MODELING PEDESTRIAN SAFETY AT ROUNDABOUTS

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This study proposes a method for using a human participant in a field experiment to model pedestrian safety at roundabouts in the United States. Studies show that roundabouts are safer for vehicles, but are inconclusive as to whether pedestrians are at greater risk at roundabouts than at signalized intersections. Recent simulations, including virtual reality, can model pedestrian vehicle interaction, but the proposed technique could use real-world data to calibrate these models. Eight hours of video was made to gather data at a signalized intersection and a roundabout. A physical simulation was used to assess the pedestrian's cross/don't cross decision. Standard walking pace was simulated at 3.5 feet per second and a disabled pedestrian at half that pace. This study focused on factors such as signalization, approach streams, exit vs. entrance lanes, pace and direction to provide a realistic picture of the cross vs. don't cross decision. Data showed that slow pedestrians had a significantly higher rate of don't cross decisions at the roundabout. Roundabouts are thought to be safer for pedestrians than signalized intersections due to a lower number of conflict points, but the confusing multiple streams of roundabout traffic converging on exit lanes and the frames of approaching traffic at roundabout entrances may mean that another concept may be needed to fully capture pedestrian risks. The data on 'relevant traffic' showed that pedestrians had to be attentive to almost six times as many approach streams of traffic in the roundabout as in the signalized intersection. The value of this study is four-fold: 1) Future studies could revisit the conflict point at the core of Traffic Conflict Analysis and consider conflict streams as well; 2)

Future studies could consider the cross/don’t cross decision as an important data point with which to evaluate the safety of roundabout crossings; 3) Slow pedestrians fared worse in their ability to cross at the roundabout than at the signalized intersection; 4) The human participant in a field experiment method can be a valuable source of data for calibrating pedestrian safety simulation systems.

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PREFACE

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1.0 INTRODUCTION

A review of past literature has shown that roundabouts are a safer alternative for motorized vehicles than traffic-light controlled intersection, but do roundabouts actually increase the risk to pedestrians and non-motorized vehicles? This paper will focus on whether a new method for assessing safety at roundabouts provides more accurate data to research answers to this question.

1.1 HISTORY OF SIGNALIZED INTERSECTIONS IN THE UNITED STATES

The culture of urban and regional planning is in a constant state of change. In the last century, concerns about improving traffic circulation to support commerce, military-inspired road building projects and new ways of handling congestion came to the fore. As cities rapidly expanded, concerns about safely moving pedestrians and traffic created a need for complex intersections with traffic movement regulation.

One innovation was the electric traffic light. Osborne's (2014) research indicated that the first electric traffic light system was installed in the United States in 1912. The modern red, yellow and green light system was implemented in Detroit, Michigan in 1920. The traffic light, in less than a century of sustained use, may now be perceived as costly to municipal governments, creating congestion and causing long idling times that create pollution. Palat and DelHomme

(2012), confirmed that drivers running yellow lights was a risk of signalized intersections that contributed to accidents.

1.2 THE ROUNDABOUT ALTERNATIVE

A review of literature supports safer alternatives to traffic lights. The roundabout has been identified as a primary solution. A Pennsylvania Department of Transportation initiative to replace signalized intersections with roundabouts indicates the safety benefits for vehicles. (Lester, 2015)

> "One of the most important benefits of a modern roundabout is the increased level of safety resulting from the reduction of vehicle-vehicle conflict points... On average, roundabouts in the United States have shown total crash reductions of 37 percent and injury crash reductions of 51 percent." (PennDOT, 2001 p. 4.)

Headrick and Uddin, (2014) used geospatial data analysis to evaluate the conversion of signalized intersections to other methods. Their data evidenced more efficient traffic flow, faster average speed, reduced delay, less idling time, fewer crashes, lower pollutant emissions, and conservation of fuel. Wei, Grenard and Shah (2016) showed that capacity modeling could be used to assist planners in justifying conversions to roundabouts. But, these studies did not focus on pedestrians.

Mukai and Hayashi, (2015) were concerned that drivers may be unfamiliar with these new roundabouts as they become installed in greater numbers. This could pose additional danger to pedestrians. Allowing drivers to view instructional videos and use roundabout simulators may alleviate this unfamiliarity (Insurance Institute for Highway Safety, 2010; Forum8, 2016). Mukai and Hayashi (2015) approached this problem by using geospatial analytics to study how to best train drivers unfamiliar with roundabouts.

Replacing traffic lights with roundabouts has been supported by initiatives at several levels of Government in the United States and has been a topic of research and priority for the Federal government since at least 2002, at the federal level (U.S. DOT, FHWA, 2015), state level (Lester, 2015; PennDOT, 2001), and municipal level. Most notable is the City of Carmel, Indiana (Brochure [n.d.]), which has been converting almost all traffic lights to roundabouts.

A survey of pertinent literature will show that other nations and some municipalities in the United States, such as Carmel, Indiana (Brochure, [n.d.]) have used roundabouts and traffic circles to replace traffic lights. While current literature has shown that these conversions resulted in a significant reduction in the severity of vehicular accidents anecdotal evidence may show a higher risk to bicycles and pedestrians.

The FHWA (2015) in “A Review of Fatal and Severe Injury Crashes at Roundabouts” used data on roundabouts from Washington State and Wisconsin. They specifically examined pedestrian accidents at roundabouts. They looked at geometry, noting that splitter islands separate entering and exiting traffic, deflect and slow entering traffic and provide a pedestrian refuge. They noted that fatal roundabout crashes were less likely to involve pedestrians or bicyclists when compared to fatal intersection crashes, but this may be due to the small number of roundabouts in general.

The FHWA (2015) actually observed no pedestrian fatalities at roundabouts. Although pedestrians and bicyclists were noted to be involved in only a small percentage of crashes, these crashes were more likely to be severe. Bicycles were noted to be more commonly involved in injury crashes at roundabouts than pedestrians; this could be due to bicycle sharing the traffic lanes upon entering and traversing roundabouts. Accidents at roundabouts were only observed in Washington State and pedestrian accidents only accounted for only 2-3% of all accidents at roundabouts.

1.3 ROUNDABOUT DESIGN

The PennDOT Guide to Roundabouts (PennDOT, 2001) on p.2, distinguishes roundabouts from traffic circles and rotaries. A roundabout has seven characteristics: 1) Yield control is used on all entries, 2) Approaching roadways do not enter the roundabout perpendicular to the circulating roadway, but, the traffic is deflected by splitter islands to enter at as small an angle as possible, 3) Circulating vehicles within the roundabout have right of- way, 4) Pedestrian access is only allowed across the legs of the roundabout behind the yield line, 5) Parking is not allowed within the circulatory roadway or at the entries, 6) Vehicles circulate counter-clockwise and pass to the right of the central island and 7) Raised Splitter Islands.

“Roundabout” is the term preferred by the United States and Pennsylvania governments. PennDot distinguishes rotaries and traffic circles as follows:

> "Rotaries generally had large diameters that resulted in high speeds within the circulatory roadway. They typically provided little or no deflection of the through traffic paths, and some required the circulating traffic to yield to entering traffic. The latter caused congestion, and the intersection would often ‘lock-up.’ Neighborhood traffic circles are typically built to calm traffic and/or improve the aesthetics of local street intersections. The approaches may by uncontrolled or stop controlled." PennDOT (2001) p.3

What does a roundabout look like and how does it work? We may examine the graphic from PennDOT (2016b) at p.3-7. Note the entry and exit points, the circulatory roadway and the truck apron. The PennDOT (2016b) diagram at p.3-8 shows the roundabout from the perspective of moving traffic.

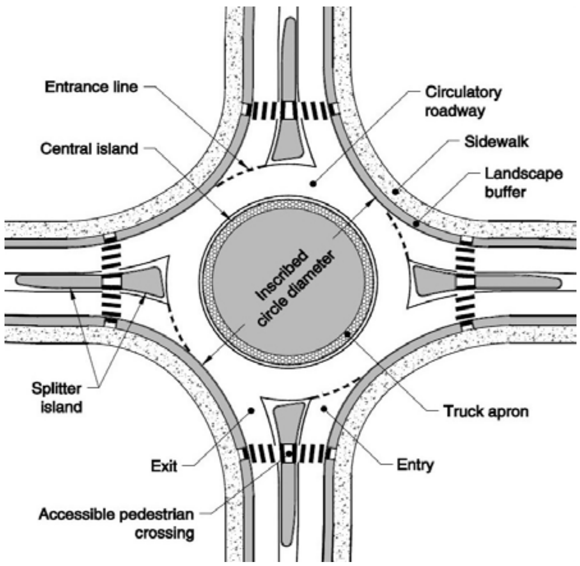

Figure 1.1: Basic Geometric Elements of a Roundabout

(PennDOT, 2016b Figure 3.6 at p. 3-7)

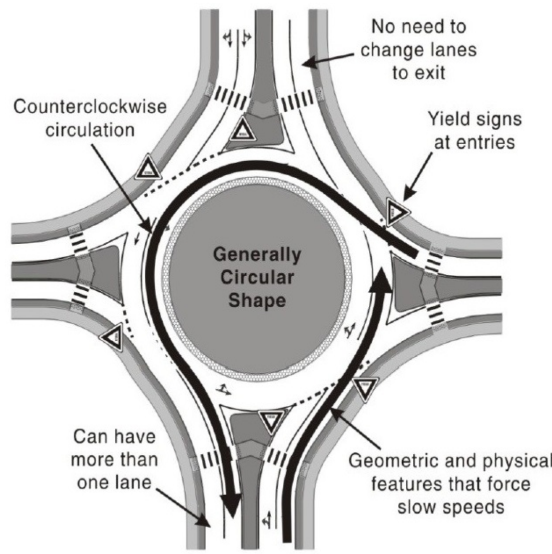

Figure 1.2: Key Roundabout Characteristics

(PennDOT, 2016b Figure 3.1 at p. 3-8)

The PennDOT (2016b) diagrams show roundabout characteristics that will be referenced throughout this study. It is an optimal design, not necessarily reflective of all roundabouts. Number of lanes, direction of travel and marked pedestrian lanes all have an effect on safety as we will see in the review of the literature. While there are several categories for roundabout design, this study will only focus on a single-lane roundabout with a 15-mph entry speed and one entering lane approach.

1.4 SAFETY STANDARDS IN ROUNDABOUT DESIGN

The Public Transport Authority of Western Australia (2016) (PTAWA) set forth comprehensive guidelines for roundabout design to make them safer for pedestrians. First, they noted two dangers for pedestrians: 1) Right of way for vehicles and 2) Waiting for gaps in traffic to cross. Item one would not hold true in Pennsylvania, as pedestrians proceeding legally in a marked crosswalk, always have the right of way over vehicles. Furthermore, Pennsylvania being the locus of the study, mandates right-of-way for the pedestrian once they enter the crosswalk:

> Pa. Cons. Stat. 75 § 3542. "Right-of-way of pedestrians in crosswalks. (a) General rule.--When traffic-control signals are not in place or not in operation, the driver of a vehicle shall yield the right-of-way to a pedestrian crossing the roadway within any marked crosswalk or within any unmarked crosswalk at an intersection.")

Disadvantages noted by the PTAWA were that: 1) Turning vehicles have right of way over pedestrians crossing the carriageway and 2) Pedestrians need to select appropriate gaps in the traffic stream. The gaps are where the danger may arise for the elderly, the handicapped and children as they must make decisions about when to traverse the entering and exit lanes of the roundabout. (PTAWA, 2016 p. 172)

The PTAWA recommended several engineering countermeasures including: reducing vehicle approach speeds via entry curvature or deflection on approaches, ensuring unobstructed sight lines between pedestrians and motorists, ensuring crossings are located within pedestrian walk lines, splitter islands which are as large as the site allows and locating signs and vegetation so as not to obscure pedestrians, particularly children and people in wheelchairs. (PTAWA, 2016 pp. 173). These design issues, while not the focus of this study aided in site selection, evaluating the overall safety of the physical site and the geometric design of the location being studied.

1.5 CONFLICT POINTS AS AN ALTERNATIVE DATA COLLECTION EVENT

In the absence of the rare actual collision and injury observation, recent analysis presumes that it would be nearly impossible to observe enough accidents at intersections to draw valid conclusions about safety, unless one had unlimited automated traffic monitoring 24 hours a day for a year at multiple intersections. (Sadeq and Sayed, 2016). The strength of the 'Traffic Conflict Technique' for analyzing traffic safety as a proven solution to this lack of data was analyzed at length by Sadeq and Sayed (2016). Amundsen and Hydén (1977) viewed traffic conflicts as events where two or more road users approach one another in space and time such that there will be an imminent collision if their movements don't change.

Roundabout geometry is important in understanding these 'conflict points'. Gross (2013, p.235), defined conflict points as points in an intersection where traffic is "crossing, converging and diverging", as illustrated in the graphic below. This definition is critical, because many studies used conflict points as criteria for assessing safety. Retting (2003) defined 'conflicts' as locations where a vehicle had to change direction to avoid a collision.

Possible data collection techniques may include:

- Before and after studies of pedestrian injury at converted roundabouts. (Gross, 2013)
- Review of comprehensive datasets on pedestrian injury at roundabouts. (Stone, 2002)
- Broad and continuous automated observation of intersections for accidents with injury (requiring intense application of resources). (Hourdos, 2012; Flannery, 2001)

- Anecdotal evidence of roundabout safety issues from multiple sources. (Flannery, 2001)
- Manual observation of traffic and pedestrian flow through hypothetical conflict points. (Ismail, 2009)

There are many possible measures for assessing safety risks that focus on conflict points. A brief survey of these methods proved instructive in determining which measures to select. Ismail (2009), selected (TTC) as it was the primary traffic conflict indicator in the literature. Ismail (2009) noted that accurate estimation of TTC required considerable field measurement of road user position, speed, and direction of movement. Other conflict indicators mentioned by Ismail (2009) were gap time (GT), post-encroachment time (PET), and deceleration rate (which are the primary measures for left-turn conflicts).

- Post encroachment time (PET) - time difference between the moment an offending road user leaves an area of potential collision and the moment of arrival of a conflicted driver with right-of-way.
- Gap time (GT) – was calculated at each instant by projecting the movement of the interacting road users in space and time.
- Deceleration-to-safety time (DST) - deceleration to reach a nonnegative PET value if the movements of the conflicting road users remain unchanged. (DST captures greater details of the traffic event.)

Sadeq and Sayed (2016) mention that video (such as the University of British Columbia 'automated traffic safety tool') is the favored mechanism for recording traffic flow by use of various computerized and automated techniques due to rich detail accuracy and a permanent record allowing conflicts to be reviewed and analyzed at any later time.

What is it about the Traffic Conflict Technique (TCT) that would prove more helpful than observation of real accidents? TCT gathers real field data in contrast to hypothetical simulations, such as that of Saccomanno (2008), who presented a comprehensive analysis of traffic simulations. However, Sadeq and Sayed (2016) point out that the video technique allows analysts to proactively observe unsafe driving at the roundabout and investigate the relationship between maneuvers and road characteristics.

Sadeq and Sayed (2016) used five cameras mounted on buildings above a roundabout in Vancouver, British Columbia, Canada. The roundabout was similar in geometry to the Latrobe Roundabout used in this study, except that the Vancouver Roundabout is two-lane at all entry and exit points and it had marked pedestrian crossing across each lane and through the splitter islands.

Video recording is a proven technique, as manual data collection of conflict point activities is too difficult to record due to high traffic volume, but use of measures such as TTC, while valuable, might prove very complex for studying understand the pedestrian decision-making process.

1.6 A CASE FOR COMPREHENSIVE ANALYSIS OF PEDESTRIAN SAFETY AT ROUNDABOUTS

Retting (2003) observed that roughly 100,000 pedestrians are injured and 4,500 pedestrians are killed every year by motorized vehicles. He observed that the problem is worse for vulnerable pedestrians. Retting (2001) in his earlier study, viewed the greatest danger as vehicle speed. He saw the solution to be in traffic engineering. His study concluded that regression to the mean among high samples sizes gave results that might not be conclusive about whether roundabouts really were effective countermeasures. Thus, the few European studies that directly addressed pedestrian safety at roundabouts may require further examination.

Ismail (2009) encouraged collection of more data and further analysis to understand the processes that cause pedestrian collisions. He also noted that pedestrian injuries and fatalities occur with unexpected frequency in traffic incidents, despite the fact that the volume of data on pedestrian exposure to collision risk was sparse, compared with data on vehicle collisions. He also mentioned a growing municipal sustainability movement, which encouraged improvement of pedestrian traffic conditions, with increasing public fund allocation for safety programs that focus on pedestrian injuries.

Harkey's (2006) U.S. study noted that as roundabouts gained popularity in the U.S., there was concern that although roundabouts were safer for vehicles, they might not provide pedestrians greater safety benefits. Harkey (2006, p.2.) notes:

> "Although available information suggests that Roundabouts are relatively safe, there is concern about the effects of different design configurations on the safety of bicycles and pedestrians, particularly pedestrians with disabilities. For example, pedestrians with blindness and low vision use cues from traffic sounds to determine

> when to cross the roadway. The free-flowing traffic at a Roundabout can sometimes make this task extremely difficult." p.2

Gross (2013) also noted the need for a substantially larger database than earlier U.S. studies provided. This lack of data led to inconsistent knowledge on the safety effects of conversion of signalized intersections to roundabouts. More data was needed to shore-up safety estimates and to better identify geometry and traffic conditions where conversion to roundabouts would provide safer conditions.

Gross (2013) did a 'before and after' analysis of converted roundabouts in eight states in the U.S. He claimed that his study accounted for the 'Regression to the Mean' problem noted by Retting (2014) which had been a possible concern about the European studies of pedestrian safety. Barnett, Pols and Dobson (2005, p.215) describe this phenomenon:

> "Regression to the mean (RTM) is a statistical phenomenon that can make natural variation in repeated data look like real change. It happens when unusually large or small measurements tend to be followed by measurements that are closer to the mean...The effect of RTM in a sample becomes more noticeable with increasing measurement error and when follow-up measurements are only examined on a sub-sample selected using a baseline value... RTM is a ubiquitous phenomenon in repeated data and should always be considered as a possible cause of an observed change. Its effect can be alleviated through better study design and use of suitable statistical methods."

