The evaluation of modern roundabouts as an alternative to signalized and two-way stop controlled intersections in a urban and rural environment
by Travis John Eickman

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Civil Engineering
Montana State University

Abstract:

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The results indicate that roundabouts are a viable alternative to a two-way stop and signal. For a more accurate, long-term evaluation, growth projections should be applied to existing conditions to determine the operational effectiveness of the intersection traffic control type at some point in the future. Depending on the purpose and need of any intersection being evaluated, additional focus can also be concentrated on obtaining additional field information for driver behavior, gap timing, headway distances, delay times and average queue lengths.

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Travis John Eickman

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APPROVAL

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This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

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Date June 10, 2004

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ABSTRACT

The comparison of roundabouts with other intersection forms of traffic control is becoming an increasingly common occurrence. With little overall experience within the United States, the data for roundabout comparison is somewhat varied. This report includes the results of five models created using VISSIM traffic modeling software in the comparison of a two-way stop, signal and roundabout in an urban environment, and a two-way stop and roundabout in a rural environment.

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CHAPTER 1

INTRODUCTION

The overall purpose and goal of public and private entities involved in transportation is, in one way or another, tied to providing safe and efficient movement from an origin to a destination. Automobile transportation comprises multiple components that work together as a system to provide this safe and efficient movement. Intersections (i.e., nodes), roads (i.e., links), signals, regulatory and warning signs, striping, guardrail and other elements are part of this “system”.

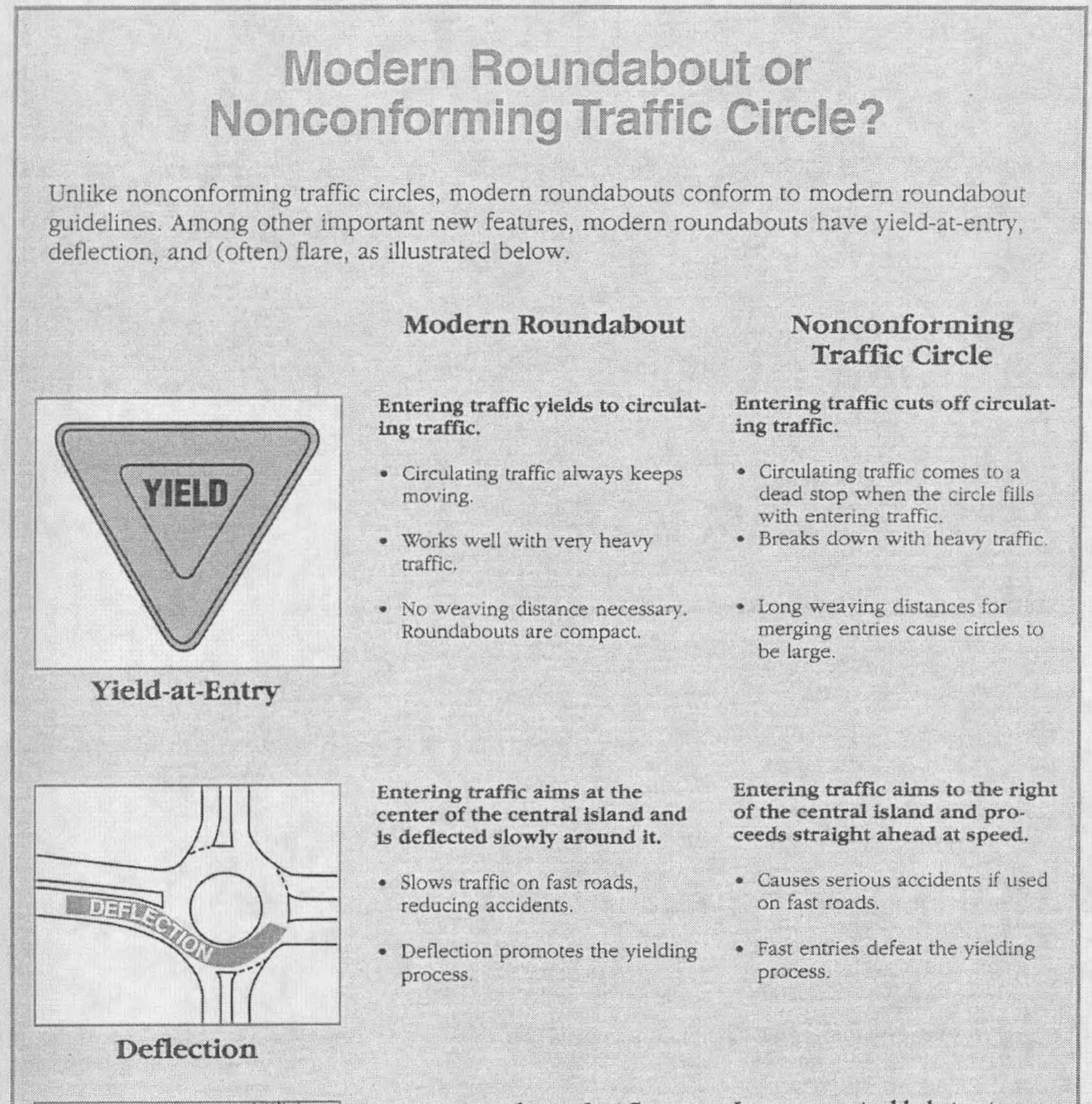
As the volume of traffic approaches the capacity of the roadway system, delays grow rapidly, particularly at intersections. One strategy used to alleviate these intersection-related delays and minimize associated safety risks is to remove all left-turn movements. In doing so, the associated left-turn start-up and clearance lost times in the intersection are eliminated. This, in turn, adds to the amount of time that can be dedicated to through traffic movements. While this strategy may improve overall delay at an intersection, direct accessibility for those making the left-turn movement is compromised.

