of Lanes	On Street Parking 0=none, 1 = Yes
Horne N of Hillsboro	4	8	0.5	415	221	30	10	1	0
Horne S of Hillsboro	1	8	0.125	145	306	30	10	2	1
Hillsboro E of Horne	3	8	0.375	331	2118	48	10	4	1
Hillsboro W of Horne	3	8	0.375	372	2152	48	10	4	1
Dixie N of Hillsboro	0	5	0	55	373	30	10	3	0
Friendly S of Hillsboro	1	5	0.2	35	263	30	10	3	0
Hillsboro W of Dixie	4	5	0.8	5	2157	50	12	4	0
Hillsboro E of Dixie	4	5	0.8	21	2269	50	10	5	0
Dan Allen S of Hillsboro	0	5	0	149	423	30	10	3	0
Hillsboro W of Dan Allen	2	5	0.4	6	2156	60	10	6	0
Hillsboro E of Dan Allen	2	5	0.4	159	2086	50	10	5	0
Brooks N of Hillsboro	1	5	0.2	145	585	32	10	3	0
Brooks S of Hillsboro	0	5	0	92	376	24	12	2	0
Hillsboro W of Brooks	2	5	0.4	89	2133	50	10	5	0
Hillsboro E of Brooks	1	5	0.2	64	1981	50	10	5	0
Gardner N of Hillsboro	0	5	0	144	156	25	12	2	0
Gardner S of Hillsboro	0	5	0	120	116	25	12	2	0
Hillsboro W of Gardner	3	5	0.6	200	1804	48	10	4	0
Hillsboro E of Gardner	1	5	0.2	124	1765	48	10	4	1
Pogue N of Hillsboro	0	5	0	250	132	30	12	1	1
Hillsboro W of Pogue	1	5	0.2	113	1935	48	10	4	1
Hillsboro E of Pogue	2	5	0.2	133	1875	48	10	4	1
Chamberlain N of Hillsboro	1	5	0.4	472	162	30	12	1	0
Hillsboro W of Chamberlain	3	5	0.6	26	1758	48	10	4	1
Hillsboro E of Chamberlain	4	5	0.8	423	2034	48	10	4	1

Table 5.2. Stepwise Correlation of Pedestrian-Vehicle Crashes

Model	Variables	R^2	Y- Intercept
1	Pedestrian Crashes vs. Traffic	0.41	0.074
2	Pedestrian Crashes vs. Pedestrian Flows	0.021	0.265
3	Pedestrian Crashes vs. Crossing Distance	0.40	-0.304
4	Pedestrian Crashes vs. Traffic & Crossing Distance	0.41	-0.061
5	Pedestrian Crashes vs. Traffic & Ped Flows	0.47	-0.018
6	Pedestrian Crashes vs. Pedestrian Flows & Crossing Distance	0.47	-0.429
7	Pedestrian Crashes vs. Traffic & Ped Flows & Crossing Distance	0.48	-0.208
8	Pedestrian Crashes vs. Traffic & Pedestrian Flows & Crossing Distance (with Y-intercept = 0)	0.47	0

Table 5.3. Predicted Pedestrian Crashes for the Proposed Roundabout

Roundabout Leg	**Peak Ped Flows** (peds/hr)	**Conflicting Vehicle Traffic** (vph)	**Max Crossing Distance** (feet)	**Estimated Ped Crashes** (crashes/yr)	**Actual Ped Crashes** (Table 5.1) (crashes/yr)
Horne N of Hillsboro	415	166	13	0.219	0.50
Horne S of Hillsboro	145	230	13	0.108	0.125
Hillsboro E of Horne	331	1589	13	0.465	0.375
Hillsboro W of Horne	372	1614	13	0.489	0.375
Total (crashes per yr)				1.28	1.37
Reduction				7.5%	

Summary

Implementation of the model to the proposed roundabout predicts 1.28 collisions per year that represent a 7% reduction in pedestrian-vehicle crashes for the actual rate of 1.37 annual crashes. Small sample size statistics suggest a minimum sample of at least 25 to 30 data points. While the 43 data points of this analysis satisfy that threshold, the relatively low R^2 coefficient of about 0.50 indicates that only half of the pedestrian accidents are "explained" by the model variables. Besides pedestrian flows, conflicting traffic volumes, and crossing distance, other variables such as those discussed in Chapter 4 affect pedestrian accidents. At best the regression model for the Hillsborough-Horne location shows the relative improvement in pedestrian that a roundabout design might contribute compared to a conventional intersection. The results of the regression analysis are generally consistent with the case study results of the conflict analysis. The regression model predicts a 7% reduction and the case analysis suggests that three accidents of 11 would be avoided. If the two wrong-way accidents are eliminated from the case, one in 11 accidents would be avoided, a 9% reduction.