Gross (2013) argued that the studies of pedestrian safety at roundabouts are only now at the same starting point where studies of vehicular safety at roundabouts were at their inception. There is just not sufficient attention to pedestrian accidents to build a sufficient dataset worthy of statistical significance. This work hopes to build on Gross' (2013) desire for more data and provide a useful method for gathering pedestrian safety data at roundabouts.

2.0 BACKGROUND AND RELATED WORK

This chapter will focus on two aspects: 1) a review of existing datasets to provide an overview of data on pedestrian injuries and Fatalities in the United States and 2) a discussion of related international and U.S. work on this topic. The datasets and literature will be reviewed to determine if accidents with serious injury or death are reduced by roundabouts for pedestrians and if the existing methods to gather data pedestrian roundabout safety may be augmented.

Data from PennDOT and the Fatality Analysis Reporting System (FARS) from the National Highway Traffic Safety Administration (NHTSA) was reviewed. FARS is a census of fatal motor vehicle crashes that occurred within the U.S. since 1975. The Highway Safety Information System (HSIS) is a multistate database published by the University of North Carolina Highway Research Center (HSRC) and sponsored by the Federal Highway Administration (FHWA) containing crash and safety data from a select group of states.

2.1 PUBLIC DATASETS ON ROUNDABOUTS, ACCIDENTS AND INJURIES

The Pennsylvania Department of Transportation embarked on an effort to transform signalized intersections to roundabouts. See PennDOT (2016a). As of this date, 29 of 60 contemplated conversions were completed. 10 of these converted signalized intersections were analyzed by PennDOT, using the ‘before-and-after’ technique to determine if they provided a higher level of safety after conversion. The trends were similar to those seen in other studies. The study found that fatalities, major and moderate injuries were reduced, possibly by the 'calming effect' of roundabouts on vehicle traffic. Oddly, minor injury and property-damage-only accidents increased, possibly due to driver confusion about roundabout rules or geometry. (PennDOT 2017). However, pedestrian accidents were not examined.

The dataset PennDOT provided is sparse, as the 10 converted signalized intersections are in low-volume areas as opposed to urban centers like Philadelphia. The small dataset does s some trends supported by other research. At the 10 intersections studied, they noted 16% fewer crashes overall, 49% fewer accidents with significant injury or fatality, but 15% more accidents without injury

The NHTSA (2017) collects data on vehicle accidents and injuries across the United States. They tracked injuries from 2001-2015. Their data showed that roughly 70,000 pedestrians are injured from vehicles accidents out of approximately 2.5 million accidents per year. The number of accidents with injury has declined over this period, but the percentage of pedestrians injured relative to all vehicle accidents with injury has risen (NHTSA, 2017). As noted in the literature cited later in this study, it is unclear how many of these accidents occurred at roundabouts.

An NHTSA (2017b) breakdown from the Fatality Analysis Reporting System (FARS) does show many different categories of intersections where pedestrian injuries occurred, but there is not yet a specific category for roundabouts, making it a time-consuming task determine which accidents occurred at roundabouts.

A website created by Kittelson & Associates (2017a), one of America’s foremost experts on roundabout design engineering, visualizes an in-depth survey of roundabouts in the United States. Kittelson’s searchable database comprises roundabout data from 1999 to the present, identifying approximately 3,800 existing and proposed roundabouts. While Kittelson's (2017b) work is a good start to allow matching of accidents to roundabouts, much more data is needed to understand the safety effects of converting signalized intersections to roundabouts in the United States.

A first-hand exploration of the data confirmed what most of the U.S. studies note: that available data is too sparse. This requires a more comprehensive effort to get clearer data to determine whether roundabouts are safer for pedestrians than signalized intersections.

2.2 RELATED WORK: THE EUROPEAN STUDIES

The FHWA's (2000) research relied on European countries due to a lack of United States research on the topic of pedestrian safety at roundabouts in the U.S. at that time. They examined the studies from the U.K. (Crown, 1998; Maycock, 1984), Holland (Schoon, 1993), France (Alphand (1991); CETUR (1992); SETRA (1998)) and Norway (Seim, 1991). Sixteen types of collisions were organized in the FHWA table "Comparison of Collision Types at Roundabouts" (FHWA, 2000) on p. 114, which examined roundabout accidents from France, the U.K. and Australia. They listed three types of pedestrian accidents by percentage of all accidents at roundabouts: Pedestrian on crosswalk (3.5-5.9%), pedestrian outside crosswalk (1%) and pedestrian in circulatory roadway (3.5%).

The FHWA (2000) noted that while roundabout safety was improved for motor vehicles, but less so for pedestrians, citing Maycock's (1984) British study and Schoon's (1993) Dutch study. The FHWA (2000) reasoned that the safety effects of roundabouts were due to lower vehicle speeds, fewer conflict points and the splitter island which allows pedestrians to observe entering and exiting vehicles separately.

Seim's (1991) Norway study of 59 roundabouts and 124 signalized intersections on crash data between 1985 and 1989 showed that only one of 33 crashes with injury recorded at the roundabouts involved a pedestrian, compared with the signalized intersections, where pedestrians were involved in 57 of 287 injury crashes. Maycock's (1984) study broke down the types of roundabouts where accidents occurred, including mini, conventional, flared and signalized, while Schoon's (1993) study compared vehicle types as well as pedestrian-involved crashes at roundabouts. Single-lane roundabouts were considered safer than multilane because of fewer conflicts between road users, and shorter pedestrian crossing distances. In general, the safety effects from roundabouts were due to: 1) roundabouts having fewer conflict points than signalized intersections reducing crash rate and severity, 2) lower absolute vehicle speeds, 3) consistent relative speeds among vehicles, 4) Pedestrians only having to observe one direction per lane, meaning fewer places to check for conflicting vehicles, 5) vehicles approaching from defined paths and 6) a lower magnitude of conflicting flows at each conflict point vs. the chaos of signalized intersections FHWA (2000, p. 103-104).

The U.S. Insurance Institute for Highway Safety (IIHS), also relying heavily on the earlier European studies, concluded that:

> "Roundabouts generally are safer for pedestrians. Pedestrians walk on sidewalks around the perimeter and cross only one direction of traffic at a time. Crossing distances are relatively short, and traffic speeds are lower than at traditional intersections." (IIHS 2016)

The IIHS Highway Loss Data Institute (HLDI) stated on their site that "Two studies also have reported reductions in pedestrian crashes of about 75 percent after conversion to Roundabouts." But the articles and supporting data were not cited. (HLDI, 2004). Retting (2003 p. 1457), discussing Brilon's (1993) German study and Schoon's Dutch study (1994) addressed the issue directly:

> "European studies indicate that, on average, converting conventional intersections to Roundabouts can reduce the rate of pedestrian crashes by about 75%. Single-lane Roundabouts, in particular, have been reported to involve substantially lower pedestrian crash rates than comparable intersections with traffic signals."

Retting (2001) goes on to compare the three best known studies on the issue of pedestrian safety at roundabouts, albeit the most recent study is almost 25 years old: 1) Brilon (1993) – Germany: Before-and-after study on 25 intersections converted from traffic signals or stop signs to modern roundabouts: pedestrian crashes decreased 75%. 2) Schoon (1994) – Netherlands: Before-and-after study on 181 intersections converted from traffic signals or stop signs to modern roundabouts: pedestrian crashes decreased 73%. 3) Brude and Larsson (2001) – Sweden: Empirical data for 72 roundabouts compared with comparable intersections with signals: One lane roundabouts: pedestrian crashes were 3–4 times lower than predicted for comparable signalized intersections, but two lane roundabouts showed pedestrian crash risk comparable to signalized intersections.

It is striking that Brude and Larsson (2001) noted that single-lane roundabouts are safer for pedestrians than double-lane roundabouts. This could be due to a higher number of conflict points. In a previous study of pedestrian safety, Retting (2001) did a broad survey of before-and-after data on vehicle accidents after roundabout installation, but he noted that only four pedestrian and three bicycle accidents were observed in all of the data. He stated: “However, these samples are too small to give conclusive evidence on the safety of these road-user groups at Roundabouts.” Retting (2001) at p.631.

The European studies were based on European installation of roundabouts preceding the American effort by at least 20 years, and it should be studied whether the culture and rules of European driving and pedestrian behaviors are significantly different from those of the U.S.

2.3 RELATED WORK: THE U.S. STUDIES

Recent U.S. efforts to evaluate safety at roundabouts were conducted by Hourdos (2012), Stone (2002), Rouphail (2005) and Harkey (2006). As discussed below, Stone (2002) noted the limited amount of U.S. pedestrian safety data, because pedestrian-vehicle crashes are rare when compared to vehicle-vehicle crashes. Thus conflict data, models and simulations are needed to gather adequate data to draw valid conclusions. Stone (2002) observed that a lack of data could be due to documented intersections being located where there is few pedestrians and that roundabouts lack identifiable categories in accident reports and thus are not easily identified in the U.S. accident databases.

Stone’s (2002) goal was to study the safety aspects of modern roundabouts for pedestrians. While roundabouts were common throughout the world, the U.S. only recently saw them as potentially safe. Stone’s (2002) team also sought to 1) identify useful methods to study the problem, 2) compare existing methods to synthesize a research methodology and 3) by case study, to understand the safety of a roundabout compared to a conventional signalized intersection.

Stone (2002) does touch on the issue of pedestrian safety as a matter of perception, finding that many pedestrians do not perceive roundabouts as safe even though approach speeds are lower and unexpected turning movements are precluded. He observed that both roundabouts and two-way stop-controlled intersections require pedestrians to judge ‘gaps’ in the major stream of traffic. He mentioned that while some literature concluded that pedestrian safety was worse at roundabouts vs. stop sign controlled intersections, there was a lack of studies to substantiate their opinions.

Stone (2002) learned that roundabouts may be difficult to traverse for pedestrians with physical impairments due to: 1) longer crossing distances, 2) traffic in constant motion, and 3) difficulty for visually impaired pedestrians to judge gaps from sound alone. He recommended that signalized intersections offered explicit guidance to pedestrians through visual and audible signals, so that the decision process for visually impaired pedestrians may be easier than at roundabouts. He noted that at signalized intersections, pedestrian signals protect pedestrians when traffic volumes are heavy. Walk signals consisting of illuminated words or symbols assigned right-of-way and guaranteed adequate crossing time.

First, Stone (2002) observed that as roundabouts were implemented in the U.S., pedestrians could be prone to unsafe crossings for reasons including new geometries and lack of signalization. He discussed European, Australian and U.S. studies that documented how slower speeds and (relying on the FHWA’s (2000) definition of ‘conflict point’) a reduction in conflict points from 32 at the signalized intersection to 8 at the roundabout, improved vehicular and pedestrian safety. But, Stone (2002) asserted that existing literature on U.S. roundabouts was unclear on pedestrian safety, especially for the disabled, due to scarcity of pedestrian accident data at roundabouts, especially at signalized intersections reconstructed as roundabouts.

In his research, Stone (2002) employed a case study, statistical analysis and simulation to compare pedestrian safety at a conventional signalized intersection to a modern roundabout. Pedestrian accident histories for the signalized intersection were examined with and without the proposed roundabout. The goal was to quantify the magnitude, frequency and severity of the pedestrian safety problem, conduct crash analyses for certain pedestrian accident cases at roundabouts and signalized intersections and identify factors that correlate with pedestrian accident causation and safety improvement.

Stone (2002) chose a location to collect data on traffic and pedestrian volumes, road geometry and accidents. Next, he performed forensic analysis on collected data to document causes of pedestrian accidents. The final step was to conduct accident analysis by hypothetically retrofitting the signalized intersection with the proposed roundabout design. Traffic Conflict Analysis was used to measure the comparative operation of roundabouts and conventional intersections.

In the end, Stone's (2002) simulation analysis showed that 1) the planned roundabout would have equivalent pedestrian capacity and potentially better safety than the original signalized intersection 2) traffic diversion at roundabouts with fewer lanes than the intersection it replaced, would produce a reduction in pedestrian accidents, and 3) that a single-lane roundabout could handle more pedestrians safely than a four-lane signalized intersection.

Another issue explored in the U.S. studies was how to measure pedestrians' judging of 'gaps' in traffic at crossings. Harkey (2006), used timings to understand the gaps, similar to Sadeq and Sayed's (2016) 'TTC' measurement. Harkey's (2006) objective was to develop methods of estimating the safety impacts of roundabouts. He collected observational data in multiple states from a large number of roundabouts with different geometries. The study was undertaken as a part of an NHRCP (2006) project entitled: ‘Applying Roundabouts in the United States’ NCHRP 3-65 Final Report.

Harkey’s (2006) study used digital video to collect data. He applied site selection criteria which included a high number of pedestrians, adequate geometry and traffic. He collected data on 769 crossing events at 10 approaches. The measures he used were based on what happens when the pedestrian arrives at the cross walk and assesses the gap between approaching vehicles. But Harkey’s (2006) focus was on the pedestrian’s assessment of gaps and motorist yielding behavior, rather than pedestrian decision-making. He measured a ‘normal’ pace of crossing, but did not measure the slow gait of a physically disabled or elderly pedestrian. He did compare data on entry vs. exit legs. Harkey (2006) was disappointed to note that during 769 crossing events only 4 actual pedestrian-vehicle conflicts were observed.

Harkey (2006), observed five different pedestrian actions: 1) go around blocking vehicle, 2) run to avoid vehicle, 3) stop for a vehicle while crossing, 4) aborted crossing and 5) proceeded normally across. Harkey (2006) compared crossing pace, using 4.4-5.0 feet per second which is faster than the standard 3.5 fps, stated in the Manual on Uniform Traffic Control Devices. (FHWA, 2009):

> “Except as provided in Paragraph 8, the pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the curb or shoulder at the end of the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of 3.5 feet per second to at least the far side of the traveled way or to a median of sufficient width for pedestrians to wait.” (FHWA, 2009 at p. 497)

Harkey (2006) concluded that safety problems with roundabouts included: 1) sight lines from vehicles to the pedestrian 2) exit legs being higher risks than entry legs for disabled pedestrians and 3) two-lane approaches being riskier than one lane approaches. Harkey did note that vehicles not yielding to pedestrians occurred: 32% of the time at roundabouts, 15% of the time at signalized intersection and 4% of the time at stop signs.

Rouphail (2005) made the first attempt in a U.S. study to explicitly modeling pedestrian-vehicle interactions at roundabouts in a micro-simulation traffic environment. He sought to document visually impaired pedestrian crossing performance at roundabouts by using exploratory computer modeling. He sought then to use the model to examine impacts of alternative treatment by capturing 'gap acceptance behavior' into a simulation model of pedestrian and vehicular operation at roundabouts. He observed that pedestrian volumes were too low at roundabouts to provide statistical confidence regarding their performance.

Rouphail (2005) focused on the concept of 'delay', and pedestrian gap perception behavior. He observed higher delays for blind pedestrians at exits than at entrances. They noted that adding signals would make roundabouts safer but it defies the entire concept of a roundabout which is continuous motion with a yield to pedestrians in crosswalks and a yield to other vehicles in the circulatory roadway.

Rouphail's (2005) process consisted of selection of a tool, selection and coding of a test roundabout, incorporating observational data of actual pedestrian gap perception behavior and conduct of modeling experiments related to the differential performance of sighted and blind pedestrians at roundabouts. Due to a lack of sample size, he assumed that pedestrian gap acceptance behavior was homogenous. One limitation he noted was that although he used real-world observation for calibration of pedestrian gap perception parameters, they had to use default values for others. Their volumes, turning movements, speed limits and geometry did in fact come from actual test sites.

He used the VISSIM (2017) traffic simulation software package for coding and modeling pedestrian behavior. VISSIM uses a Windows-based interface, simulation processor for moving traffic and people and outputs a movie in a common software format. Rouphail (2005) used latency and crossing time to assess gaps, applied the concept of crossing points and he explored the situation where if the vehicle is behind the yield line, when the pedestrian is at the crossing point, the vehicle yields.

For site selection, he observed three different roundabouts to collect data. The preferred roundabout was a single lane 'compact urban roundabout'. They simulated traffic for based on actual noon peak hour. They used a crossing pace of 1.22 m/s (equating to 4.0 fps, where the FHWA (2009) standard mentioned above is 3.5 fps.). He called the situation where a pedestrian confronted multiple vehicles 'queuing'. Rouphail (2005) used sensitivity analysis to investigate the relationship between delay for blind and sighted pedestrians and vehicle volume. Empirical distribution was coded in as time went on. For visualizations, their model was able to create trendlines from the data.

Rouphail's (2005) study is valuable for its understanding of the value of a simulation model where volumes of data are low and risk to human participants is high.

> "The effective use of computer modeling in the present case suggests that modeling may represent a viable alternative to traditional field data collection methods where subjects are placed at risk for the sake of treatment evaluation. While modeling does not rule out the need for eventual evaluation of effects "in the field," it does permit one to approach operational field evaluations with the knowledge (from the model) that the treatments being evaluated have been shown to have a high probability of success." (Rouphail, 2005, p. 218).

In Retting's (2001) first study, he noted that traffic signals were the primary devices to regulate traffic lights at intersections, roundabouts being seldom used in the U.S. at that time. In Retting's (2001) study, he used before and after with empirical Bayes to account for regression to the mean as a way of accounting for differences in traffic volume. He reviewed data from eight different U.S. states. The data showed reductions in accidents. Retting (2001) concluded that there is significant accident reduction from conversion to roundabouts, due to elimination of certain vehicular conflict points that exist at signalized intersections.

In Retting's (2003) next study, he cited the European studies which showed a 75% reduction in pedestrian crashes by conversion to roundabouts. Retting (2003) isolated the vulnerable populations: 1) pedestrians were 35% of motor vehicle deaths in urban areas, 2) children 5-9 had the highest population injury rate, 3) pedestrians older 80 had the highest population-based death rate, and 4) pedestrians older than 65 years were more likely than younger pedestrians to be struck at intersections.