In the last several decades, the desire for a safer, more efficient intersection that does not compromise accessibility has resulted in new designs and methods that include circular intersections. Three distinct types of circular intersections exist: rotaries, neighborhood traffic circles, and roundabouts (1). Rotaries, used in the United States prior to the 1960’s, are characterized by a large diameter that promotes excessive speeds. This geometric feature, when combined with no yield to entering traffic practices and little to no horizontal deflection, discourages its use today. An alternate form of circular intersection that is more prevalent today, the traffic circle, is typically built at the intersection of local streets for reasons of traffic calming and aesthetics. Roundabouts, the topic of this thesis, are similar to traffic circles aside from a few design points related to yield-at-entry practices, traffic deflection and upstream roadway flares (i.e., additional lanes) (see Figure 1).

Roundabouts are being effectively used throughout Europe and the rest of the world with favorable results related to both safety and efficiency. However, several impediments include unfamiliarity, a lack of design guidelines, differences in interchanges/intersections and traffic control preferences and regulation inhibit widespread implementation in the United States. With further research and public education, however, the roundabout may be a powerful addition to the transportation engineer's toolbox.

Background

A roundabout is a circular type of intersection that has been widely used throughout Europe and is quickly gaining popularity throughout the rest of the world as a replacement for two-way stop-controlled (TWSC), all-way stop-controlled (AWSC), and signalized intersections. It's predicted that roundabouts in the United States will be built by the hundreds in the upcoming years and by the thousands annually in the next few decades, duplicating trends observed first in Britain and Australia during the 1970's and 1980's and now being reported throughout western Europe (2).



Modern Roundabout or Nonconforming Traffic Circle?

Unlike nonconforming traffic circles, modern roundabouts conform to modern roundabout guidelines. Among other important new features, modern roundabouts have yield-at-entry, deflection, and (often) flare, as illustrated below.