6. Simulation Analysis

Introduction

Recent U.S. studies have shown that roundabouts enhance vehicle safety compared to other types of intersections[6]. Yet, pedestrian safety enhancements are not documented by research as are those for vehicles. However, anecdotal evidence is promising.

The reduction in accidents is attributed to slower speeds in the conflict areas and to the reduced number of vehicle-to-pedestrian conflict points from 16 to 8 (Figure 4.8). Perhaps most importantly, the opposing left turn, which is the cause of most fatal or serious pedestrian accidents at intersections, is eliminated. Also, lower speed limits approaching roundabouts ensure lower risk and severity of pedestrian accidents (Figure 1.3). Furthermore, the division of the pedestrian crossing into two stages with the splitter island acting as a mid-street refuge (Figure 4.6). The splitter island allows pedestrians to focus on crossing one direction of the traffic stream at a time, and it removes the pedestrian from conflict areas where they might be hit by a vehicle. Single-lane roundabouts may be safer than any other type of intersection for pedestrians[7]. Pedestrians with vision disabilities, however, may have difficulty judging gaps in the traffic stream from auditory cues.

Tudge in Australia, Stuwe in Germany, and Persaud in USA have conducted vehicle accident studies on roundabouts. Their before-and-after studies have shown modern roundabouts are safer for vehicles than conventional four-way intersection. Their studies suggest that roundabout installation should be strongly promoted as an effective safety treatment for intersections. However, there is no clear evidence for improved safety for pedestrians. As evidence of improved pedestrian safety, most studies usually point to lower roundabout speeds that decrease severe injuries and deaths of pedestrians and to fewer conflict points. Generally research about pedestrian safety attempts to find the frequency of pedestrian accidents and severity of injuries. However, it is difficult to obtain results due to the infrequency of pedestrian accidents and other possible contributing factors such as speed limit, street design features, weather, driver and pedestrian age and gender, and presence of drugs or alcohol in the drivers or pedestrians involved in accidents[8].

To overcome the paucity of pedestrian safety research for roundabouts, this report applies simulation analysis in addition to the case study analysis and regression analysis of previous chapters. Again, the analysis compares the Hillsborough-Horne signalized intersection with pedestrian signals to a "replacement" roundabout. The focus is pedestrian capacity because roundabouts usually do not provide pedestrian priority or

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[6] Crash Reduction Following Installation of Roundabouts in the United States, Insurance Institute for Highway Safety, March 2000.

[7] Nordic Road & Transport Research Report No. 2 2000, Swedish National Road & Transport Research Institute (VTI).

[8] W.A. Leaf & D.F. Preusser. Literature Review on Vehicle Travel Speeds and Pedestrian Injuries. Nov. 1999.

pedestrian signals according to accepted design guidelines[9]. Rather, they encourage pedestrians to identify gaps in traffic and to cross when acceptable gaps are available.

At conventional intersections, pedestrian signals protect pedestrians when volumes are heavy. Usually pedestrian signals consist of the illuminated words WALK and DON'T WALK, and/or the illuminated symbols of a walking person and an upraised hand. Pedestrian signals assign right-of-way in a similar way as vehicular signals do and they guarantee adequate crossing time. If a pedestrian signal at a signalized intersection guarantees that pedestrians can cross safely in the crosswalk, then the maximum pedestrian capacity at a roundabout should be compared with that of a signalized intersection. This analysis makes that comparison when pedestrians cross the proposed roundabout (space sharing) and when they cross the existing signalized intersection (time sharing) at Hillsborough and Horne Streets.

To determine the relative safety of the two intersection designs the following assumption is made:

> If a simulated roundabout handles crossing pedestrians that are equal to or greater than those crossing at a conventional intersection, the roundabout is safer because the slower traffic speeds and fewer conflict points result in accidents that are less severe and less likely to result in death.