Hourdos (2012), in a more recent study touching directly on this topic, examined data on pedestrian and bicycle safety at roundabouts in the State of Minnesota, United States. It was the intention of Hourdos' study to attempt to. In the most direct sense, he collected data and analyzed both who yielded (vehicle or pedestrian) and also very specific pedestrian timings of pedestrian delay while waiting for traffic at the conflict point to pass.

Hourdos (2012) discussed results of research on accessibility of modern urban roundabouts for pedestrians and bicycles. Like the Pennsylvania law cited above, Minnesota law also requires all vehicles to yield to pedestrians already in the crossing. The primary focus was driver yielding behavior. He noted that:

1. A pedestrian crossing starting from the splitter island had a higher probability for driver yielding, due to ambiguity of pedestrian intent.
2. When vehicles exited the roundabout, there was a lower probability the driver would yield possibly due to increased pressure on the driver to clear the roundabout quickly.
3. The more vehicles in the roundabout the lower probability of yielding to pedestrians.

Hourdos (2012) collected long periods of video records and observed tens of thousands of pedestrians using the crossings at two different sites in order to capture near-accident events. But, there were no observations of such interactions with traffic and only three cases out of thousands of crossing events were even considered as close-calls. Hourdos (2012) study was also not able to observe the interaction of people with disabilities, making it inconclusive whether roundabout crossings are perfectly safe. Investigated conditions that could affect the yielding behavior of drivers.

Friction was however seen between pedestrians and drivers at roundabout crossings. The location where crossing starts and the direction of the vehicle were seen to be determinants of driver yielding behavior. The size of the pedestrian group, indicated a slight tendency for drivers to yield to larger groups. The focus was on the driver's perspective and not the pedestrian. Hourdos (2012) found that for multiple vehicles confronting the pedestrian, the more vehicles in the roundabout, thus the lower probability of a driver yielding to pedestrians.

Hourdos (2012) noted real problems with the safety and comfort of visually impaired individuals at roundabout crossings which were observed to be no better than signalized intersections. New roundabouts in Minnesota also generated a significant amount of complaints from pedestrians suggesting difficulties in crossing and reduced safety. Hourdos (2012) noted that some suggest signalization of roundabouts, but the Federal Highway Administration's

‘Roundabout Informational Guide’ states: “Roundabouts should never be planned for metering or signalization.” In other words, signalization would negate the benefits from constructing a roundabout instead of a traditional signalized intersection.

Hourdos (2012) used site selection criteria based on characteristics that permit evaluation of pedestrian experience in crossing a roundabout: modern urban roundabouts, adequate pedestrian traffic and geometry. Site visits for candidate study sites was conducted where information defining physical conditions was collected. At the beginning of the study, no specific attributes of pedestrian crossing events were identified, observation was intended to define them.

Hourdos (2012) used video to observe the entire scene of the roundabout during pedestrian crossing events. They collected 16 days of data, 15 hours per day and four videos per hour, for 960 hours of video in each roundabout for a total of 1,920 hours of video. Their statistical method involved quantitative analysis to identify trends and Logistic Regression was applied as a causal analysis tool to identify important influences on driver yielding behavior and the effect they have in the probability a vehicle yields to a pedestrian in a roundabout crossing, because the outcome variable was binary: Yield=1 vs. No-Yield=0. The question left unanswered by Hourdos (2012) is whether focusing on the driver’s reaction to the pedestrian is of more value to assess safety than the pedestrian’s reaction to the vehicle.

Table 2.1: Table of Comparison of U.S. Studies of Pedestrian Safety at Roundabouts

	Stone (2002)	Harkey (2006)	Rouphail (2005)	Hourdos (2012)
Study:	safety aspects of modern roundabouts for pedestrians. simulated retrofit of signalized intersection to roundabout	accessibility of modern urban roundabouts for pedestrians. develop methods to estimate the safety impacts of roundabouts	recommend improved treatments at roundabouts for blind pedestrians	safety of abled and disabled pedestrians at roundabouts
Results:	reduction in pedestrian accidents. single-lane roundabouts safer than four-lane signalized intersection	roundabouts need re-design for safe access for pedestrians. exit legs are riskier than entry legs. two lane approaches riskier than one lane	higher delays for blind pedestrians at exits than at entrances. adding signals would make roundabouts safer for the blind	pedestrian crossing from splitter island, higher probability of driver yielding. exiting roundabout, lower probability of driver yielding
Pedestrian Cross/Don't Cross Decision	pedestrian gap assessment	pedestrian gap assessment, motorist yielding behavior	pedestrian gap assessment, motorist yielding behavior, delay	pedestrian yield, motorist yielding behavior, timing
Tools:	simulation modeling,- forensic accident report analysis, case study	statistical analysis	exploratory computer traffic simulation modeling - VISSIM	statistical analysis
Site Selection:	traffic volumes, pedestrian volumes, road geometrics, and accidents	high number of pedestrians, number of lanes and average daily traffic.	single lane 'compact urban roundabout'. simulated traffic based on actual noon peak hour.	modern urban roundabouts, adequate pedestrian traffic and geometry
Data Collection:	analysis of crash records	digital video	observed three roundabouts to collect data for the simulation.	digital video
Crossing Pace:	2.5-5.5 fps range in 0.5 fps increments in simulation	4.4-5.0 fps	1.22 mps	observed, not controlled
Multiple Vehicles:	focus on traffic volume	queuing	queuing	the more vehicles in the roundabout, lower probability of driver yielding
Conflict Points:	roundabouts reduce conflict points from 32 down to 8 (FHWA)	pedestrian-vehicle conflict, not conflict point	conflict with vehicle flow, not conflict point	considered only in citing Harkey (2006)

The U.S. studies examined the issue of pedestrian safety at roundabouts in depth. Stone (2002), Harkey (2006) and Rouphail (2005), considered pedestrian decision-making via gap assessment while Hourdos (2012) examined pedestrian yield behavior. This study seeks to more directly isolate the pedestrian’s cross/don’t cross decision. While accident histories for the signalized intersection were available for Stone's (2002) study, the principal investigator has no such available data for either intersection, requiring a different technique. Rouphail (2005) and Stone (2002) used simulation techniques to create models that could be enhanced by seeding with additional data gleaned form a live setting.

2.4 USE OF CONFLICT POINTS AND VIDEO FOR ANALYSIS

Ismail (2009) noted how recognized measures for analyzing traffic conflict data could be applied to pedestrian conflicts at intersections. He also recommended that video could be applied to analyze pedestrian safety at crosswalks. In line with those conclusions, this study, after encountering high traffic volume at various observed intersections, concurred that video was essential for accurate data collection.

Ismail (2009) recommended studying conflict points with video for several reasons: 1) collisions are rare and random, requiring years of study, over which time many factors can change, 2) collision-based safety analysis is reactive, requiring a significant number of collisions to be recorded and 3) collision data reporting is often incomplete and biased toward very severe collisions. In one study noted by Ismail (2009), over a decade, pedestrian-involved collisions accounted for only 3.6% of the all collisions in British Columbia, Canada, 4) pedestrian traffic is sparser than motorized traffic as collecting such data is complex.

Ismail (2009) thus recommended Traffic Conflict Techniques (TCT's) for several reasons: 1) Traffic conflicts are more frequent than collisions, 2) TCT's produce estimates of average accident frequency comparable with those of accident-based analysis. On the other hand, data collection is subject to observer variability, compromising reliability and repeatability of data collection. Employment of human observers can be expensive, including the effort to extract pedestrian data from videos. Ismail (2009) solved these problems with his unique advanced automated video analysis system to "(a) detect and track road users in a traffic scene and classify them as pedestrians or motorized road users, (b) identify important events that may lead to collisions, and (c) calculate several severity conflict indicators."

Ismail (2009) collected video data over two days at an intersection in Vancouver, British Columbia. Four conflict indicators were automatically computed for all pedestrian–vehicle events and provided detailed insight into the conflict process. Simple detection rules on the indicators were tested to classify events. Ismail proved the value of video data collection and automated object analysis as a tool for collecting data on pedestrian safety at roundabouts.

2.5 METHODS OF CONFLICT ANALYSIS

Conflict point analysis or the 'Traffic Conflict Techniques' favored by Ismail (2009) should include the following factors: 1) existence of a conflict, 2) exposure to the conflict (measuring the product of the two conflicting stream volumes), 3) severity of the conflict (relative velocities of the conflicting streams and angle, 4) vulnerability of the pedestrian (survivability) (FHWA, 2000) at p. 104-105 and 5) additional lanes considerably increasing pedestrian conflict points. (FHWA, 2000) at p. 106.

The FHWA (2000) compared vehicle-pedestrian conflicts at signalized intersections and roundabouts. Signalized intersections reduce pedestrian-vehicle conflicts by signal phasing that allows only a few legal movements at any given time. In the diagram below, a pedestrian crossing at a signalized intersection with protected-permitted turns, right on red allowed, creates four vehicular conflicts, each from a different direction, for a total of 16 pedestrian-vehicle conflicts: 1) crossing movements on red (typically high-speed, illegal), 2) right turns on green, 3) left turns on green (legal for protected-permitted or permitted left turn phasing) and 4) right turns on red.

The FHWA (2000) noted that for pedestrians at roundabouts, there are two conflicting vehicular movements on each approach, as shown in their diagram: conflict with entering vehicles and conflict with exiting vehicles.

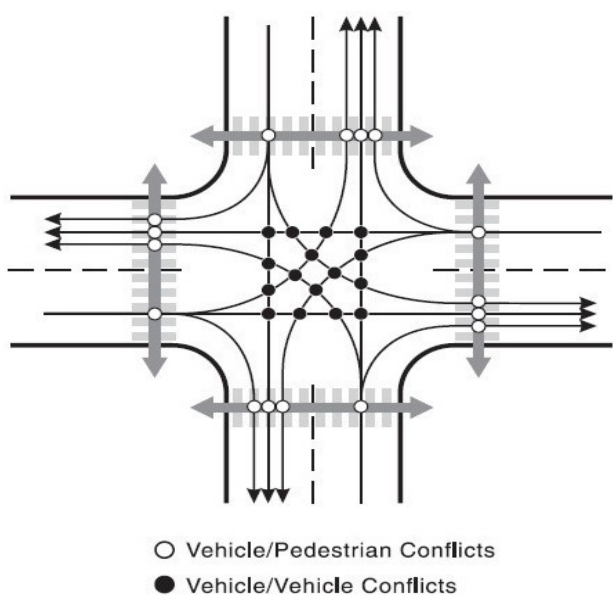

Figure 2.1: Vehicle-pedestrian conflicts at signalized intersections (FHWA, 2000, Ex. 5-5)

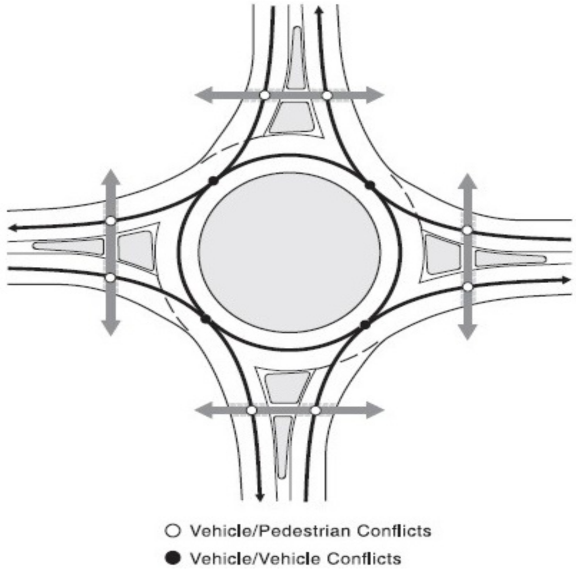

Figure 2.2: Vehicle-pedestrian conflicts at single-lane roundabouts (FHWA, 2000, Ex. 5-6)

With multiple approach lanes, additional conflicts are added with each additional lane that a pedestrian must cross. (FHWA, 2000) at p. 109.

2.6 DISABLED, ELDERLY, VISUALLY IMPAIRED AND CHILD PEDESTRIANS

The FHWA (2000) noted that crash data was non-existent on pedestrians with disabilities at roundabouts. Considerations for vulnerable pedestrians included: 1) roundabout crossing is difficult for disabled pedestrians without help, 2) roundabout legs could be equipped with a pedestrian-activated signal at crossings, 3) heavy vehicle volume leaving insufficient gaps in traffic to cross, may warrant audible signals.

Visually impaired pedestrians are obviously more vulnerable when there is no phasing of traffic and pedestrians. Some of the possible design remedies mentioned in the FHWA (2000) report included: raised speed tables with detectable warnings, treatments for the visually impaired to find crosswalks and raised pavement markers with flashing lights to alert drivers of pedestrians. They concluded that more research is required to develop the information that governments need to determine where installation of roundabouts may be appropriate and what design features are required for people with disabilities.

Rouphail's (2005) work, discussed extensively above, focused on visually-impaired pedestrians and concluded that roundabouts would be safer for visually-impaired pedestrians with certain engineering modifications, but particularly, the installation of traffic signals which negates the entire concept of continuous traffic flow at roundabouts.

2.7 BICYCLE SAFETY AT ROUNDABOUTS

Bicycle traffic is fundamentally different than pedestrian traffic, but bicycles are relatively slow and vulnerable compared to motorized vehicles, like pedestrians. Cumming (2011) noted that bicycles have extra risk at roundabouts as they must enter the circulating lane of a roundabout and follow the flow of motorized vehicle traffic.

Cumming (2011) studied accidents and conflict points in Victoria, Australia from 2005-2009. He noted that at urban roundabouts there was more significant bicycle traffic than was observed at six high- speed rural roundabouts which had relatively no bicycle traffic. Cummings (2011) identifies a much higher number of conflict points or 'conflict streams' at roundabouts than other studies. Cumming (2011) referred to conflict points as ‘Danger Points’ where the paths of two vehicles may coincide. He noted that due to roundabouts having fewer conflict points and the geometry of roundabouts deflecting traffic, it creates safer conditions for motorists than traditional intersections. Cumming (2011) did actually observe eight pedestrian accidents with vehicles at roundabouts over the four-year period of observation, but that was not the focus of his study. He noted greater danger from two-lane roundabouts where the number of bicycle conflict points increases dramatically from four to sixteen.

It is Cumming’s identification of the concept of ‘conflict streams’ that has the most relevance for the current study. It seems truer to the FHWA’s (2000) definition of ‘conflict point’ with converging and diverging traffic, in essence, a pedestrian or bicycle must be observant of streams or paths of vehicle traffic instead of a fixed point.

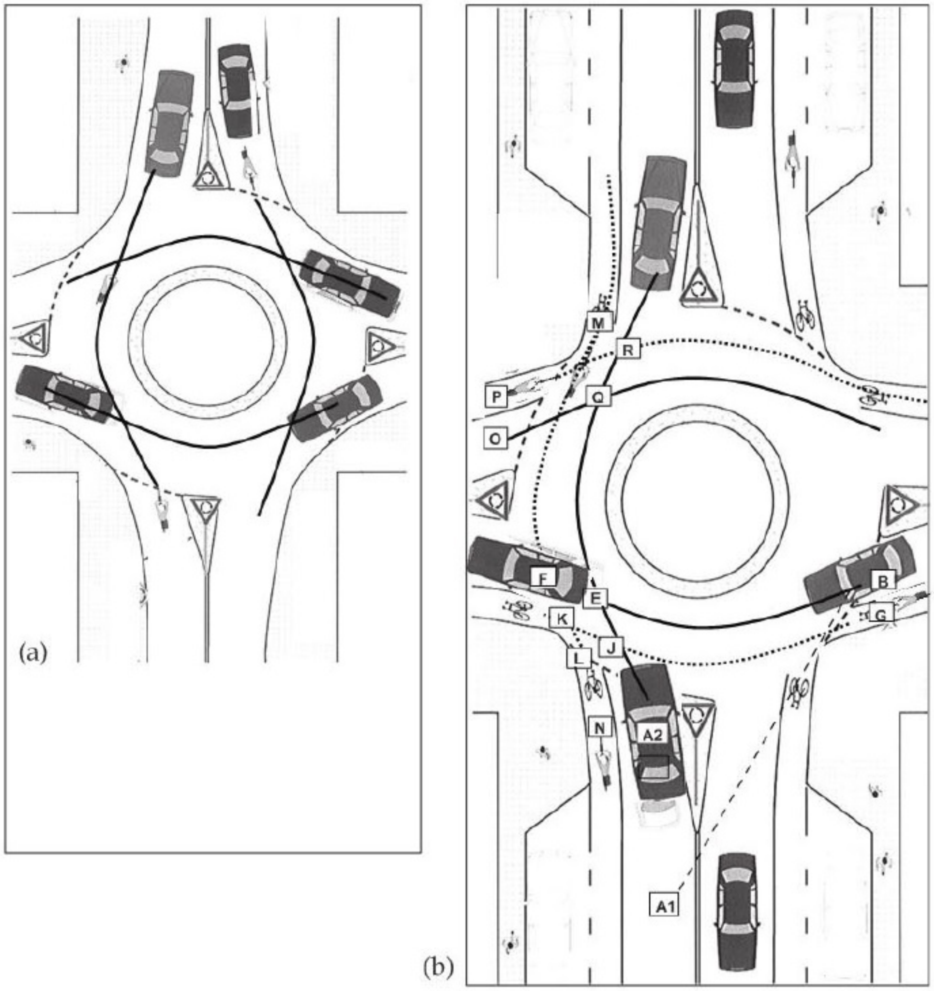

Figure 2: 1-lane roundabout, conflict point scenarios with 1 and 2 traffic streams (Bob Cumming) – (a) cyclists positioned centrally, 1 traffic stream, 4 conflict points (adapted from Austroads, 2009, p. 51); and (b) cyclists positioned at edges, 2 traffic streams, 24 conflict points (adapted from Austroads, 2009, p. 52).