	Modern Roundabout	Nonconforming Traffic Circle
Yield-at-Entry	**Entering traffic yields to circulating traffic.** • Circulating traffic always keeps moving. • Works well with very heavy traffic. • No weaving distance necessary. Roundabouts are compact.	**Entering traffic cuts off circulating traffic.** • Circulating traffic comes to a dead stop when the circle fills with entering traffic. • Breaks down with heavy traffic. • Long weaving distances for merging entries cause circles to be large.
Deflection	**Entering traffic aims at the center of the central island and is deflected slowly around it.** • Slows traffic on fast roads, reducing accidents. • Deflection promotes the yielding process.	**Entering traffic aims to the right of the central island and proceeds straight ahead at speed.** • Causes serious accidents if used on fast roads. • Fast entries defeat the yielding process.
Flare	**Upstream roadway often flares at entry, adding lanes.** • Provides high capacity in a compact space. • Permits two-lane roads between roundabouts, saving pavement, land, and bridge area.	**Lanes are not added at entry.** • Provides low capacity even if circle is large. • For high capacity, requires multilane roads between circles, wasting pavement, land, and bridge area.

Figure 1. Circle Components Comparison – Roundabout vs. Traffic Circle (2)

Because roundabouts are still relatively new to the United States (approximately 250 are in service (2), a number of issues have yet to be addressed. Public acceptance, safety concerns, ability to function acceptably with existing infrastructure and their integration with established signal networks are just a few of the factors that come into question.

The modern roundabout was developed in the United Kingdom in 1966 with the adoption of the mandatory "give-way" rule for entering traffic at circular intersections (1). Since its inception, the design has spread to most British-influenced countries like Australia, New Zealand, Ireland, Barbados, and Bermuda, as well as France, Switzerland, Norway, Denmark, Sweden, Germany, Spain, Portugal and the Netherlands.

In the U.S., the preferred type of intersection is the crossroads, or four-leg cross intersection with the traffic signal or stop signs as a predominant form of traffic control. Contrary to this practice, Britain chooses not to use this type of intersection in new construction due to its inefficient traffic performance and poor accident record; existing crossroads are often converted to offset intersections that promote safety. Further, traffic signals are used only when no other alternatives exist (see Figure 2) (3).

All-way STOP sign control is not used in Britain or in any other country outside of North America. YIELD signs instead of STOP signs are used in Britain except at intersections having poor sight distance. Such STOP sign policies promote respect for the law, while at the same time reducing delay, emissions, and fuel waste.

Contrary to this practice, the United States favors use of the STOP sign; the YIELD sign is used on a limited basis. Citations are issued for sensible driver actions: making a