Methodology

For various traffic and pedestrian volumes a simulation analysis permits calculations of maximum pedestrian capacity (MPC) at the multilane, signalized Hillsborough-Horne intersection and its proposed replacement roundabout. The simulation also allows sensitivity analysis of pedestrian capacity at the roundabout versus vehicular demand to reflect changing traffic volumes that will occur if the roundabout replaces the case study intersection. The simulation parameters used in this analysis come from various studies[10, 11, 12, 13]. Hypotheses of the simulation, decision rules, and data follow:

- Signalized Intersection without Flashing Don't Walk (FDW)

$$Nped = T \div \lambda \qquad (1)$$

$$T = C \times Gw \qquad (2)$$

$$Gw = Gv - \alpha \text{ and } Gw \geq t \qquad (3)$$

$$t = L \div \beta \qquad (4)$$

where:

$Nped$ = maximum pedestrian capacity, pedestrians per hour;

[9] Roundabouts: An Information Guide, USDOT, FHWA, Pub. No.: FHWA-RD-00-067, June 2000.
[10] Transportation Research Board.(1997). Highway Capacity Manual. TRB, National Research Council, Washington, DC
[11] Transportation Research Board.(2000). Highway Capacity Manual. TRB, National Research Council, Washington, DC
[12] A New Vision for Hillsborough Street, Prepared by Walkable Communities, Inc. for the Hillsborough Street Partnership, October 26, 1999.
[13] Wasserson, D. Hillsborough Street Roundabout Study of Traffic Diversion Due to Roundabout, NCSU 2000.

T = maximum pedestrian crossing time, sec;
λ = minimum headway of pedestrian during an interval, sec/ped;
C = total cycles during one hour ;
Gw = WALK Interval, sec;
Gv = green time for vehicle, sec;
α = pedestrian start-up time, sec;
t = average time spent by pedestrian on the crosswalk, sec;
L = length of the crosswalk, ft; and
β = pedestrian walking speed , ft/sec.

- Signalized Intersection with FDW

$$Nped = T \div \lambda \quad (5)$$
$$T = C \times Gf \quad (6)$$
$$Gf = Gp - FDW - \alpha \quad (7)$$
$$Gf \geq t \quad (8)$$

where:

Gf = effective WALK Interval with FDW, sec;
Gp = green time for pedestrian, sec; and
FDW = Flashing Don't Walk time, sec.

- Roundabout with splitter island

$$Nped = Tr \div \lambda \quad (9)$$
$$Tr = Min\left[\sum Gi, \sum Go\right] \quad (10)$$
$$Gi = g - (\alpha + It) \quad (11)$$
$$Go = g - (\alpha + Ot) \quad (12)$$
$$g \geq \alpha + It \text{ and } g > T\min \quad \text{and}$$
$$g \geq \alpha + Ot \text{ and } g > T\min \quad (13)$$
$$It = Ll \div \beta \quad \text{and}$$
$$Ot = Lr \div \beta \quad (14)$$
$$T\min = PIEVd + (V \div 2a) \quad (15)$$

where:

$Nped$ = maximum pedestrian capacity, ped;
Tr = maximum pedestrian crossing time at roundabout, sec;
λ = minimum headway of pedestrian during an interval, sec/ped;
Gi = acceptable gap at inbound direction, sec;
Go = acceptable gap at outbound direction, sec;
g = gap between vehicles or platoons, sec;
$T\min$ = minimum stopping time, sec;
$PIEVd$ = driver PIEV time (2.5), sec;
V = posted limit speed or actual operating speed, mile/h; and
a = deceleration rate, mpss.

Study Area

Hillsborough Street, as described in Chapter 4, is one of the primary arterials connecting downtown Raleigh with Cary, western Wake County and the Research triangle Park. For this reason, it carries heavy local and through traffic. Numerous local businesses and two educational institutions on the street contribute to high pedestrian volumes, making it a highly accident-prone area. Indeed, the Hillsborough-Horne intersection is the fourth worst intersection in the state on the basis of pedestrian accidents.

If proposed street improvements occur, pedestrian movements at the case study intersection of Hillsborough and Horne Streets would be converted from protected, signalized crossings at the multilane signalized intersection to unprotected crossings at a single-lane roundabout[6]. The existing Hillsborough Street cross-section with four through lanes and parking would become two through lanes with parking and bike lanes. The vehicle volumes (traffic demand) on Hillsborough Street are expected to decrease by 25% to 30% as lanes and capacity decrease[7].

Simulation Program

Traffic simulation models can be used to evaluate the performance of proposed intersections including roundabouts. Advantages include the ability to assess vehicles arriving in platoons from upstream signals, queue spillback into the roundabouts from downstream signals, signalization of a leg of the roundabout, and the relation between pedestrian and vehicle flow. Five commercially available microscopic simulation models are available: CORSIM, Integration, SimTraffic, VISSIM, and Paramics. This study uses Paramics because it models roundabouts explicitly rather than by a set of one-way, stop-controlled links. The empirical method used by Paramics has been used in the United Kingdom and internationally for a wide range of simulation projects. It has been favorably compared with ARCADY for evaluating roundabouts[14].