Figure 2.3: One-Lane vs. Two-Lane Roundabout Conflict Points (Cumming, 2011, at p.28)

2.8 RELATED WORK: THE HUMAN PARTICIPANT SIMULATION

The closest related work to this study is the remarkably similar effort by Wu (2009) to use virtual reality to have a human participant actually experience a computer-modeled roundabout environment. While Wu's (2009) effort had exciting possibilities for training pedestrians on how to use roundabouts, his effort combined with the method I propose, could allow this study's method to be used to more extensively model Wu's (2009) simulation and virtual reality system.

Wu (2009) sought to use a virtual reality environment to assess how human participants acting as pedestrians tend to judge the 'gap' between approaching vehicles as they attempt to make a decision to cross a lane of a roundabout like Stone (2002), Harkey (2006) and Rouphail (2005) who also used the gap estimation as a measure. Wu's (2009) simulation used validated models of vehicle behavior to add realism to the experiment. Wu (2009) mentioned the decision-making process, but did not approach the cross/don't cross decision directly.

Wu (2009) focused on the roundabout exit lane crossing only but not the entrance lane as drivers were considered to be less likely to yield when exiting a roundabout, thus creating a more interesting conflict. He did allude to the conflict point conundrum: "The issue is likely to be more confusing in a roundabout, where vehicles can be entering the circulating pathway from several directions" (Wu, 2009, p. 35). He discusses this confusion in terms of 'connecting points', but he describes the ¼, ½ and ¾ approaches in similar terms as this study.

Wu (2009) used The Maya (Autodesk, 2017) and Vizard (Worldviz, 2017) tools to create the simulation model. The model created a variety of traffic scenarios at the virtual roundabout. These tools could model traffic volume, pedestrian volume and vehicle speeds. He programmed the traffic in streams, to allow for multiple vehicle scenarios to affect decision-making. The virtual roundabout provided both visual and auditory cues. Images from the virtual reality roundabout may be seen in Figures 2 and 3 of Wu's (2009) study on p.36.

Wu (2009) used twelve human participants ages 20-45, all able-bodied adults, who were trained on how to use the system. The system simulated speed, paths of approaching vehicles and duration of gaps to test the pedestrian's decision-making. The experiment took place inside a large room. The participants could physically cross when they felt safe and comfortable crossing. In this instance, an unsafe crossing could be thrown out. In real life, the experiment ends with a collision. He simulated crossing in both directions, which allows for the study of facing or not facing circulating traffic.

Limitations included the horizontal field of view, which affects the realism of the experiment to a degree and that the pedestrians would likely be more conservative in their decisions in a real environment. Wu (2009) voiced a concern (shared by Hourdos (2012)) that visually-impaired pedestrians would have safety issues at roundabouts due to confusing auditory cues. Wu's experiment is intriguing as it can safely model behavior of live pedestrians at roundabout crossings, but 1) it lacks some elements of realism, 2) it does not account for traversal of entrance lanes, 3) it doesn't make a comparison to a signalized intersection and 4) while it does reflect pedestrian decision-making, it doesn't focus on the binary cross/don't cross decision. Wu's (2009) model however could be enhanced in these regards with additional data from a live field setting.

The U.S. based studies of pedestrian safety at roundabouts since the year 2000, have used a variety of techniques to gather data. Datasets of actual accidents were reviewed, before and after studies conducted with real data, video software with automated capture of activities was employed and an assortment of computer modeling techniques were used, ranging from statistical modeling tools to virtual reality.

The question is: how can we improve upon modeling given the difficulty and cost of long-term observation of numerous roundabouts? The method proposed in the study, could provide an answer: actual decision-making data from a live pedestrian to build a realistic simulation model.

3.0 HYPOTHESIS, METHODS AND ANALYSIS

3.1 HYPOTHESIS – RESEARCH QUESTION

A review of past literature has shown that roundabouts are a safer alternative for motorized vehicles than signalized intersections, but do roundabouts actually increase risk to pedestrians and non-motorized vehicles? Does the roundabout give the vulnerable pedestrian the same ability to cross a lane of traffic safely as does the signalized intersection? Can a method using a human participant in a field experiment calibrate existing modeling and virtual reality techniques with real world data?

3.1.1 Summary of Methods

In order to answer these questions, this study collected and extracted data from several hours of video at two comparable intersections: The first, a one-lane, four-way roundabout and the other a traditional four-way signalized intersection. The data was manually extracted from the video by observation and recorded into a spreadsheet. Entrance and exit lanes were considered separately and slow pedestrians were simulated to get a better understanding of safety in the crosswalk for the elderly and disabled.

3.1.2 Human Participant in the Field Environment

The principal investigator of this study acted as a staged participant crossing at each lane around each intersection in either a clockwise or counter-clockwise direction in constant motion. At all times, the principal investigator obeyed traffic rules and exercised due caution. In the signalized intersections, cross buttons were always pressed and the principal investigator did not proceed until the walk sign was illuminated, however two of the eight walk sign activation buttons intermittently malfunctioned. This is not uncommon in literature to use oneself as human participant, but it avoids placing another participant at physical risk, albeit, a participant obeying traffic rules and taking due care would be at no more risk than any other pedestrian. Different protocols and participant training will have to be used in future studies attempting this technique if a human participant is involved in the field environment.

3.1.3 Accounting for Bias in the Experiment

Because the principal investigator of this study acted as pedestrian, informal controls were necessary to account for bias in the conduct if the experiment and in decision-making. The principal investigator obeyed all traffic rules at all times. The principal investigator only proceeded in the signalized intersection when the walk signal was illuminated. The principal investigator proceeded with caution where the walk light was malfunctioning. The principal investigator never proceeded into the traffic lane in either intersection when a converging vehicle would have already had right of way under Pennsylvania Law. (In Pennsylvania, as stated above a driver must yield right if way for a pedestrian already in the crosswalk). However, common sense presumes that a driver obeying the traffic laws must be given reasonable time to react to a pedestrian, i.e. a pedestrian cannot enter the crosswalk and deliberately place themselves in imminent danger.

3.1.4 Entrance and Exit Lane Data

The exit lane data documented a pedestrian's cross/don't cross decision upon arrival at each exit lane of traffic at the roundabout. The data included the pedestrian's consideration of vehicles already in the circulatory roadway plus vehicles entering from one of the four entrances at ¼, ½, ¾ and 1 complete revolution from the lane being crossed.

The entrance lane data documented the pedestrian's cross/don't cross decision upon arrival at each entrance lane of traffic at the roundabout, where the pedestrian must assess vehicles in three frames of view: 1) 'Blocking' (physically blocking the pedestrian's path across the lane of traffic), 2) 'In-Frame' (visible to the horizon on the approaching road) 3) 'Out-of-Frame' (vehicle becomes relevant to the crossing decision from over the horizon only because of blocking or in-frame approaching vehicles). The 'framing' concept is presented as a unique innovation in evaluating the pedestrian crossing decision, indicating that the roundabout may be a much richer and riskier environment than the 'one conflict point per lane' concept proposed by the FHWA.

Hourdos (2012), used a similar labeling concept for the legs of a roundabout, with the '¼' lane being at 90°, '½' lane being at 180° and so forth. What this study labels as the '¼' lane is the closest entrance lane to the pedestrian who is crossing the nearest roundabout exit (assuming counter-clockwise U.S. vehicle flow). The labels used in this study are relative positions based on the location of the pedestrian as they cross an exit lane. The '¼' lane is nearest the pedestrian, the '½' lane is across the roundabout, the '¾' lane is opposite the ¼ lane (but ¼ more distant than the

½ lane) and ‘1’ is the entrance lane adjacent to the exit lane the pedestrian is crossing, where the vehicle does a full revolution and exit to conflict with the pedestrian.

The highest risk is from proximity, ‘¼’ away being the most imminent danger, but then, other vehicles may come into play, creating a much higher level of risk than is normally explainable by the ‘one conflict point per exit lane’ concept in the literature. A hypothesis being that the closer the entering vehicle, the more likely the pedestrian will decide in favor of ‘don’t cross’.

This is contrasted with the signalized intersection, where this study examined a pedestrian’s cross/don’t cross decision at each exit or entrance lane of traffic at a phased crosswalk where the pedestrian had to consider vehicular traffic coming from up to three lanes at once to make their crossing decision.

3.1.5 Conflict Streams

Traffic Conflict Techniques were used for analysis rather than a longitudinal survey of roundabouts, as actual pedestrian-at-roundabout accident report data is sparse. Conflict Streams were evaluated in order to account for paths of multiple converging vehicles. I initially used the term ‘conflict vector’ as a label in this studies’ data collection, but it might be confused with the scientific concept of a vector. I did not change the data label, however. ‘Conflict stream’ as used by Cumming (2011) might be a more descriptive term to describe the path of a vehicle as it traverses a roundabout.

This study will complement the video-based studies of Sadeq and Sayed (2009) and the United States studies by Hourdos (2012), Stone (2002), Rouphail (2005), Wu (2009) and Harkey

(2006), but will differ by virtue of capturing data from the pedestrian's perspective with a simple binary cross/don't cross decision instead of a complex gap time estimation, or assessment of driver yielding behavior.

3.2 SITE SELECTION METHODOLOGY

Site selection criteria for this study was similar to the techniques used by the studies referenced herein to find a suitable four-way roundabout and a four-way signalized intersection to compare and contrast as opposed to doing a 'before-and-after' study with actual accident data. However, the amount of time to collect that sort of data is measured in years, as actual pedestrian incidents at Intersections are rare compared to vehicle accidents and extremely sparse where roundabouts are concerned.

Site selection was based on similar methods used by Flannery (2001) in her study. She conducted a three-year study of various roundabouts using actual crash data along with conflict point analysis to understand vehicle safety at roundabouts.

Flannery (2001) reviewed actual accident data, driver testimonials and videotapes developed at roundabouts in Maryland, Florida, and Nevada. She noted the need to improve geometric design on approaches to rural roundabouts to reduce loss-of-control accidents (which were observed to be 47% of roundabout accidents); the need for adequate right-of-way to deflect vehicles around the center island (the center island was a critical part of design for traffic slowing); and in municipal choice of roundabout location, the need for guidance regarding volume-to-capacity ratios. Additional sites were used as case studies despite lacking some of the needed characteristics.

Flannery (2001) noted eight *vehicular* conflict points at a single lane roundabout and 32 at one-lane-in, one-lane-out, four-way signalized intersections based on diverging, merging and crossing traffic flow. The large number of conflict points makes manual recording and observation of vehicle conflict point data nearly impossible at traditional intersections.

Thus, the principal investigator, in line with Flannery's (2001) analysis, restricted this study to pedestrian conflict points and conflict streams. Flannery (2001) noted that some geometry-based safety risks at roundabouts were: lack of proper sight distance, lack of available right-of-way for proper deflection at urban roundabouts, and lack of balanced traffic flows.

Flannery (2001) noted some driver anomalies at roundabouts that could be related to driver unfamiliarity with roundabouts: 1) Drivers increased their speed on entry. 2) Drivers cut across several lanes in the circulating roadway to exit the roundabouts (double-lane roundabout geometry) and 3) several drivers entered the roundabouts by making a left turn and proceeding clockwise to exit.

This study focused on moderate and low speed roundabouts where pedestrian and non-motorized vehicle conflicts would be most likely. Thus, this study sought single-lane roundabouts with good sight distance from all directions, rural roundabout locations and balanced traffic flow in all four directions. Two intersections were compared, the first, being a standard roundabout as defined by PennDOT, the other a standard, nearby four-way, signalized intersection. The choice of a nearby comparable intersection, was to achieve observation of similar traffic composition in terms of driver characteristics and volume. The time of day and week was chosen to be similar as well.

3.2.1 Proof of Concept Data Collection Effort

The objectives of the preliminary data collection were exploratory only, with the goal to: 1) learn techniques for traffic data collection, 2) understand traffic flow, 3) understand pedestrian and other non-vehicular traffic patterns, 4) understand the effects of traffic controls and 5) understand roundabout geometry.

The data collection started with the selection of three intersections as a proof of concept. Data was collected at each intersection between 7:00AM and 8:00 AM on four Wednesdays in February 2017 under good visibility, despite cold temperatures and light rain. Five minutes of data was collected for each leg of each intersection. There were some issues: 1) an engineering schematic would be helpful for each intersection, 2) it is difficult to try to capture data for each traffic signal when there are opposing lanes proceeding and 3) it is almost impossible for a human observer to capture light timing, traffic volume and time through the intersection simultaneously. Three different intersections were selected for observation: 1) a traffic triangle, 2) a yield sign controlled four-way roundabout, both located in South Park, PA and 3) a five-way signalized intersection with pedestrian crossing signals in Bethel Park, PA.

The data collection efforts involved photographs, film and manual counting of vehicles in an intersection. Timings were sampled. Indications of driver confusion, if any, were recorded, such as: not obeying a traffic control, proceeding in the wrong direction of traffic flow or near conflicts with other vehicles or non-vehicular traffic. The roundabout proved inadequate due to inadequate traffic flow from two of the four approaches. The geometry of the comparable three and five-way intersections made them likewise unsuitable for the study. A four-way comparable traditional intersection was preferable instead.

More suitable locations were scouted with the following requirements: 1) both intersections in close proximity for similar volume and type of traffic, with adequate visibility for videography and four approach lanes for similar geometry of traffic and adequate traffic flow, 2) a yield-controlled roundabout with one entrance and exit lane at each approach and 3) a signalized intersection with protected pedestrian crossing signals. Two intersections, near Latrobe, PA, met these criteria. The intersections selected were a roundabout next to St. Vincent's University along Monastery Drive and a contiguous, four-way signalized intersection at PA Route 981 and Monastery Drive. The table below captures characteristics of the selected intersections against Retting's (2003) intervention techniques for safe design.

Table 3.1: Table of Intervention Techniques (Adapted from Retting, 2003)

Intervention	Signalized Intersection	Roundabout	Safety Benefit
Traffic Signal	yes	no	50% fewer pedestrian-vehicle conflicts
Traffic Signal Change Interval Timing	yes	n/a	95% fewer pedestrian-vehicle conflicts
Pedestrian Prompting Devices	(visual, no audio cues)	no	
Advance Stop Lines	yes	(yield lines only)	
Refuge Islands	yes (yellow waiting pad)	(raised splitter islands)	
Crosswalk Marking	yes	No	

3.3 DATA COLLECTION MEASURES

Two sessions of four hours each were observed at each intersection. The video recorded all vehicles at each intersection. The video also documented the pedestrian's decision-making. The data was later extracted to find traffic volume at each intersection. Ismail's (2009) timing measures were not used, as the focus was on the decision itself. The cross/don't cross decision was decided upon as the simplest to record and the most basic indicator or safety that could answer these research questions: 1) how likely is a pedestrian to make a decision to cross a lane of traffic at the signalized intersection compared to the roundabout? 2) which factors influence the cross/don't cross decision?

3.3.1 Video Camera Data Collection

A 'GoPro Hero Session' video camera system with accompanying 'GoPro Capture' App were used from a single fixed emplacement at each intersection as selected by the videographer. The VLC Media Player software (VLAN, 2016) was used for video playback video to permit manual transcription of the video data to a spreadsheet. Variables for video collection included: 1) unobstructed views allowing capture of all vehicles and pedestrians entering and exiting each intersection, 2) battery life to ensure at least four hours of video and 3) clear resolution to ensure that the vehicles and pedestrians could be correctly counted during playback.

3.3.2 Method: Contemporaneous Comparator Data

There was no empirical data for the roundabout at Monastery Drive prior to its installation (PennDOT 2016b; PennDOT 2016d). Existing data from 'before and after' studies of pedestrian safety at roundabouts in the United States was almost non-existent. Thus, the method of finding a comparable signalized intersection and then comparing data between the two was chosen for this study.

Assumptions included: 1) drivers generally obey traffic law, 2) the pedestrian can reasonably rely on signals when if legally in crosswalk, 3) the pedestrian has an unobstructed view of each intersection and 4) the rational human participant will make safe, valid crossing decisions.

The data would address the following questions in this study:

- How many 'cross/don't cross' decisions made under each circumstance and why?
- How many 'cross' decisions will the slow pace pedestrian make compared to the standard pace pedestrian?
- At which location is the pedestrian more likely to make a 'cross' decision?
- Is the roundabout more dangerous for all pedestrians?
- a pedestrian moving counter-clockwise (back to traffic) has less opportunity to assess safety of a crossing decision and will make fewer 'cross' decisions
- a pedestrian moving clockwise (facing traffic) has a better opportunity to assess safety of a crossing decision and will make more 'cross' decisions
- multiple vehicles create greater risk for pedestrians

Table 3.2: Data Description

Label	Data	Description	Where Collected
Decision	cross/don't cross (binary)	the pedestrian decides whether to cross a lane of traffic or to wait for a safer opportunity	each lane crossing
Conflict Stream – Signalized Intersection	left front right front left rear right rear (nominal)	the direction of an approaching vehicle from the pedestrian's reference at the point of crossing	each lane crossing
Conflict Stream – Roundabout Entrance Lane	Blocking in-frame out-of-frame (nominal)	the proximity of approaching vehicles in proximity to the pedestrian	each lane crossing
Conflict Stream – Roundabout Exit Lane	¼, ½, ¾, 1+, in-the-circle (vehicles moving inside the circular roadway) (nominal)	proximity of approaching vehicles from the four approach directions from the pedestrian's reference at the point of crossing	each lane crossing
Multiple Vehicles	number of vehicles influencing a pedestrian's crossing decision (numeric)	vehicles may queue and limit opportunities to cross until some or all have passed the point of crossing	each lane crossing
Pace of Travel	Standard - 3.5fps Slow - 1.75 fps (nominal)	simulates an able or disabled pedestrian's walking pace	each hour of data
Total Traffic Volume	average per hour (numeric)	total vehicle count	all traffic
Traffic Influencing the Decision	relevant, irrelevant (count)	vehicles which influence the pedestrian's decision to cross	all traffic
Direction of Travel	Clockwise counter-clockwise (nominal)	clockwise walking direction faces traffic in the roundabout	each half hour of data

3.3.3 Data Scenarios

The following scenarios were observed with one hour of video data each:

- Scenario 1: Roundabout, Standard Pace, CCW (Counter-Clockwise) Direction
- Scenario 2: Roundabout, Standard Pace, CW (Clockwise) Direction
- Scenario 3: Roundabout, Slow Pace, CCW Direction
- Scenario 4: Roundabout, Slow Pace, CW Direction
- Scenario 5: Signalized Intersection, Standard Pace, CCW Direction
- Scenario 6: Signalized Intersection, Standard Pace, CW Direction
- Scenario 7: Signalized Intersection, Slow Pace, CCW Direction
- Scenario 8: Signalized Intersection, Slow Pace, CW Direction

3.3.4 Data Coding: Roundabout

Data Set 1: Standard Pace/**Data Set 5:** Slow Pace, Walking Direction, Counter-Clockwise.