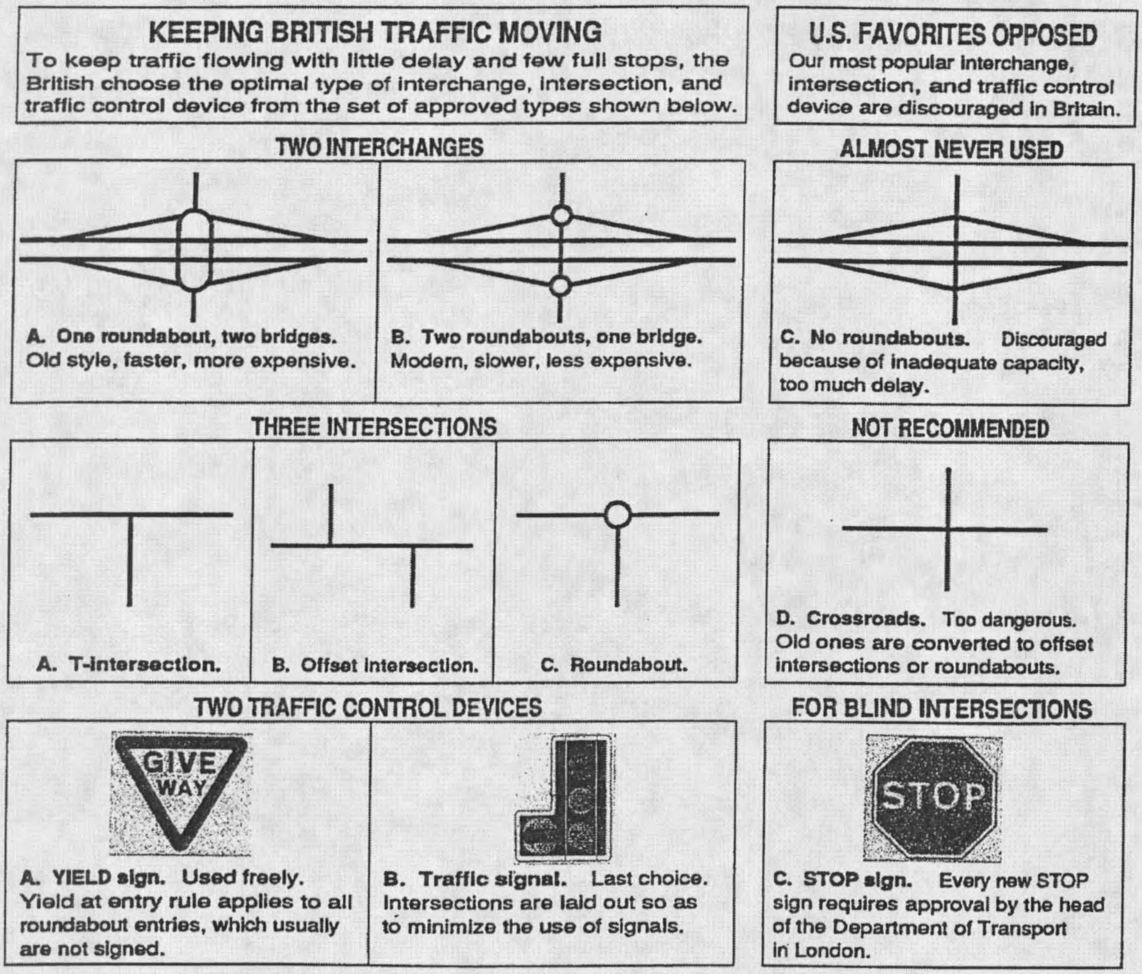


Figure 2. Traffic Control Preference – European vs. U.S. (3)

rolling stop where sight distance allows (3). Issues such as these need to be addressed before widespread implementation of roundabouts can occur in the United States.

Report Purpose and Contents

The purpose of this thesis is to compare modern roundabout performance with that of traditional intersections in both a rural and an urban environment. The case studies to be used for this research include an intersection in Missoula, Montana and Bozeman, Montana, encompassing both the urban and rural spectrum of traffic challenges. Specifically, the proposed signalized Higgins Avenue/Hill Street/Beckwith Avenue intersection in Missoula, will serve as the urban testbed, while the Huffine Lane/Cottonwood Road intersection in Bozeman will serve as the rural testbed. Areas of evaluation include operations, safety, economics, and other considerations.

An operational evaluation of roundabouts as compared to signalized and two-way stop controlled intersections is the primary focus of this thesis. Using VISSIM traffic simulation software, the traffic flow through both types of intersections will be compared to the traffic flow through a modern roundabout at these locations. The underlying question is whether a reduction in travel speeds attributable to roundabouts, is offset by an improved overall traffic flow rate through the intersection.

The safety issues to be evaluated involve the comparison of existing conditions to the possible effects of adding a roundabout or signal. This is to be enhanced by review of safety improvements noted from established roundabouts. Those issues addressing pedestrians, cyclists, and handicapped will be reviewed, with each of the three conditions (existing base case, roundabout, or signal). The reduction of fatalities, injuries and property damage will also be discussed based on data obtained from before and after implementation from existing sites around the world.