Case Study Data and Simulation

The Hillsborough-Horne intersection is currently a traditional signalized intersection that may become a roundabout if proposed plans progress. Hillsborough Street has four 10-foot lanes. The limit speed is 35 mph. North of Hillsborough Horne Street has two one-way southbound lanes. South of Hillsborough Horne has two-way lanes. According to the improvement plan, the Hillsborough Street limit speed will decrease to 20 mph and there will be two 12-foot lanes (Table 6.1). The roundabout will have a 13-foot diameter inscribed circle with splitter islands (Figure 6.1).

The improvement plan estimates that about 25%-30% of the Hillsborough Street traffic will be diverted to parallel routes after installing the roundabout leaving 70%-75% of the original traffic on Hillsborough to pass through the roundabout. The Paramics simulation (Figure 6.2) includes diverted traffic cases from 50% to -25% (50% decrease to 125% increase) to test varying Hillsborough traffic demand (Table 6.2) on pedestrian capacity. Also the simulation includes several experiments and sensitivity analyses to determine the effect of pedestrian reaction time and walking speed on pedestrian capacity at the existing intersection and the proposed roundabout. It is assumed that reaction time and walking speed increase as traffic increases and gaps decrease (Table 6.3). Pedestrians may have different crossing characteristics depending on whether they are

[14] Paramics, Ltd. Comparison of Arcady and Paramics for Roundabout Flows, August 1993.

males or females, visually or physically impaired, or young or old[15]. So this study examined a range of expected pedestrian reaction times and walking speeds. However, reaction time in the simulation is the key factor because of its close relationship to what crossing pedestrians find as acceptable gaps between vehicles or platoons. The simulation confirms that the estimated traffic diversion will be 25%-30%, and that for this range of traffic demand the appropriate pedestrian reaction time is about 3.2 sec and the walking speed is about 4.0 ft/sec (Table 6.3). For this reasonable pedestrian reaction time and walking speed the simulation determines the effects on roundabout pedestrian capacity of varying Hillsborough traffic demand, and how the roundabout pedestrian capacity compares to that for the signalized intersection with and without "flashing don't walk" (FDW) controls.

Table 6.1. Case Study Data

Parameter	Signalized Intersection	Roundabout
Speed Limit (mph)	35	20
Number of Through Lanes	4	2
Lane Width (ft)	10	12
Hillsborough Traffic (vph)	2400 (3000*)	~
Horne Traffic (vph)	400*	~
Hillsborough Pedestrian Crossings (peds/hr)	700*	~
Horne Pedestrian Crossings (peds/hr)	560*	~

* Chapter 5

Table 6.2. Case Study Demand

	Roundabout							Signalized Intersection
Traffic Demand*	50%	55%	65%	75%	85%	100%	125%	100%
Traffic Demand (veh/hr)	1202	1322	1562	1802	2043	2403	3004	2403

* Compared to the base year 2000 traffic of the Hillsborough Street signalized intersection

Table 6.3. Simulation Conditions

Traffic Demand	50%	55%	65%	75%	85%	100%	125%
Ped. Reaction Time (sec)	2.5	3.0	3.2	3.5	4.0	4.5	7.0
Walking Speed (sec)	2.5	3.0	3.5	4.0	4.5	5.0	5.5

[15] Rouphail, N., Hummer, J.E., Literature Synthesis for Pedestrians, Chapter 3, Highway Capacity Manual, Feb. 1998.