Data Set 2: Standard Pace/**Data Set 6:** Slow Pace, Walking Direction, Clockwise.

1. Exit Lane (Traffic exits from the Circulatory Roadway on the left/behind)
    a. C - car is already in the circulatory roadway
    b. ¼ - car is in the nearest entrance lane, ¼ of the distance to the exit lane
    c. ½ - car is on the opposite side of the circulatory roadway, ½ of the distance to the exit lane
    d. ¾ - car is at the furthest distance from the exit lane, ¾ of the distance to the exit lane
    e. M - Multiple cars in the Circulatory Roadway Grouped on one line In Italics
    f. 1+ - car travels at least 360° around the Circulatory Roadway before exiting

2. Entrance Lane (Traffic is entering the Circulatory Roadway from the right)
    a. B - Car is blocking the pedestrian’s path or imminent
    b. F - Car is traveling towards the Circulatory Roadway and is within the horizon

c. O - Car is traveling towards the Circulatory Roadway and is not within the horizon until the pedestrian has to make a decision to cross

3. Total traffic volume per hour.

- Total Hourly Traffic (THT) will be collected as THT = TTR + TTI
- Total Traffic Relevant (TTR) (traffic with an effect on the crossing decision)
- Total Traffic Irrelevant (TTI) (traffic with no effect on the crossing decision)
    - o Vehicle passes after the pedestrian clears the conflict point
    - o Vehicle crosses a lane which is not a conflict point for that pedestrian

Figure 3.1: Still from Video of Roundabout Pedestrian Simulation

3.3.5 Data Coding: Signalized Intersection

Data Set 3: Standard Pace/**Data Set 7:** Slow Pace, Walking Direction, Counter-Clockwise

1. Exit Lanes (Traffic exits from the Signalized Intersection)

a. car is already in the intersection
b. car is in front turning legal left
c. car is from behind turning legal right
d. multiple cars in the intersection
e. car violates no right/left on red or runs red light

2. Entrance Lane (Far Lane) (Traffic is entering from the right on legal right on red) Time the pedestrian waits on the safety pad until the car passes or stops

3. Total traffic volume per hour.

Data Set 4: Standard Pace/**Data Set 8:** Slow Pace, Walking Direction: Clockwise

1. Exit Lanes (Same)

2. Entrance Lane (Near lane) (Same, except traffic is entering from the left on legal right on red)

3. Total traffic volume per hour.

Figure 3.2: Still from Video of Signalized Intersection Pedestrian Simulation

3.3.6 Data Extraction Technique

A spreadsheet was prepared with the column attributes for each data item listed in the previous sections. The video was played back by the principal investigator in twelve-minute segments. The start and stop time of day was recorded. The pedestrian was observed in each scenario as they approached each lane of each type. The pedestrian decision at each lane crossing was recoded into either a ‘cross’ or ‘don’t cross’ column in relation to each vehicle that influenced the crossing decision. Total traffic volume was recorded and then categorized as influencing the pedestrian’s crossing decision (recorded as relevant traffic) or not influencing the pedestrian’s decision (recorded as irrelevant traffic). Columns were added to aggregate data and determine crossing percentages under each circumstance. Charts were then prepared from the data to cluster or compare data.

4.0 EMPIRICAL DATA

The advantage of empirical data obtained from observation is that real-world observations of U.S. traffic patterns for this specific purpose can lead to more comprehensive modeling of the issue of pedestrian safety at roundabouts. Wu's (2009) virtual reality method could be expanded to entrance lanes of roundabouts and even extended to comparison studies of signalized intersections.

4.1 LIMITATIONS AND WEAKNESSES OF THIS STUDY

The weaknesses of this study are that 1) it depends upon the reliability of human and video observation and data collection at a busy intersection, and 2) the principal investigator as human participant may unknowingly bias the results. The only other options are observations of the public (Sadeq and Sayed, 2016), virtualized environments with human participants (Wu, 2009) or simulations Stone (2002).

Another limitation was that data had to be manually observed from video and then transcribed to a spreadsheet, leading to transcription errors. A more extensive effort could use electronic civil engineering traffic monitoring systems for more accurate counts or use carefully-placed video monitoring systems which included advanced data- scraping object recognition and analysis software.

This study could have also compared odd-geometry intersections such as three and five-way, stop-sign controlled intersections, mixed-control intersections and roundabouts with multiple lanes or roundabouts with lighted crosswalks, but the added complexity would make valid comparisons difficult without carefully defined parameters.

4.2 CASE STUDY: ROUNDABOUT AND SIGNALIZED INTERSECTION, UNITY TOWNSHIP, PENNSYLVANIA

A roundabout needed certain characteristics as defined in the literature to be a good subject for the comparison study: 1. four-way like the comparator signalized intersection, 2. yield-based entry, roughly equal and constant traffic flow from all directions, good fields of observation and one-lane rather than multi-lane approaches and circular roadway.

4.2.1 The Roundabout

The Monastery Drive roundabout is located just below St. Vincent's University on one end and a highway on the other. It met all of the required characteristics, except it lacked a marked pedestrian crosswalk. It proved to otherwise be a sufficient location for evaluating pedestrian decision-making and conflict stream data.

Intersection 1: Monastery Drive/Saint Vincent Drive, Latrobe, Unity Township, Westmoreland County, Pennsylvania, USA Type: Roundabout; Status: Existing; Control Type: All Way Yield; Year Completed: 2010; Approaches: 4; Latitude: 40.2957; Longitude: -79.39741:

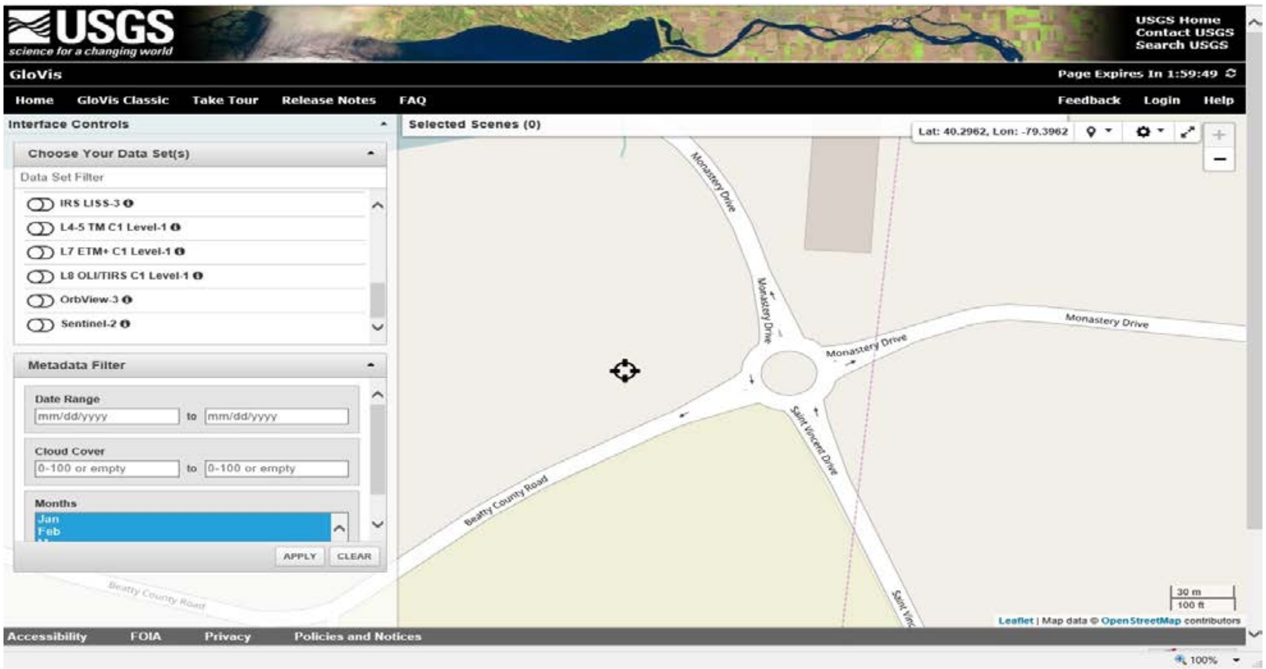

Figure 4.1: Monastery Drive Roundabout (Glovis, EROS Center, USGS, 2017)

Reprinted with permission of Glovis, courtesy of the USGS Earth Resources Observation and Science (EROS) Center, U.S. Geological Survey (2017)

Traffic at the roundabout was moderate and constant in all directions. It averaged about 450 vehicles per hour. All manner of traffic proceeded through the roundabout during my observation: a runner, a walker, a bicycle, a three-wheeled motorcycle, two-wheeled motorcycles, pickups hauling trailers and cars. Traffic slowed significantly upon approach.

The geometry has no marked pedestrian walkways or sidewalks. Splitter islands on all four approaches allow a pedestrian to only look one way when crossing each entrance lane. Each pedestrian crossing of a lane took about 5-6 seconds for an able adult on foot, while paying attention to traffic. Pedestrian crossing points were marked with ‘P1’ to ‘P8’ for reference.

4.2.2 The Signalized Intersection

The signalized intersection also required certain characteristics: 1) traditional four-way intersection, 2) signalized control at each entrance, 3) signalized and marked pedestrian crossing, 4) moderate and constant traffic flow from each approach, 5) clear fields of observation for the video camera.

The Four-Way signalized intersection at Monastery Drive and State Route 981 in Unity Township, Westmoreland County, Pennsylvania was deemed suitable. It averaged about 725 vehicles per hour. Route 981 is a relatively high-speed state road. Four approaches converge at the traffic light into three three-lane approaches and one two-lane approach.

There are marked pedestrian crosswalks with button press to request a crossing signal. The buttons were pressed on every crossing. The signal buttons on the east side of the signalized intersection were malfunctioning and did not elicit the walk light at all. Pedestrian crossing points are marked with a gold ‘P’ at each lane.

There were eleven lane crossings for pedestrians. Twelve conflict streams were observed. The pedestrian signal blocked converging vehicles from directly across the signalized intersection and blocked a right turn with a ‘no turn on red’ sign. The only converging vectors were permissive right into the exit lanes, permissive left into the exit lane and permissive right at the entrance lane (where permitted). This indicated only twelve possible conflict streams and not twenty-four or thirty-two as the literature assumed.

A conflict stream as “a vehicle approach which influences a pedestrian’s cross/don’t cross decision at a given vehicular approach lane”. The conflict stream provides a more realistic measure of vehicle-pedestrian convergence than the static conflict point. Pedestrians, in real-life, must beware of moving traffic, not artificially designated points on the ground.

Intersection 2: Monastery Drive and 5919 Pa. 981, Unity Township, Westmoreland County, Pennsylvania, USA. Type: Four Way Intersection; Status: Existing; Control Type: Traffic Light; Year Completed: Unknown; Approaches: 4; Latitude: 40.2958; Longitude: -79.3941:

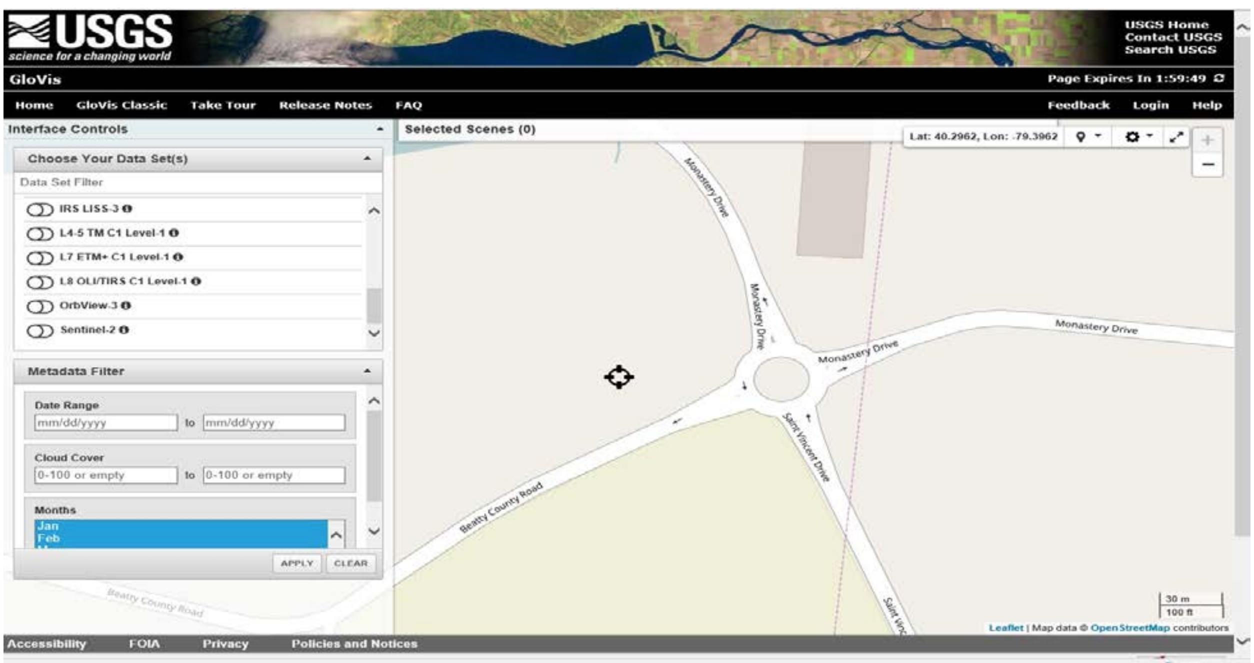

Figure 4.2: Pa. Route 981 Signalized Intersection (Glovis, EROS Center, USGS, 2017)

Reprinted with permission of Glovis, courtesy of the USGS Earth Resources Observation and Science (EROS) Center, U.S. Geological Survey (2017)

Approximate traffic light and pedestrian light times were recorded below. Traffic was moderate to heavy in all directions and often relatively high-speed, around 45-50 MPH. The crossing required an alert pedestrian or bicyclist. Pedestrian runners and a bicyclist were observed, albeit rarely, along with all manner of vehicular traffic. Observation of the signalized intersection was good in all directions

Timings were taken facing the traffic lights from the viewpoint of the driver of an automobile. Pedestrian walk signals were observed from the viewpoint of the pedestrian. Vehicle and pedestrian counts were not taken at the proof of concept evaluation of the intersection. Pedestrian walk signals were roughly 20 seconds total, traffic lights were 7-10 seconds for protected turns and 14-33 seconds for through traffic.

The issue with the roundabout in Latrobe, Pennsylvania along Monastery Drive is that the yield-controlled roundabout lacks pedestrian crosswalks, creating a mismatch in geometry with the signalized intersection. The ideal roundabout would have had pedestrian crossings. Neither location had sidewalks, making them relatively comparable. While the goal was to find the perfect comparable intersections within a reasonable driving distance of the School of Computing and Information in Pittsburgh, Pennsylvania, these intersections, proved sufficient, as perfect geometry is not always available without a more intensive national or regional survey.

4.3 ANALYSIS

More accurate empirical data based on live participants may help validate whether roundabouts are safer for pedestrians than signalized intersections by improving existing automated modeling techniques. The lack of controls for elderly pedestrians, children or the visually impaired to traverse roundabout crossings with continuous traffic flow is a known safety issue. (Rouphail, 2005). This concern may require re-design of roundabouts where pedestrian traffic may be high regardless of whether the location is rural or urban. Due to the scarcity of existing data, consideration of conflict streams together with conflict points may add precision to traffic conflict techniques for assessing the question of safety at roundabouts.

Computer simulation, modeling and virtual reality simulation have proven to be effective tools to understand pedestrian safety risks at roundabouts (Wu, 2009). Experiments such as this one could feed valuable real-world data about pedestrian decision-making into simulation systems like Wu's (2009) virtual reality to create a more accurate assessment of safety risks at roundabouts without requiring extensive surveys.

4.3.1 Case Study Experimental Design

The design of the experiment that is the foundation of the case study is simple. There are not an adequate number of pedestrians to study at most of the suitable modern roundabouts. Thus, the principal investigator acts as pedestrian in a constant movement around the intersection. The most critical assumption of the experiment, is that a rational actor, acting as pedestrian, doesn't want to be struck by a vehicle. Hence the method of using a live participant as the pedestrian moving across conflict streams at real intersections making rational cross/don't cross decisions is internally valid.

This method has several benefits: 1) there is an adequate supply of data (Preliminary observation at different intersections showed that pedestrian and bicycle traffic were almost non-existent), 2) every standard pedestrian scenario is covered and 3) the movement of the pedestrian and the cross/don't cross decisions are easily tracked by video.

The unique aspects of this study are: 1) examination of pedestrian’s perspective of safety at roundabouts, 2) use of the conflict stream instead of conflict point as the true influence in the pedestrian’s decision and 3) use of human participant in a field experiment data on real roundabouts as a basis for simulation data. The relevant data include: 1) the cross/don’t cross decision, 2) the pedestrian’s perspective of approaching traffic that influenced these decisions and 3) total traffic volume per hour.

The current study is unique as that the principal investigator used himself as a simulation tool, by constantly circling each intersection. Video was taken from ground-level to capture the pedestrian's perspective. The study did not focus on timings, as a rational pedestrian doesn’t think in terms of timings. Pedestrians are not standing at a crossing point with a stopwatch, but rather, estimating vehicle distance, gaps between vehicles, vehicle approach speed and visual cues such as activated turn signals or driver eye contact.

Data was manually transcribed by observing playback of the recorded video and performing a manual count of vehicles and decisions. The manual counting may be imperfect (missing counts while viewing hours of film), but object recognition software could also be imperfect (inability to recognize certain objects or distinguishing individual objects among groups of objects).