The economics and overall cost effectiveness of these traffic control measures can be evaluated in a number of ways. Actual construction costs in terms of materials and manpower may differ substantially between the two traffic measures. Design requirements and costs related to right-of-way, pedestrians, cyclists and handicapped could also be an issue. The economic issues concerning the long and short-term maintenance requirements of roundabouts versus signals will be discussed. Cost savings related to improved safety and reduced delay will also be investigated.

Following this introductory information, Chapter 2 summarizes applicable findings from a review of related literature. Chapter 3 details the methodological approach for this evaluation including a description of the study area, data collection efforts and traffic simulation procedures, including model calibration and validation. Chapter 4 summarizes comparative findings related to operations, safety, economics and other considerations for the two-way stop controlled and signalized intersection and a modern roundabout. Chapter 5 provides concluding remarks and recommendations related to the use of modern roundabouts in both urban and rural environments.

CHAPTER 2

LITERATURE REVIEW

Despite their limited use in the United States, formal literature on this topic is surprisingly numerous. Findings from the literature are detailed below and categorized into three main areas: (1) operations, (2) safety and (3) economics, though information pertaining to the planning process and design is also included.

Operations

Operational considerations for stop controlled, signalized and roundabout intersections include delay, traffic calming, environmental impacts, legal and system considerations.

Delay

When roundabout intersections operate within their capacity, vehicles typically experience lower delays as compared to other intersection forms and control types (1). Traffic is not required to come to a complete stop if there are no conflicts present. At low-volume intersections or during off-peak times, vehicle-actuated traffic signals can achieve comparable operational efficiency. In most circumstances however, signalized intersections achieve much lower operational efficiencies. The need to provide green time to each cycle movement creates intervals during which the intersection is void of vehicles. With the most critical of these movements determining the duration of the green time; inefficient use of green time by the non-critical movements results. Compounding this inefficiency is “lost time” from startup and termination of a green phase.

Dedicated left turn phases result in similar inefficiencies. Further, non-dedicated right-of-way (i.e., shared lanes) can also attribute to delay with left turns blocking other movements in the lane.

Mechanical failures and signal violations, as well as additional areas of conflict, can also cause undo delay.

Two-way stop controlled (TWSC) intersections experience many of the same advantages and disadvantages as signalized intersections. Disadvantages include lost time resulting from stopping and assessing who has the right-of-way, delays attributable to shared through and left turn lanes and potential traffic control violations. Advantages include reduced right-of-way requirements and operation/maintenance costs, among others (2).

While traditional intersections suffer from several sources of inefficiencies, roundabouts too have operational disadvantages. Entry headways are steady and shorter at signalized intersections when compared to roundabouts due to right-of-way that is positively assigned. By minimizing the effects of startup lost time through long cycle times it is possible to achieve higher capacities on signalized intersection approaches.

Further, roundabouts generally treat all intersection movements equally regardless of the street hierarchy. All that is required is to yield to circulating traffic. This however, can present a problem where high volume arterials intersect minor collectors or local streets, resulting in more delay to the major movement.

Lastly, traffic signals on arterial roads are often coordinated to minimize stops and delay to the major traffic flow. The introduction of a roundabout into such a coordinated signal system may actually disperse and rearrange platoons of traffic, resulting in the potential reduction of progressive flow.

Roundabouts: An Informational Guide, developed by the Federal Highway Administration (1), used the Manual of Uniform Traffic Control Devices (MUTCD) peak hour traffic signal warrant information and compared roundabout delays with corresponding delays for signalized intersections. The comparison was performed for various control alternatives and used SIDRA analysis software to estimate the delay. Assumptions for the comparison included the following: (1) the roundabout was a single-lane and that its capacity was adequate for all cases at the MUTCD volume warrant thresholds; (2) left turns on all approaches were 10 to 50 percent of the total approach volume and (3) the major street had two lanes, the minor street one lane. Based on these assumptions, the average vehicle delay is presented in Figure 3.