Figure 6.1. The Proposed Roundabout

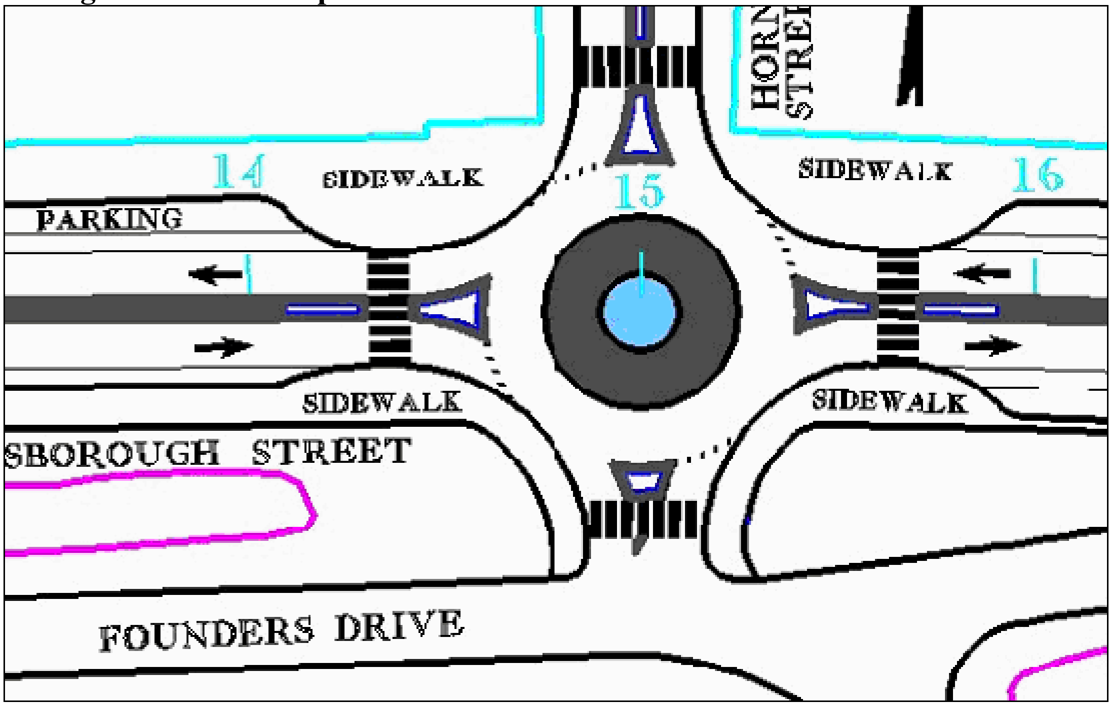
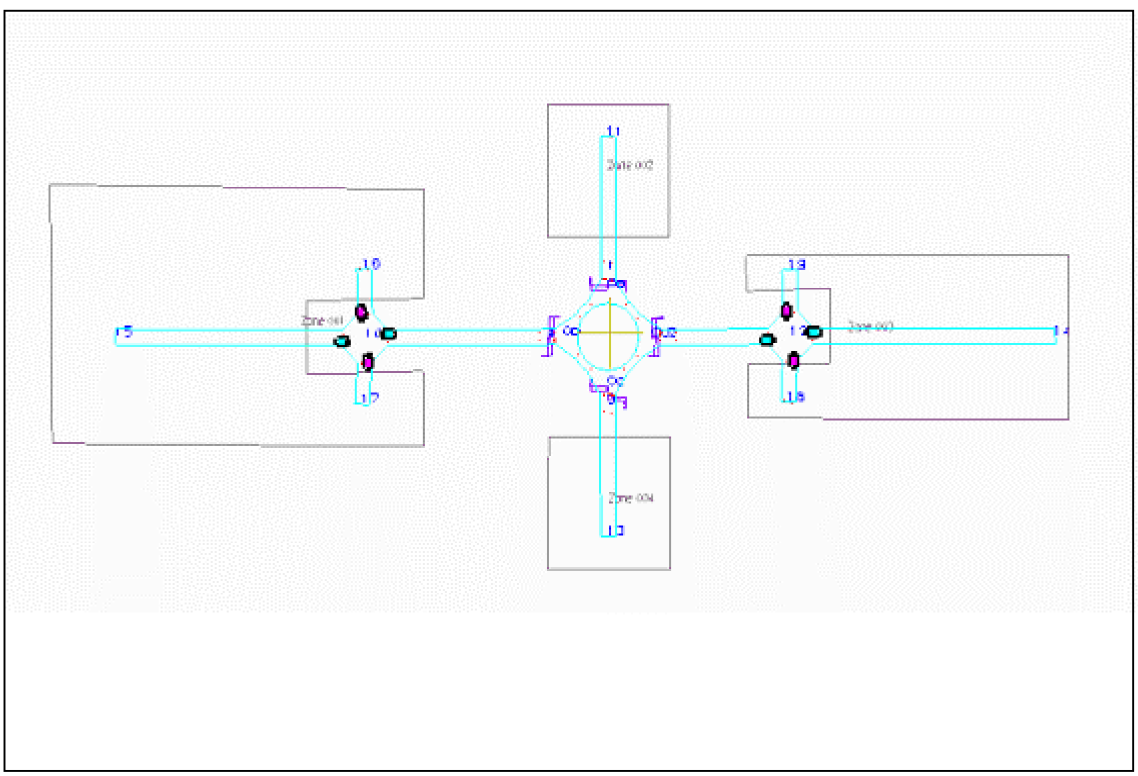


Figure 6.2. Roundabout Analysis Network



Results

The simulation uses various Hillsborough traffic volumes (demand) to define roundabout traffic. Results indicate that the single-lane roundabout will have the same pedestrian capacity as the original signalized four-lane intersection with FDW when the roundabout volume is about 70% of the year 2000 Hillsborough Street traffic (Table 6.4, Figure 6.4). This result implies that pedestrian safety at the new roundabout will be improved compared to the original signalized FDW intersection because there are fewer vehicle-pedestrian conflicts and vehicle speeds are lower. If there is no FDW pedestrian control the signalized intersection can process more pedestrian crossings, and the equivalent vehicle demand volume for the roundabout must drop to about 65% of the original Hillsborough volume to allow more roundabout pedestrians to cross. The seemingly counterintuitive observation that the FDW intersection has a lower pedestrian capacity than the no-FDW intersection is explained by the shorter crossing interval allowed by FDW. This finding tends to argue for an unsignalized roundabout and its lower pedestrian reaction time of about 3.2 sec.