There are many observations about the data that must be defined, explained or clarified. The key item of data is the ‘cross/don’t cross decision’. This is where the participant pedestrian must decide whether it is safe to proceed across a single lane of traffic. The key assumption is that an intersection-type where a pedestrian makes significantly more ‘cross’ decisions per lane versus don’t cross decisions, is safer than another intersection where the percentage of cross decisions is much lower.

4.3.2 Crossing Position

For this study, ‘crossing position’ is defined as the physical point where the pedestrian is standing at the traffic lane and must make a decision to cross or not cross. On the video, the pedestrian can be observed turning their head to look for traffic as a signal that they are in a crossing position. The pedestrian may also turn body towards oncoming traffic to signal that they are in a crossing position. Decisions are only counted from the point where the pedestrian has assumed the crossing position, otherwise it is premature, likewise if the pedestrian has already entered the traffic lane.

4.3.3 Traffic Volume

Traffic video was made on a weekend day and on a weekday. The day of the week showed more traffic on a weekday than a weekend, but the differences in traffic volume were not significant. A higher traffic volume could affect the comparison between the two intersections, but does not impact the cross/don’t cross decision-making process in any observable way. The volume of traffic relates more to site selection and not intersection geometry. Traffic volume can be seen in the table. Total traffic is differentiated from relevant traffic. Relevant traffic is defined herein as that traffic which enters into the pedestrian’s decision-making process. The total of all traffic through both intersections was manually recorded from the video. A total of 4,889 vehicles went through both intersections. The chart shows almost twice as much traffic at the signalized intersection.

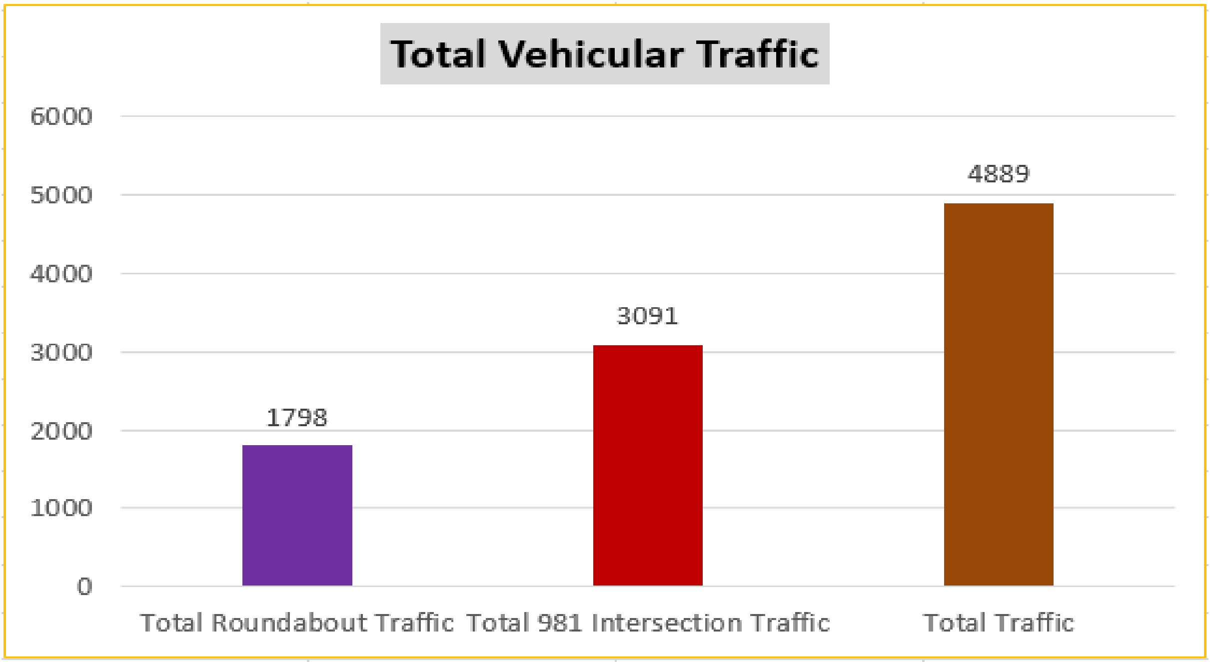

Figure 4.3: Chart of Total Vehicular Traffic

A total of 3,091 vehicles were observed at the signalized intersection (Route 981) in four hours of video, of which only 8.70% were relevant to the cross decision, while 1,798 vehicles were observed at the roundabout in four hours of video, of which fully 48.94% factored into the cross/don't cross decision. The preliminary indication was that a pedestrian had to be eight times as alert to traffic at the roundabout as at the signalized intersection. This was an unexpected result. The chart shows the huge disparity in 'relevant traffic'.

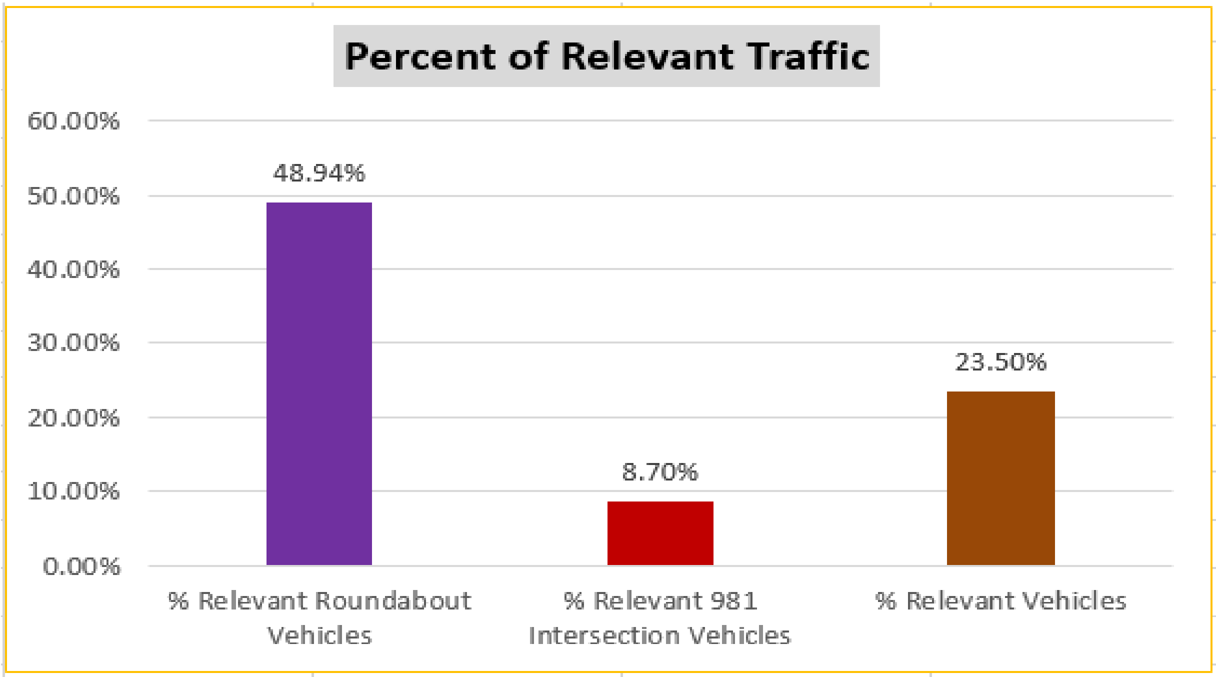

Figure 4.4: Chart of Percent of Relevant Traffic

The signalized intersection was on a main, undivided highway with traffic going to and from Latrobe and U.S. Route 30. The pedestrian's direction of travel, clockwise vs. counter-clockwise, is independent of traffic volume, as each conflict is a single decision. Volume of traffic does factor into pedestrian decision-making, when the traffic is clustered around one particular lane crossing decision as multiple vehicles tend to queue up over time when the slow pedestrian is trying to cross one lane of traffic. Total traffic by direction of pedestrian travel was recorded to test a hypothesis that where the pedestrian faces traffic at exit lanes, they would make significantly more cross decisions as they could observe the closest converging vehicles.

4.3.4 Roundabout Geometry

The roundabout at Monastery Drive and St. Vincent's Road is not to modern code (FHWA, 2000). It had a tree and sign in the center island that obstructs the view from two angles of entry. It has no marked crosswalks. It does have a slowdown marking where a crosswalk would be hypothetically located on the entrance lane. The roundabout does have splitter islands which can be used for pedestrian refuge.

Speed limits at the roundabout are 15 miles per hour (mph) from all directions, as a consequence, most drivers approached the roundabout slowly. Drivers did not appear to know how or when to use turn signals once in the circular roadway portion of the roundabout. Use of a signal can be confusing as it could be difficult to determine when to signal, i.e., a signal too early or too late could indicate the wrong exit point to another driver or pedestrian. Traveling a full circuit through the circular roadway is rare. It is used on purpose for making a U-turn or change of mind, see for example, Hourdos' (2012) 360□ U-Turn Concept.

It was also difficult to define when a vehicle is in the circular roadway once the pedestrian assumed a crossing position. For the purposes of the experiment, it was assumed that once a vehicle had started to enter the circular roadway and/or was still within the circular roadway when the pedestrian assumed the crossing position, it was assumed to be 'in the circle'.

4.3.5 Signalized Intersection

Speed limits for the signalized intersection at U.S. Route 981 are 25 mph on Monastery Drive and 40 mph on State Route 981 on the approach to the signalized intersection. There are protected pedestrian crosswalks with 20 seconds or less of crossing signal time. One of the entrance lanes, Monastery Drive (eastbound), has a protected right-turn light and the two opposing entrance lanes on Route 981 have protected left-turn lanes. The data is ranked by percentage of decision to cross for each feature. Slow pedestrians tended to make significantly lower cross decisions than the standard speed pedestrians in almost every situation.

4.3.6 Crossing Decisions

The crossing decision is simply cross or don't cross. By don't cross, the pedestrian waits for the next opportunity to cross that particular lane. No matter how many vehicles come through that conflict point, it only counted as one decision. Some decisions might be hurried out of safety, technically, this might be considered a bad cross, but an effort was made to be sufficiently careful so as not to affect the results.

Some drivers made eye contact out of courtesy, forming an unspoken agreement that the pedestrian was permitted to cross. Acting as pedestrian, I would wave my hand to allow a vehicle to proceed, as the initial decision was 'don't cross' based on the proximity of the vehicle and the goal was to accurately reflect that decision in the data.

The chart below illustrates the number of separate decisions that had to be made by the pedestrian at each intersection type. The roundabout required three times as many decisions as the signalized intersection, indicating a riskier environment where the pedestrian had to be significantly more alert to approaching vehicles.

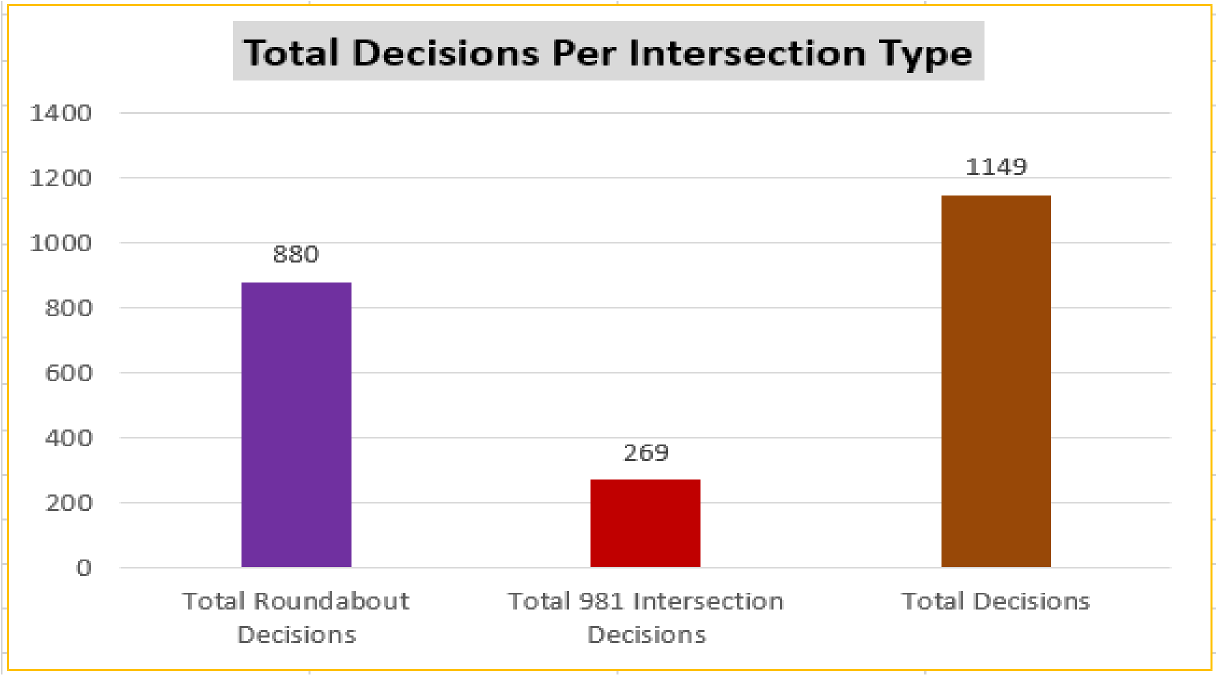

Figure 4.5: Chart of Total Decisions per Intersection Type

4.3.7 Roundabout Entrance Lane "Frame"

The concept of 'frames' was developed to capture the nature of the approaching vehicle at the roundabout entrance lanes from the pedestrian's perspective. Here, geometry dictated this measurement. A blocking vehicle, is one that is already stopped or moving into the circular roadway literally blocking the pedestrian's attempt to cross the entrance lane.

'In-frame' means that the vehicle was visible when the pedestrian arrived at the crossing position. 'out-of-frame' vehicles, were vehicles that appeared on the horizon immediately after the pedestrian assumed the crossing position, but were moving at such a high rate of speed or otherwise part of an existing queue of entering vehicles, such that the out-of-frame vehicle still *influenced* the crossing decision. When the pedestrian was walking at the slow pace, many more out-of- frame vehicles at became relevant at the roundabout entrances.

4.3.8 Observed Differences between the Signalized Intersection and the Roundabout

It is worth restating the hypothesis for the purpose of the case study: would pedestrians be safer if the signalized intersection at 981 and Monastery were replaced by a roundabout? Entrance lane cross decisions percentages are illustrated in the table below. The pedestrian made significantly fewer decisions to cross an entrance lane at the roundabout 19% than at the intersection 62%.

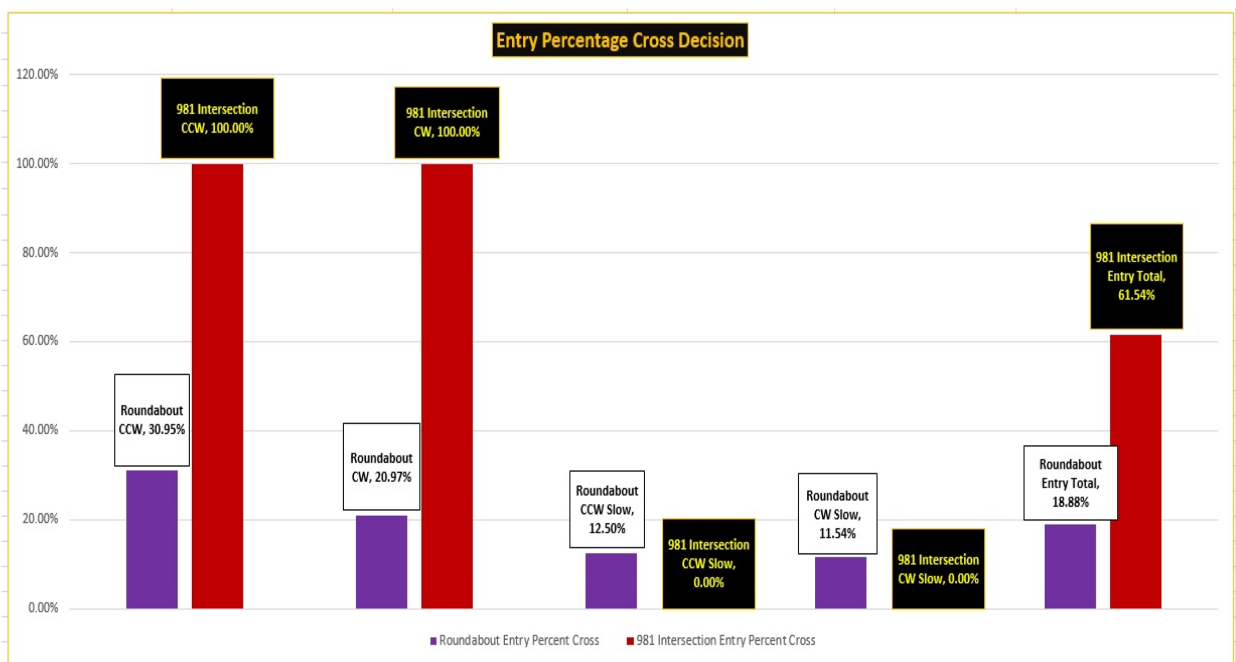

Figure 4.6: Entrance Lane Percentage Crossing Decision

Exit lane percentage cross decisions are illustrated in the table below. Across all categories, the pedestrian made significantly fewer decisions to cross at roundabout exit lanes, a rate of 29% than at the signalized intersection exit lanes, a rate of 77%. This could be due to several factors.

One of course is signalization. Cross traffic is literally stopped by the red-light signal, so traffic cannot traverse the intersection into an exit lane while the pedestrian crossing signal is activated. At one of the lanes, the protected red light was restricted by a ‘no turn on red’ sign which turned off the permissive red arrow signal when the pedestrian crossing signal was activated, preventing the nearest vehicle from turning right on red from Monastery Drive eastbound and crossing the pedestrian’s path in the exit lane of northbound-facing U.S. Route 981.