The values represent the motorist perceived approach delay and do not include the geometric delay that results from traveling through the roundabout. A point ahead of the intersection is designated in the model as a measuring point from which to record the time it takes for the motorist to traverse the varying intersection control types. The geometric delay is important to consider in network planning or when comparing

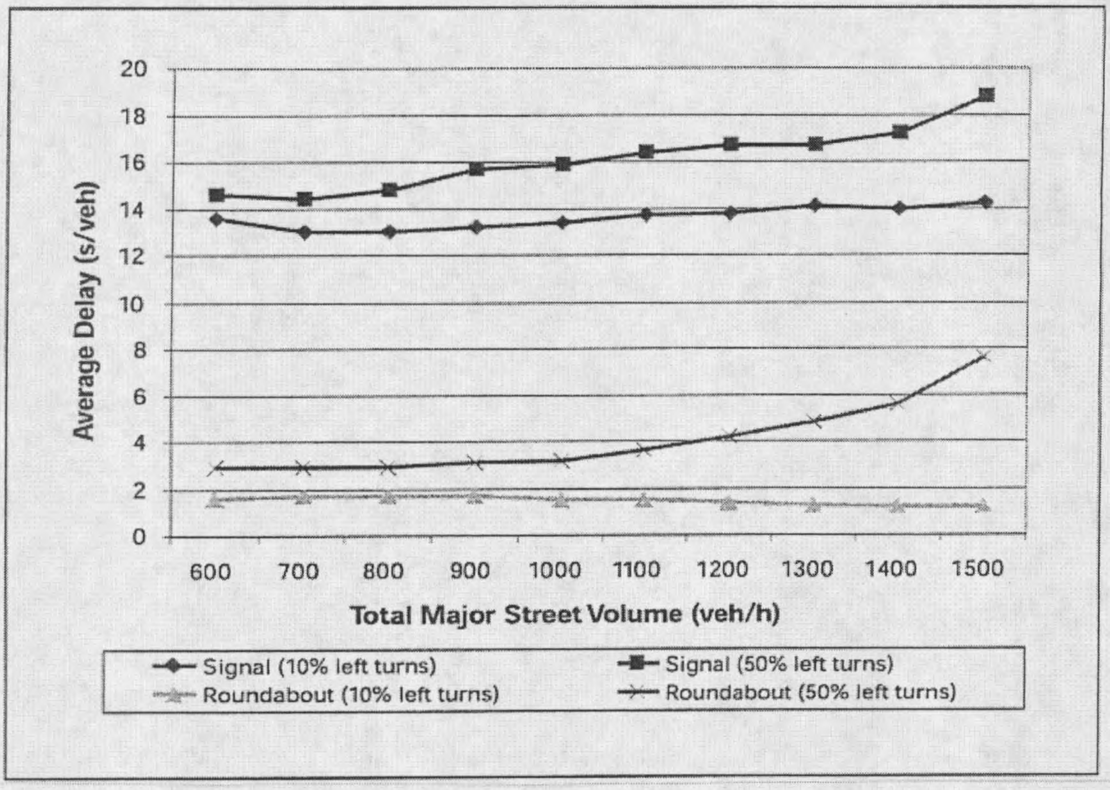


Figure 3. Average Delay per Vehicle at the MUTCD Peak Hour Signal Warrant (1)

operations of different intersection types. While geometric delay is often negligible for through movements at signalized and stop-controlled intersections, it can have more of an effect at roundabouts where movements require traveling around a central island.

The analysis shows that the performance of a single-lane roundabout is competitive with signalized intersections. It is also important to note that the approach delay for the roundabout is relatively unaffected by total major street volume, but that the left-turn percentage does have an effect (1). This reflects that, as with signalized intersections, left turn movement percentages in a roundabout increase the delay.

In addition to estimating operational efficiency in terms of the average vehicle delay, the *Guide* also estimates the annual savings in delay for roundabouts and signalized intersections. Figures 4 and 5 show various delay savings (50 percent and 65 percent, respectively) based on AADT, and the percent of left turning vehicles volume percentage on the major street. With the cost of delay estimated at $10.00/vehicle/hour, the amount of savings to the general public can be substantial, ranging from approximately $10,000 to $405,000 based on Figures 4 and 5 (4).