Sensitivity Analysis

Several sensitivity analyses were conducted. The worst case is 0 at a traffic volume dema nd 125% of the base Hillsborough traffic, an adjusted walking speed 2.5 ft/sec, and a ped estrian reaction time 7.0 sec. The best case is 3,231 pedestrians per hour at demand 50%, adjusted walking speed 5.5 ft/sec, and reaction time 2.5 sec. Table 6.5 shows the case of 6 5% demand. This result indicates that pedestrian capacity varies from 641 to 1,806 pedest rian per hour depending on reaction time and walking speed. It also shows the pedestrian capacity of 1,499 pedestrians per hour for this study using a walking speed of 4.0 ft/sec a nd reaction time 3.2 sec. Figure 6.5 shows all sensitivity analysis results. These results ca n provide other assumed pedestrian factors for other simulation cases.

Summary

This chapter developed a formula for calculating maximum pedestrian capacity (*Nped*) and showed the results of a microscopic simulation program to calculate maximum pedestrian capacity for a roundabout and for an intersection with and without "flashing don't walk" controls. Simulation conditions included varying traffic demand, pedestrian reaction time, and pedestrian walking speed.

Previous chapters suggested that the proposed roundabout may offer safety benefits over the existing signalized intersection at Hillsborough and Horne Streets for the following reasons: reduced conflicts, decreased chances of wrong-way vehicle operation, reduced walking distance, pedestrian refuge islands, and lower approach speeds.

This chapter examined the effects of vehicle volumes, reaction time, and walking speed on roundabout safety. The results suggest that if pedestrian volumes are comparable at the original signalized intersection and the replacement roundabout, and if traffic volumes through the roundabout are lower than the original signalized intersection, pedestrian safety may be better with the roundabout because roundabout traffic speeds are lower and conflicts are fewer. However, if traffic volumes through the roundabout exceed about 75% of the original signalized intersection volumes, a replacement roundabout will not meet pedestrian capacity, and pedestrian safety may suffer. For example, when pedestrian demand reaches capacity, people may try to cross without sufficient vehicle gaps. However, at or below intersection pedestrian capacity, roundabouts are likely safer for pedestrians than traditional intersections for three reasons:

- roundabouts can handle the same or higher pedestrian capacity as a traditional intersection,
- roundabouts have fewer pedestrian-vehicle conflict points, and
- any pedestrian crashes would involve lower impact speeds.

If pedestrian volumes exceed the intersection pedestrian capacity, special treatments will be needed for pedestrians such as crosswalks, all motorists would be required to yield to pedestrians, and/or pedestrian signals including enunciators.

Table 6.4. Maximum Pedestrian Capacity*

Traffic Demand (%)	50	55	65	67	75	80	85	90
With FDW (ped/hr)	1067	1067	1067	1067	1067	1067	1067	1067
Without FDW (ped/hr)	1387	1387	1387	1387	1387	1387	1387	1387
Roundabout (ped/hr)	2816	2457	1499	1226	818	16	0	0

* Walking speed = 4.0 ft/sec, reaction time = 3.2 sec

Table 6.5. Pedestrian Capacities (ped/hr) at 65% Traffic Demand (no FDW)

		Reaction Time (sec)						
		2.5	3.0	3.2	3.5	4.0	4.5	7.0
Walking Speed (ft/sec)	2.5	1,302	1,218	1,185	1,135	1,057	980	641
	3.0	1,443	1,353	1,319	1,268	1,185	1,103	737
	3.5	1,550	1,456	1,419	1,365	1,280	1,197	814
	4.0	1,635	1,536	1,499	1,443	1,353	1,268	875
	4.5	1,704	1,601	1,562	1,505	1,412	1,325	925
	5.0	1,759	1,656	1,615	1,555	1,462	1,370	965
	5.5	1,806	1,701	1,659	1,598	1,502	1,410	998