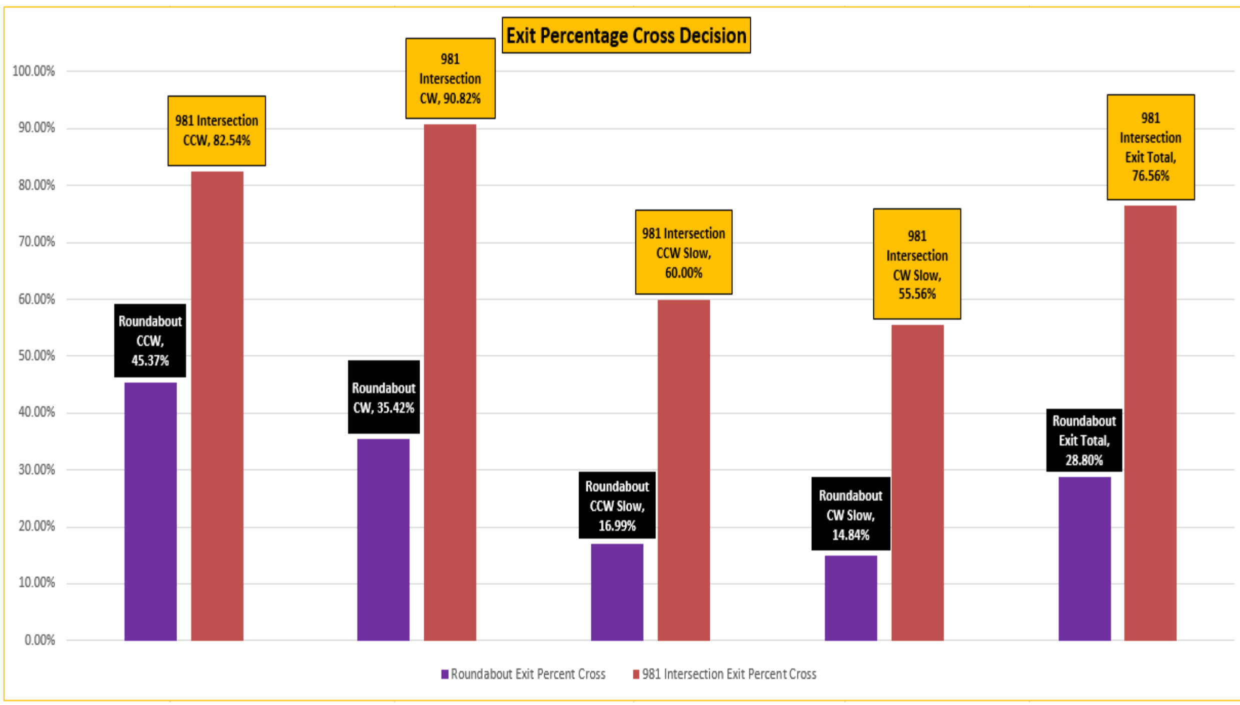

Figure 4.7: Exit Percentage Cross Decision

The decision to cross roundabout entrance lanes depended largely on how close the approaching vehicles were to the pedestrian. Blocking vehicles required almost always a ‘don’t cross' decision. 'In-frame vehicles often were in close enough proximity to require a 'don't cross' decision. So-called 'out-of-frame' vehicles were adequately distant to most often permit the pedestrian to make a 'cross' decision. A caveat, is that the small sample size must be taken into account.

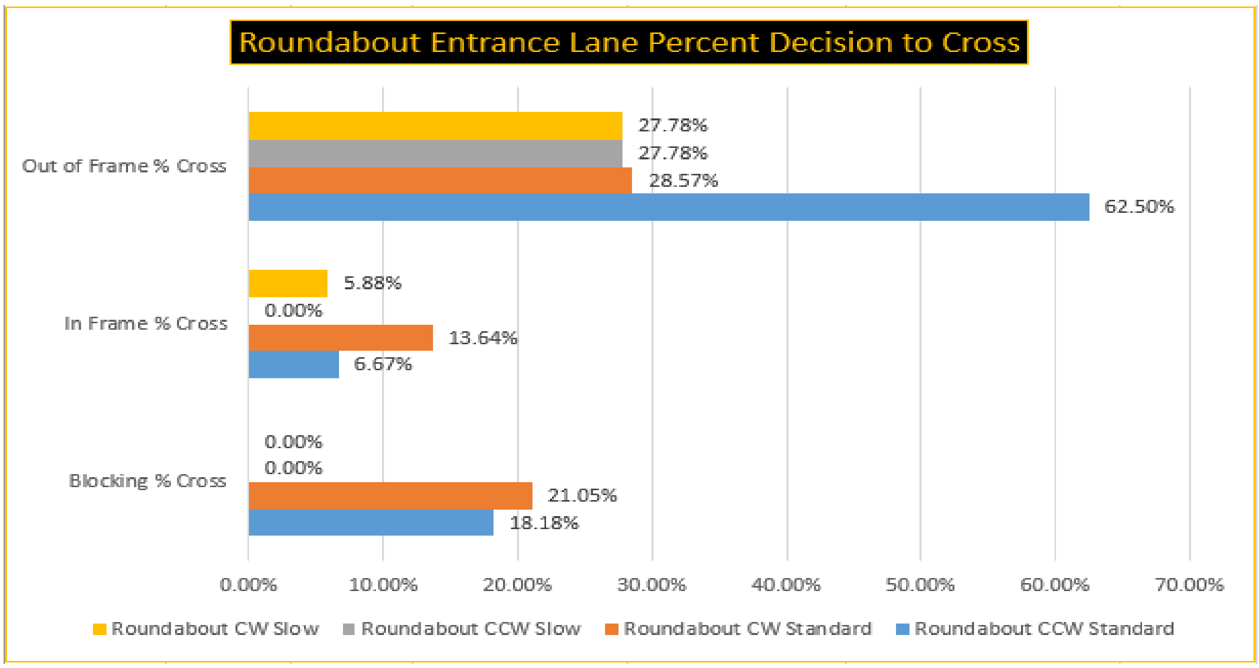

Figure 4.8: Decision to Cross a Roundabout Entrance Lane Chart

At the roundabout exit lanes, results were similar, the closer the proximity of the entering traffic ¼ turn, ½ turn, or the closer the proximity of moving traffic, by virtue of being within the circular roadway (in-the-circle) the more likely decision by the pedestrian in the interest of safety was 'don't cross'. The sample sizes are relatively well-balanced.

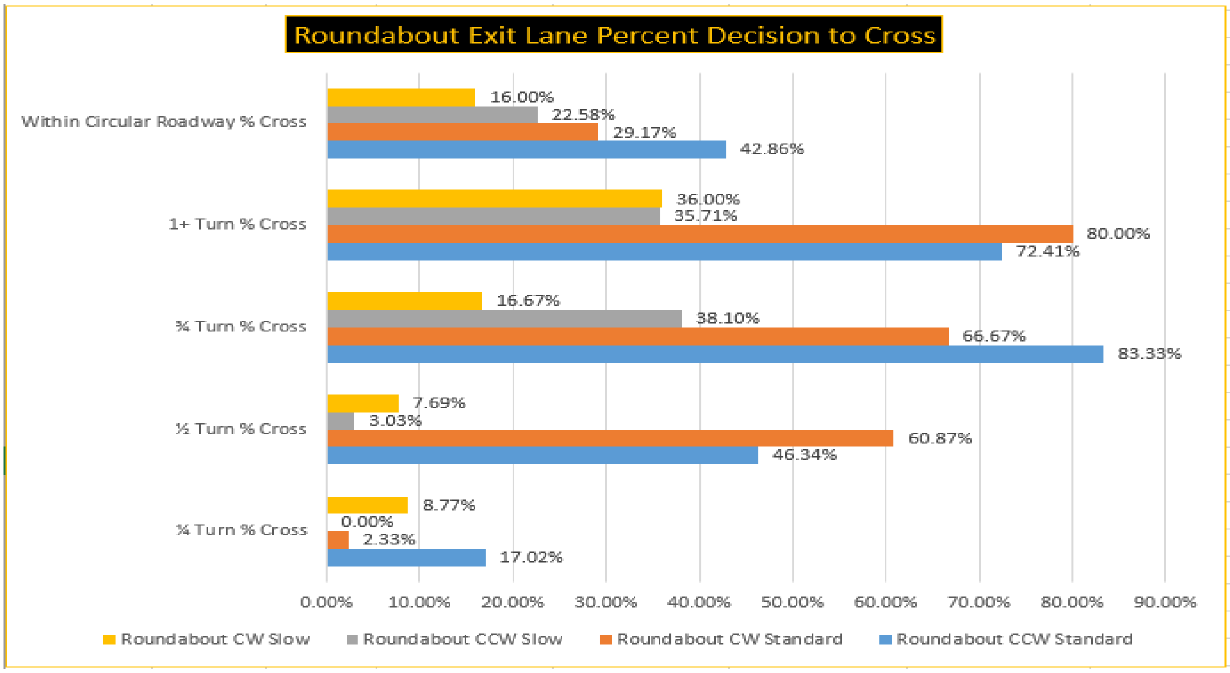

Figure 4.9: Decision to Cross at a Roundabout Exit Lane Chart

At the signalized intersection, due to the signalized pedestrian crossing light, entrance lane crossing decisions were rare or were rendered mostly unnecessary due to the traffic being stopped by the red-light signal. At exit lanes, the pedestrian favored a ‘cross’ decision where the approach was permissive right on red and mixed if it was a permissive left. This higher rate of crossing at the intersection was curious, despite the presence of much higher traffic volume at the signalized intersection. It appears to relate to the protected crossing signal unexpectedly eliminating some of the conflict streams.

While one of every two vehicles factored into a pedestrian's decision whether to cross a roundabout lane, only one of *twelve* vehicles factored into a pedestrian's decision whether to cross a signalized intersection lane which was is protected by a pedestrian walk signal. These conclusions are supported by the data, which showed that a pedestrian had to make three times as many decisions when crossing a roundabout lane as when crossing a protected pedestrian lane at a signalized intersection. However, despite almost twice as much traffic volume at the signalized intersection, the pedestrian had a much smaller number of decisions to make at the signalized intersection than at the roundabout.

Clusters of vehicles were more relevant at the roundabout in decision-making then at the protected pedestrian crossing at the signalized intersection. This could be due to the signals controlling the flow of traffic in a more predictable manner, than at the roundabout with the constant flow of traffic.

At exit lanes in both intersection types, the slow pedestrian made many fewer cross decision than the faster pedestrian. This could be due to different factors at each type of intersection. At the signalized intersection, exit lanes could be approached by vehicle from up to three directions. At the roundabout, as described above, there could be five directions of vectors from which vehicles could approach the pedestrian's lane of crossing.

4.3.9 Direction of Travel

Vehicles travel in a counter-clockwise direction in a roundabout in the United States (turning to the right upon entering). For the pedestrian's direction of travel, walking clockwise in the roundabout goes against traffic flow, thus the pedestrians is facing traffic, permitting safer crossing decisions. The counter-clockwise direction is with traffic flow and is more dangerous, because exiting traffic, especially from only ¼ of the circle away from the pedestrian is behind the pedestrian's back, forcing them to look over their shoulder.

Direction of travel was recorded to test a minor hypothesis: that the pedestrian facing traffic (clockwise) in the circular roadway of the roundabout would make significantly more ‘cross’ decisions then the pedestrian opposing traffic, as both the ¼ and ½ entries were directly in front of their field of observation at the crossing point. The only anomalous result is indicated in the Figure showing ‘*Decision to Cross at a Roundabout Exit Lane*’ where the pedestrian moving clockwise seemed to make significantly fewer decisions to cross for traffic already in the circular roundabout and traffic at ¾ vector from the pedestrian when crossing an exit lane. This could be due to the clockwise-moving pedestrian better observing and assessing the risks of the moving traffic in the circular roadway, while difficulty of assessing the approaching ¾ traffic causing the pedestrian to perceive more risk from the ¾ vector.

Direction of the pedestrian’s travel did not show a significant influence upon their decision-making, despite the clockwise pedestrian being able to face traffic in the roundabout. The differences in crossing decisions seemed to be negligible no matter which direction of travel the pedestrian took around either type of intersection. See the chart of direction for the signalized intersection with relatively equivalent decision-making no matter the pedestrian’s direction of travel.

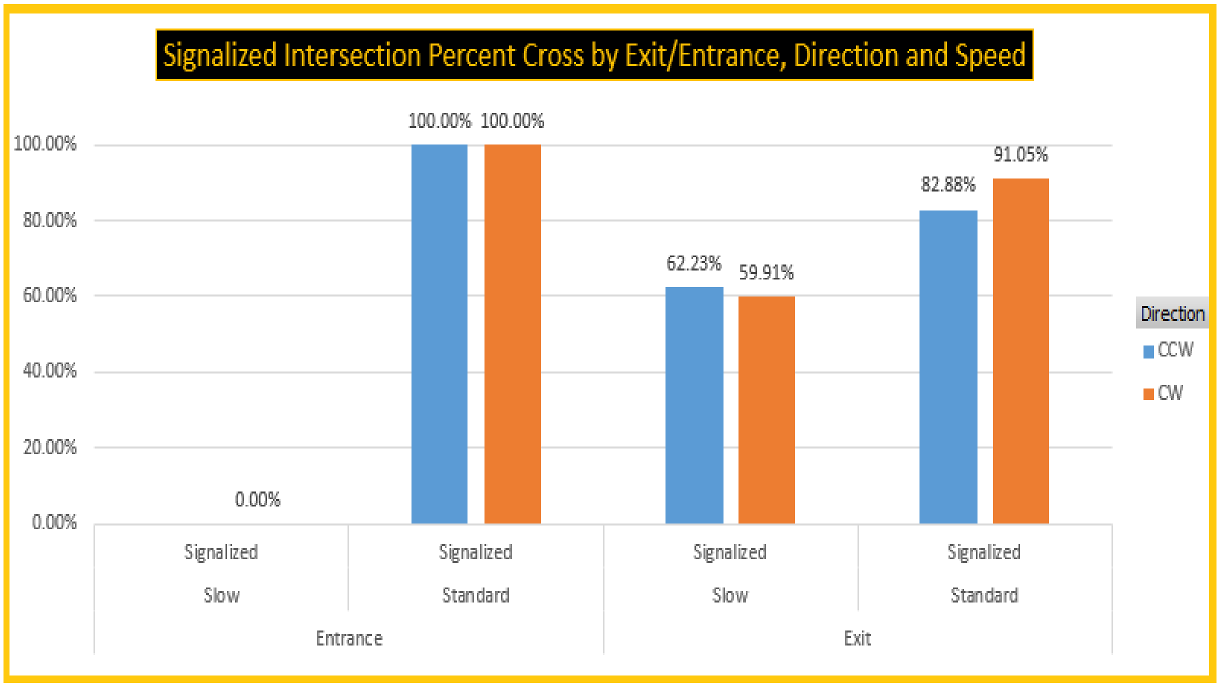

Figure 4.10: Signalized Intersection Decision-making by Direction of Pedestrian Travel

The data did not support the hypothesis, as the counter-clockwise pedestrian made 10% more 'cross' decisions than the clockwise pedestrian at a standard rate of speed and the slow, counter-clockwise pedestrian made 2% more 'cross' decisions than the slow clockwise pedestrian.

4.3.10 Speed of Pedestrian

The data showed a significant difference in cross decisions when walking at the slow pace. The slow pedestrians had to wait for more multiple vehicle clusters (queues). The fewer decisions to cross by the slow pedestrian were expected.

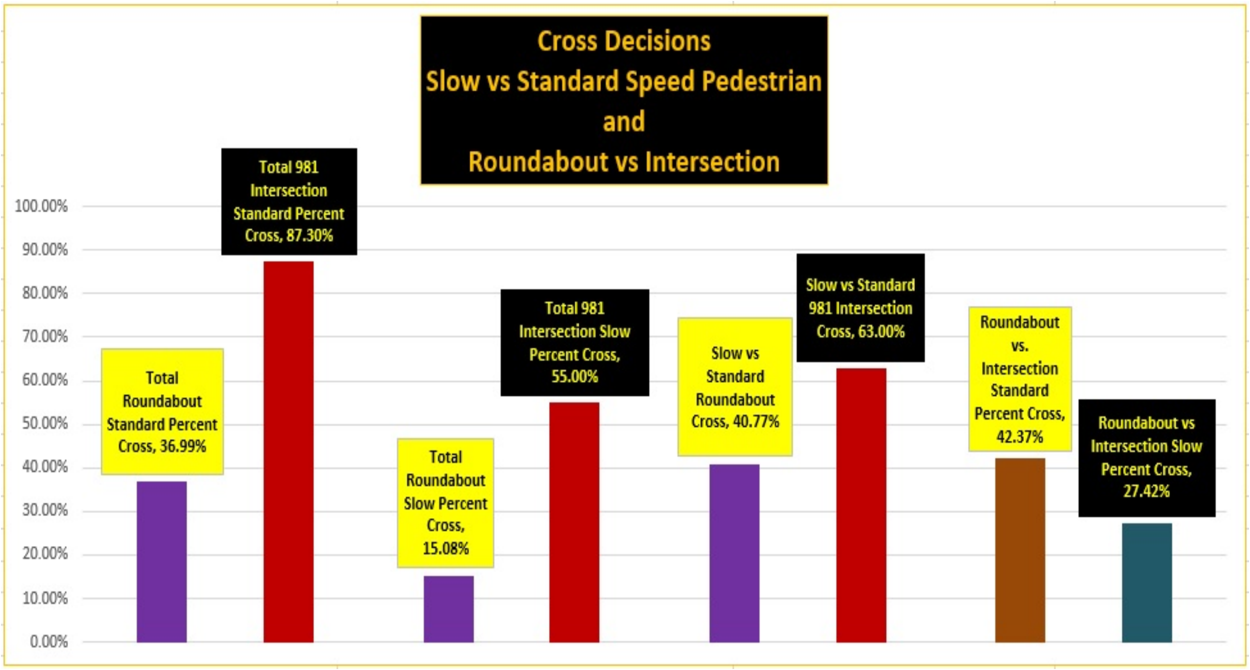

Figure 4.11: Cross Decision - Speed and Intersection Type Roundabout vs Intersection

In the roundabout, the slow pedestrian decided to cross 41% of the time that the standard speed pedestrian decided to cross. Within the signalized intersection, the slow pedestrian decided to cross 55% of the time that the standard speed pedestrian decided to cross. This shows that the slow pedestrian perceived that it was safer to cross in the signalized intersection in relation to the standard speed pedestrian than in the roundabout.