Based on these and other findings, the *Guide* notes that for planning purposes, a given roundabout operating within its capacity can be assumed to provide better operational performance than a traffic signal in terms of stops, delay, fuel consumption and pollution emissions. The *Guide* goes on to note that intersections with heavy left turn movements are prime candidates for roundabouts, and that some of the most important benefits of a roundabout occur during the off-peak periods as compared to a signal (1).

Traffic Calming

Closely related to operations, one of the obvious benefits of roundabouts is their ability to calm traffic by reducing vehicle speeds. In order to safely navigate a properly designed roundabout (travel around the central island), vehicles need to decrease speed. Since roundabout speed is controlled by the geometric design, unlike signalized intersections, speed can be regulated at all times and in any traffic volume. Roundabouts encourage speed compliance by design instead of regulatory enforcement.

Roundabouts have also been used as a method of delineation between rural and urban

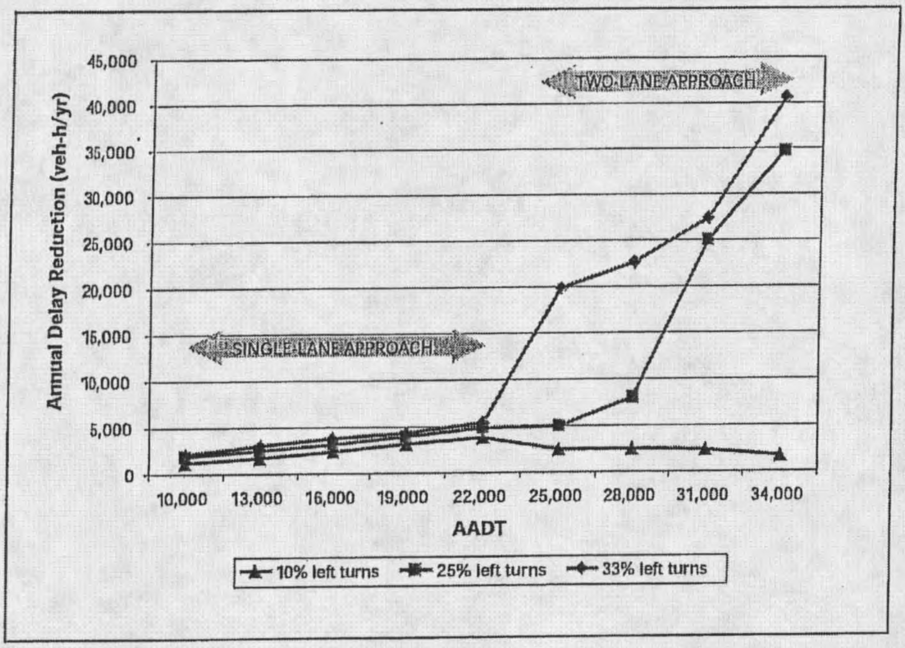


Figure 4. Delay Savings – Roundabout vs. Signal (50% Volume on Major Street) (1)