Figure 6.3. Average Roundabout Speed vs. Traffic Demand

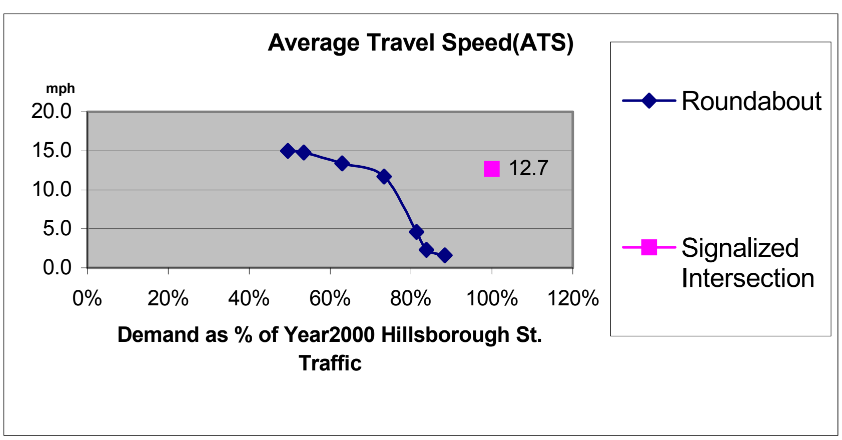
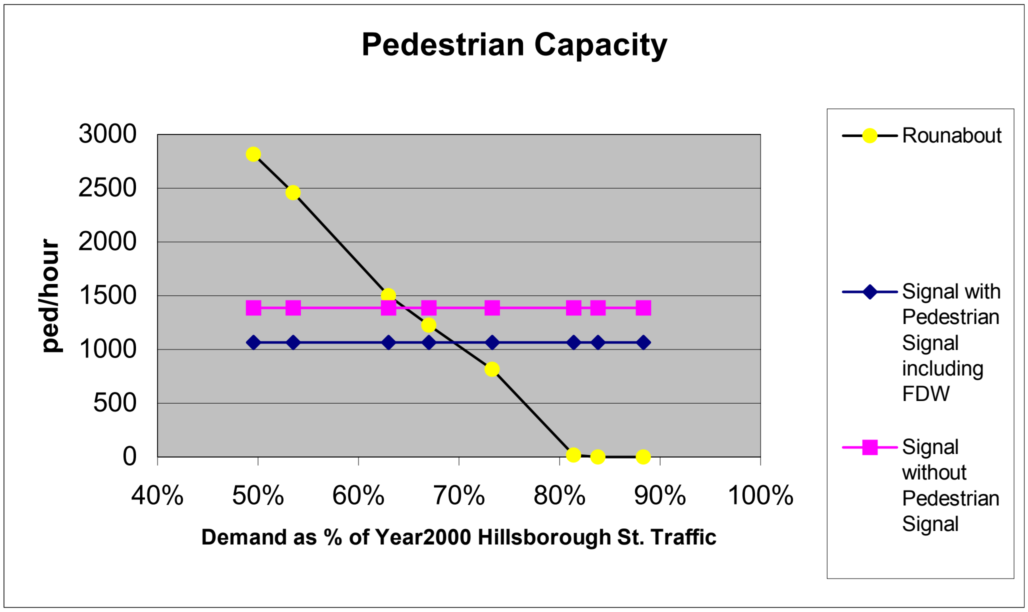
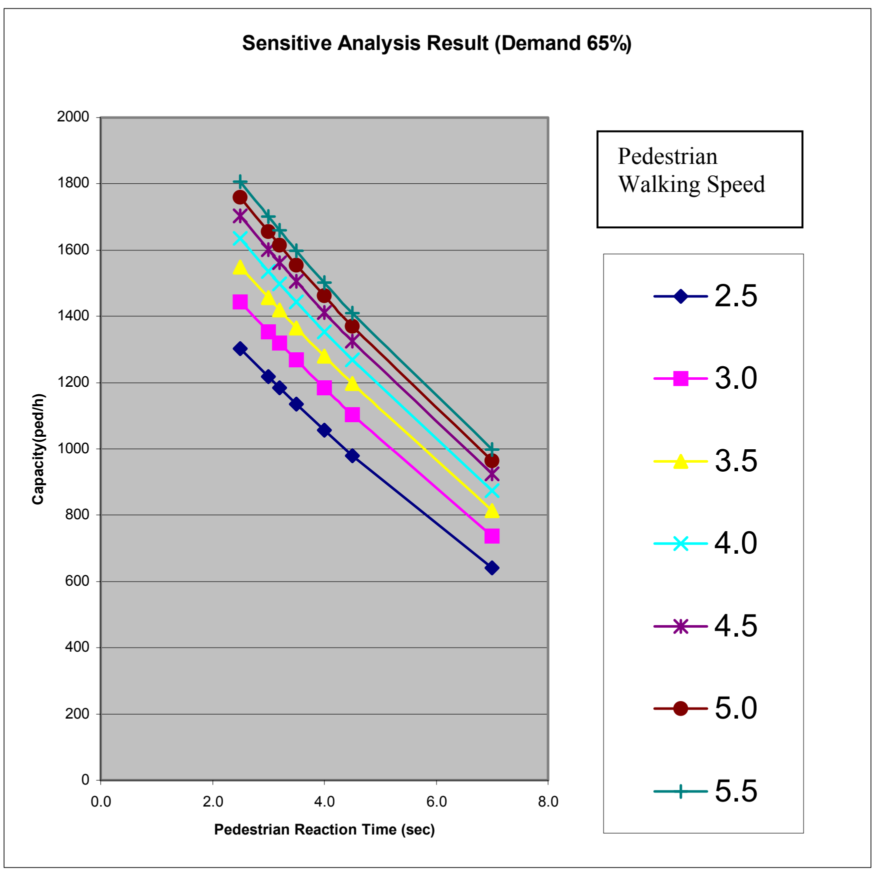