The standard speed pedestrian in the roundabout only decided to cross 42% as often as the standard speed pedestrian in the signalized intersection. This percentage drops to only 27% as many decisions to cross in the roundabout as in the signalized intersection. This demonstrates a much lower level of confidence by the slow pedestrian to cross in the roundabout.

The slow pedestrian (approximately 10-12 seconds to cross one traffic lane vs. 5-6 seconds for the standard speed pedestrian) made significantly fewer ‘cross’ decisions at exit lanes of the roundabout than at the intersection. The slow pedestrian made significantly fewer cross decisions at entrance lanes of the Intersection than at the roundabout, but the traffic volumes were so low as to render any valid comparison of those results insignificant. Both the slow and the standard speed pedestrian made significantly fewer cross decisions at all lanes of the roundabout than at the signalized intersection.

4.3.11 Effect of Multiple Vehicles

The data showed a significant difference in the effect of multiple vehicles. The presence of multiple vehicles per lane crossing attempt was almost universally higher at the roundabout than at the signalized intersections. The geometry of the signalized intersection seemed to account for fewer vehicles being in play from the perspective of the pedestrian. This could be due to the reduction in conflict streams of approaching vehicles caused by the pedestrian signals closing off otherwise expected conflict streams.

Despite one outlier at the signalized intersection in a clockwise direction, the trend was very strong that as more clusters of multiple vehicles appeared when the pedestrian attempted to cross a lane, the fewer cross decisions the pedestrian was able to make.

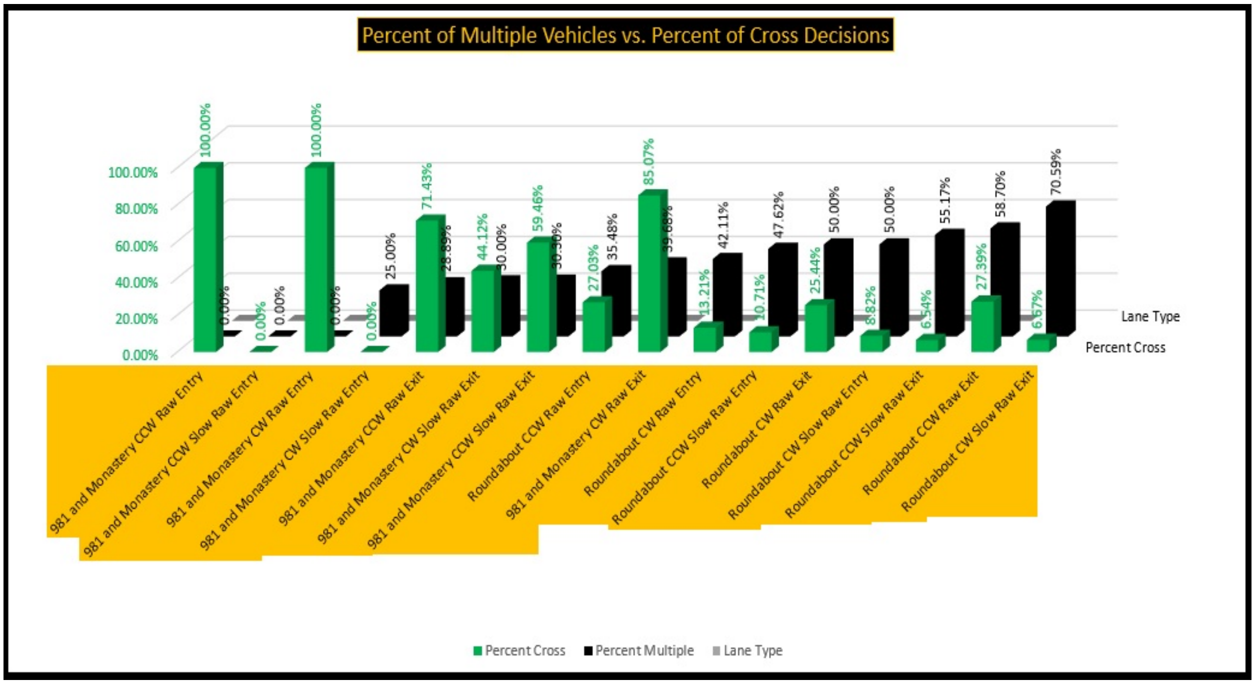

Figure 4.12: Percent of Multiple Vehicles vs Percent Cross Decisions

4.3.12 Conflict Point Anomaly

The roundabout appears from the data to be less safe for the pedestrian than the signalized intersection. Even with a marked crosswalk at a roundabout, the lack of signalization by design, permits drivers to not have to yield until a pedestrian is actually within the roadway. The number of conflict streams was dramatically reduced at the signalized intersection by virtue of the protected signalized pedestrian crosswalk.

The difference between this study and previous studies is in the subtle definition of a ‘conflict point’. Gross (2013, p. 235) defined the ‘conflict point’ as points in an intersection where traffic is crossing, converging and diverging. The FHWA (2000, p. 104) definition is: "A conflict point is a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other."

Several studies relied on the FHWA (2000) conflict point diagrams. However, these diagrams seem to count converging vehicles according to the FHWA's own definition in the intersection diagram but not in the roundabout diagram. This study views these converging vehicles as conflict streams which influence the pedestrians cross/don't cross decision. Further, when a pedestrian walk signal is illuminated, any center lanes are blocked by a signal and any crossing or entering traffic in the middle lane is blocked, so a pedestrian would never encounter more than twelve conflicts in a full revolution if they were to make a full circuit around all lanes of the intersection.

If we use the FHWA's (2000) rationale on the number of conflict points, defining conflicts the same way in each diagram, once we include converging traffic, as per the definitions cited above, the number of conflict streams at roundabout exits could be no less than thirty-two, (three per entrance lane and at least five per exit lane), which is almost three times the number of actual conflict streams at the signalized intersection.

In the roundabout, vehicles approaching from five different vectors may create a conflict at each exit lane alone. Going further, if the pedestrian is blocked at the entrance lane and another car is converging, that is two conflicts at once and a distant vehicle that becomes relevant by virtue of queues of earlier vehicles who have not yet entered the circular roadway, one could conceive of at least three conflicts at roundabout entrances alone, where the literature only expects one conflict.

This study draws an inference from these definitions. If we consider the situation from the decision-making perspective of the pedestrian, how many vehicles do they have to pay attention to at each type of intersection? If we look at the FHWA's (2000) diagram above, we see vehicle conflict points marked on the roundabout based on their own definition. But does this apply to the pedestrian's understanding of traffic streams that influence their decision to cross a lane of traffic?

Sadeq and Sayed's (2016) visualized actual vehicle-pedestrian conflicts, generated from actual conflict streams that more accurately represent the approaching vehicles that may influence the pedestrian's decision. To the pedestrian who circumnavigates the roundabout, every time they cross an entrance they only have to worry about one potential conflict, from a single lane of entering traffic. However, when they cross an exit lane, there are five points of convergence, not one, when the pedestrian arrives at the crossing position: Vehicles situated in the circular roadway at ¼, ½ and ¾ turn from the exit plus vehicles at 1 full turn, who may influence the decision by queueing if the pedestrian has to wait for closer vehicles.

At the signalized intersection in particular, there are four exit and seven entrance lanes. Four of the lanes are always blocked by the signals when a pedestrian has the walk sign. For the seven remaining lanes, at three of the lanes there is only one conflict point and for the other lanes there are two conflict points, for a total of eleven conflict streams, far less than the nineteen to thirty-two that were predicted by the literature for a four-way signalized intersection.

While the roundabout should only have eight conflict points according to the FHWA (2000), if we measure both equally, there are only eleven conflict streams at the signalized intersection at U.S. Route 981. If we count approaching vehicles, every vehicle entering the roundabout or within the circular roadway is a potential conflict for each of the four lanes, for a staggering total of thirty-two conflict streams, five at each exit lane and three at each entrance lane. This could explain the large difference in required cross/don't cross decision-making at the roundabout.

The difference in cross decisions remains constant between the slow and standard speed decision no matter what the geometry. The slow pedestrian has to be more cautious, so the result should be consistent in any type of intersection. However, the pedestrian in general seems to make significantly fewer cross decisions in the roundabout no matter what the speed of the pedestrian when we compare slow speed pedestrians to slow and standard speed pedestrians to standard when we compare data from the signalized intersection against the roundabout. The yield-controlled roundabout seems to require more caution for the slow pedestrian than the signalized intersection.

The data supports the hypothesis that the roundabout is generally less safe for the pedestrian than the signalized intersection for two reasons:

1) the literature presumes a higher number of conflict points at the four-way signalized intersection than at the roundabout, this does not consider the fact that the pedestrian walk signal actually eliminates some of these expected conflict points, thus requiring fewer decisions than anticipated;

2) If conflict points are defined the same way for each intersection type, based not on the number of lanes, but on the number of legally converging traffic vectors, the roundabout conflict points balloon from eight converging vehicles to as many as thirty-two converging vehicles.

This study could complement the other studies which concluding that roundabouts compared to signalized intersections reduced conflicts from thirty-two down to eight. The estimate of thirty-two conflict points for signalized intersections does not take into account the effect of the walk signals and red-light signals that eliminated the majority of the possible vehicle-pedestrian conflict streams.

Several of the United States simulation-based studies did not use or observe actual crossings. The advantage of a human participant for the experimental model was the assumption that no reasonable person will take a physical risk of being struck by a vehicle and thus decision-making reflects personal interest and thus assures accuracy.

5.0 SUMMARY AND CONCLUSIONS

This study proposed a unique new method for assessing and modeling pedestrian safety at roundabouts in the United States. The method uses a live human participant at two real intersections, one a roundabout and the other a signalized intersection, each with four vehicle approaches. The use of the participant proved to be internally valid, as no reasonable participant would risk injury by making unsafe cross/don't cross decisions in real life. The model may be suitable to provide real-world data to calibrate existing simulation, modeling and virtual reality systems that assess safety at roundabouts.

The second aspect of this study that was unique, was to understand a basic flaw in the literature and governmental guidance in the understanding of pedestrian conflicts with vehicles. The concept of the 'conflict point' must be revisited by researchers as it does not only fail to adequately capture either the risks inherent to the pedestrian in an intersection from converging traffic from multiple possible approach vectors or to coincide with the generally accepted definition of conflict point which specifically included 'converging' vehicles. The conflict point is thus too simplistic to capture the multiple traffic flows that may cross the conflict point in the lane to be traversed and influence the pedestrian's crossing decision.

The third aspect of this study that has value, is instead of using complex 'Gap Analysis' and 'Time to Collision' computations, the pedestrian's decision-making in conjunction with the factors such as signalization, approach vectors, exit vs. entrance lanes, slow vs. fast pace and direction provide a more realistic picture of the essentially binary decision: cross vs. don’t cross.

Fourth, the study had a practical focus on the disabled or elderly pedestrian. The experiment used a walking pace at half the rate of the standard pace pedestrian. While data expectedly showed that the slow pedestrian had a much lower rate of ‘cross’ decisions than the standard speed pedestrian, the study exposed that the slow pedestrian had a much higher rate of ‘don’t cross’ decisions at the roundabout than at the Intersection, rendering the roundabout a much riskier environment for the disabled or elderly pedestrian than the signalized intersection where the traffic signals effectively cut off many approach vectors.

Finally, roundabouts were thought to be safer for pedestrians than signalized intersections due to a lower number of conflict points, but the confusing multiple vectors of roundabout traffic converging into exit lanes and the frames of approaching traffic at roundabout entrances did not accurately capture the risks a pedestrian must take into account when traversing the roundabout. The data on relevant traffic showed that pedestrians had to be attentive to almost six times as many approach vectors in the roundabout as they were in the signalized intersection.

This study is limited, but the value in its application are four-fold: 1) conflict stream data is an improvement upon the conflict point and should be at the core of traffic conflict analysis, 2) the binary cross/don’t cross decision is critical data for evaluating the safety of roundabout crossings, 3) slow pedestrians fared much more poorly in their ability to cross at the roundabout than at the signalized intersection, 4) the human participant in a field experiment method can be a valuable source of data for calibrating pedestrian safety simulation systems.

Future studies should examine the conflict stream to 1) augment the concept of the conflict point in order to reflect traffic flow patterns that influence a pedestrian’s decision to cross a lane of traffic, 2) use the cross/don’t cross decision to evaluate the safety of roundabout crossings as a more measurable and realistic data point for understanding the pedestrian’s decision of when to cross, and 3) data from the human participant in a field experiment method can be used to calibrate simulation and virtual reality modeling systems to more accurately evaluate issues of pedestrian safety in locations with moderate vehicular traffic.

APPENDIX A. GLOSSARY OF TERMS AND ACRONYMS

CCW
Counter-Clockwise Direction of Travel

CW
Clockwise Direction of Travel

Circulatory Roadway
The circular roadway around the Central Island in a roundabout

Conflict
'"near-miss" situations in which a vehicle had to abruptly brake or swerve to avoid striking a pedestrian or a pedestrian had to take sudden evasive action to avoid being struck.' Retting (2003) at p. 1457

Conflict Point

- Points in an intersection where traffic is crossing, converging and diverging. Gross et. al. (2013 p. 235)
- "A conflict point is a location where the paths of two motor vehicles, or a vehicle and a bicycle or pedestrian queue, diverge, merge, or cross each other." FHWA (2000 p. 104)

Conflict Stream
A conflict stream is a vehicle approach which influences a pedestrian's cross/don't cross decision at a given vehicular approach lane.

Conflict Vector
See conflict stream.

Crossing Position
'Crossing Position' is the physical point where the pedestrian is standing at the traffic lane and must make a decision to cross or not cross.

Entrance Lane Terms – Roundabout

- B (blocking) - Car is blocking the pedestrian's path or imminent
- F (in-frame) - Car is traveling towards the Circulatory Roadway and is visible from the horizon one frame away (within 5 seconds)

- OF (out-of-frame)- Car is traveling towards the Circulatory Roadway and is not visible from the horizon until the pedestrian makes a decision to cross but has not yet entered the lane

Exit Lane Terms – Roundabout

- C - car is already in the Circulatory Roadway
- ¼ - car is in the nearest entrance lane, 90°, ¼ of the distance to the exit lane conflict point
- ½ - car is on the opposite side of the Circulatory Roadway, 180°, ½ of the distance to the exit lane conflict point
- ¾ - car is at the furthest distance from the exit lane, 270°, ¾ of the distance to the exit conflict point
- M - Multiple cars in the Circulatory Roadway Grouped on one line In Italics
- 1+ - car travels at least 360° around the Circulatory Roadway before deciding to exit (anomaly, lost or indecisive driver) See generally, Hourdos (2012).

FARS
Fatality Analysis Reporting System (FARS)

FHWA
U.S. Department of Transportation, Federal Highway Administration

fps
Feet per Second

HLDI
Highway Loss Data Institute of the Insurance Institute for Highway Safety, Arlington, VA, USA

IIHS
Insurance Institute for Highway Safety, Arlington, VA, USA

Intersection
(1) The area embraced within the prolongation or connection of the lateral curb lines, or, if none, then the lateral boundary lines of the roadways of two highways which join one another at, or approximately at, right angles, or the area within which vehicles traveling upon different highways joining at any other angle may come in conflict. Pa Vehicle Code, Title 75 Section 102 Definitions

mph
Miles per Hour

mps
Meters per second

NHTSA
U.S. National Highway Transportation and Safety Administration

PennDot
Pennsylvania Department of Transportation

Relevant Traffic
That traffic which poses enough risk to a pedestrian crossing a lane of traffic so as to influence the pedestrian's decision-making process.

Rotary
First Use 1836 "2 a road junction formed around a central circle about which traffic moves in one direction only —called also circle, traffic circle" https://www.merriam-webster.com/dictionary/rotary Merriam-Webster, Incorporated, 2017

Roundabout (British)
First Use 1734, "Rotary 2 https://www.merriam-webster.com/dictionary/Roundabout Merriam-Webster, Incorporated, 2017

Roundabout (US)
Roundabout—a circular intersection with yield control at entry, which permits a vehicle on the circulatory roadway to proceed, and with deflection of the approaching vehicle counter-clockwise around a central island. FHWA (2009 p.19)

Total Hourly Traffic (THT)
Total Hourly Traffic is the total traffic volume per hour at an intersection based on observed data.

- Total Hourly Traffic (THT) is computed as: THT = TTR + TTI

Total Traffic Relevant (TTR)
TTR is all vehicular traffic with an effect on the crossing decision, for example:

- The pedestrian has to stop to avoid a conflict
- The pedestrian crosses after assessing the likelihood of a potential conflict

Total Traffic Irrelevant (TTI)
TTI is all traffic with no effect on the crossing decision for example:

- Vehicle passes after the pedestrian clears the conflict point
- Vehicle crosses a lane which is not a conflict point for that pedestrian

Traffic Calming
Traffic calming is an important tool for improving quality of life. It slows or diverts cars so streets are safer and more inviting to pedestrians, bicyclists, and children. Traffic calming makes drivers more aware of sharing street space with other users. Traffic calming, Hoyle, C. 1995 Publisher: APA Planning Advisory Service (July 1, 1995)

Traffic Circle
First use 1942 "a circular area where two or more roads meet and on which all vehicles must go in the same direction" https://www.merriam-webster.com/dictionary/traffic%20circle Merriam-Webster, Incorporated, 2017

Traffic-control signal.
A device, whether manually, electrically or mechanically operated, by which traffic is alternately directed to stop and permitted to proceed. Pa Vehicle Code Title 75 Section 102 Definitions

VLC
VLC is a free and open source cross-platform multimedia player and framework that plays most multimedia files as well as DVDs, Audio CDs, VCDs, and various streaming protocols.

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