Figure 6.4. Pedestrian Capacity* and Hillsborough Street Traffic Demand



* Walking speed = 4.0 ft/sec, reaction time = 3.2 sec

Figure 6-5. Sensitivity Analysis Results



7. Summary, Conclusions and Recommendations

Summary

Current international research shows that modern roundabouts improve vehicular and pedestrian safety compared to conventional intersections. However, their effects on pedestrian safety in the U.S. remain unsubstantiated. Complicating this problem is a scarcity of pedestrian accident data at roundabouts, especially at intersection locations that were reconstructed as roundabouts and could potentially provide critical before/after accident statistics. This research seeks to examine the safety issues by summarizing the literature that describes international and U.S. experience with roundabouts and pedestrian safety. The research applies three alternate approaches to assess pedestrian safety at roundabouts: case study analysis, statistical analysis, and simulation analysis to compare pedestrian safety at a conventional signalized intersection to a case study modern roundabout.

The case study focuses on a proposed roundabout location - the Hillsborough-Horne Street intersection at North Carolina State University in Raleigh, NC. It is scheduled for reconstruction as a roundabout as part of a corridor project to improve the “front door” to NCSU, as well as improve pedestrian safety. First, pedestrian accident histories for the intersection, which has the fourth highest frequency of pedestrian accidents in North Carolina, are examined with and without the proposed roundabout. Based on reduced vehicle-pedestrian conflicts and better control of wrong-way movements, the proposed roundabout shows promise. Second, a regression model for pedestrian accidents versus street and intersection characteristics of a one-mile section of Hillsborough Street is developed. If a roundabout were constructed, the model forecasts a reduction in pedestrian accidents. Third, a simulation analysis of the Hillsborough-Horne intersection shows that the planned roundabout would have equivalent pedestrian capacity and potentially better pedestrian safety than the original signalized intersection. In summary, the three independent approaches suggest that a roundabout design will improve pedestrian safety at the case study intersection.

Conclusions

Results of this study indicate that converting conventional signalized intersections to modern roundabouts may reduce pedestrian-vehicle crashes and conflicts according to available literature and three independent approaches (case study, regression and simulation). The literature suggests that lower speeds and fewer conflict points of roundabouts are the primary contributors to the safety increase. The simulation for this research shows that if traffic diversion occurs at a roundabout with fewer lanes than the conventional intersection it replaced, it can also produce a reduction in pedestrian accidents, at least in terms of measured pedestrian capacity, a surrogate for safety. In particular for typical pedestrian reaction times and walking speeds, when a 30% traffic diversion occurs, a single-lane roundabout can handle more pedestrians more safely than a four-lane signalized intersection.

Recommendations

A primary objective of future work should be to develop a broader and better pedestrian accident database for roundabouts. As roundabouts replace signalized and unsignalized intersections in the U.S., accident data before and after the reconstruction should be collected and evaluated. This will be a long term study because of the relative infrequency of pedestrian accidents. The U.S. database should be complemented by appropriate international data. And new terminology and methods appropriate to roundabouts need to be developed for accident reports prepared by policemen.

The simulation developed in this project is a first step toward operational planning and design of roundabouts much like simulation is used to plan and design conventional intersections. In that regard appropriate simulation packages need to be identified and procedures standardized to ensure consistent design practice across the U.S. In such evaluations the concept of maximum pedestrian capacity should be further developed as a surrogate for safety, and the effects of pedestrian queues and wait times need to be added.