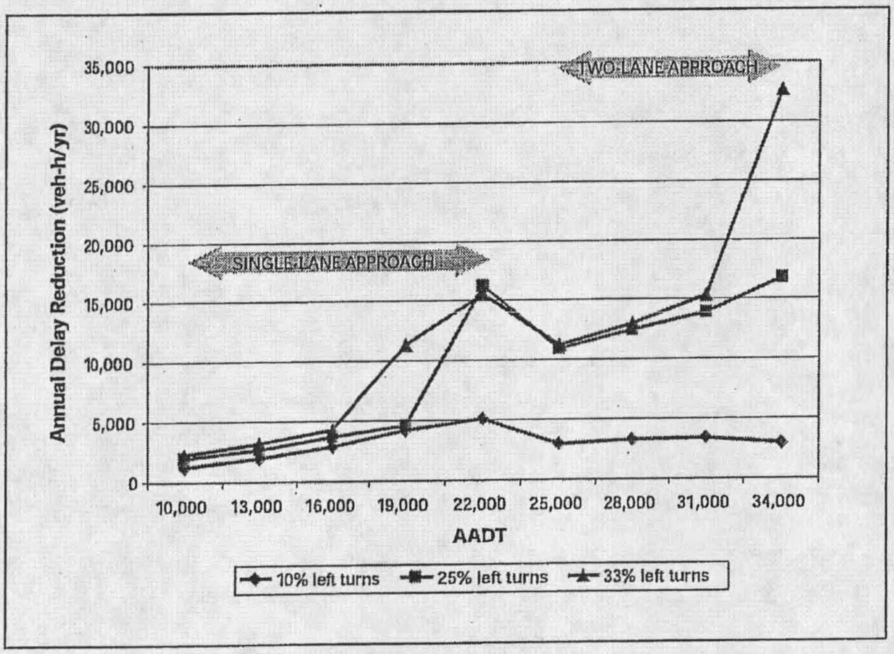


Figure 5. Delay Savings – Roundabout vs. Signal (65% Volume on Major Street) (1)

areas or commercial and residential development types. This traffic-calming tool serves to slow drivers and reinforce the notion that there is a change in the driving environment and potential speed limits. Roundabouts can also be used to facilitate U-turns in such areas as shopping centers or tourist attractions (1).

Environmental Impacts

Environmental impacts from traditional and roundabout operations result most directly from acceleration/deceleration cycle activity and the time spent idling. Reductions in these activities lead to reduction in noise, air quality impacts, and fuel consumption. With their YIELD to traffic operation, roundabouts reduce the number and duration of vehicle stops and consequently reduce potential environmental impacts.

Vehicle-actuated signals, if the volume of traffic is low, will typically cause a greater reduction in delay, fuel consumption, and emissions than roundabouts (1). Because traffic demand varies throughout the day, vehicle-actuated signals function as fixed-time signals during the heaviest traffic volumes, greatly decreasing operational efficiency and increasing environmental impacts during peak periods. Hence, when averaged throughout the day or for longer periods of time, environmental impacts may be similar for roundabouts and vehicle-actuated signals.

An intersection alternatives analysis conducted in Fort Collins, Colorado compared traditional four-lane and six-lane intersection designs with a roundabout. For the six-lane intersection alternative, 880 hours of daily delay resulting in 44 kilograms of carbon monoxide was estimated. The four-lane intersection alternative's delay and corresponding carbon monoxide emissions could not be calculated due to extreme long-term congestion. The roundabout alternative was estimated to result in only 225 hours of delay with a resultant 11 kilograms of carbon monoxide emitted; a 75 percent reduction in carbon monoxide emissions. With this study it was not identified if the roundabout was part of the same corridor as the four and six-lane facilities or if the roundabout facilities were calibrated against the four and six-lane systems. If the roundabout was in a different area of the city, receiving different volumes and vehicle types, there would need to be an identified methodology for the comparison of the intersection types (5).

Legal Considerations

Legal issues surrounding operations at two-way stop controlled (TWSC) and signalized intersections have been well addressed through the rules of the road, provisions stated in the Uniform Vehicle Code (UVC) and various governing State regulations (1). These rules of the road and State regulations are not well defined and may not even pertain to roundabout operation.

There are numerous issues that pose possible legal complications if not handled properly including: (1) proper definition of the intersection; (2) right-of-way between vehicles; (3) required lane position at intersections; (4) priority within the circulatory roadway; (5) pedestrian accessibility and (6) parking (1). The *Guide* discusses several of these issues and provides recommendations to handle these issues as they pertain to roundabouts.

System Considerations

Roundabouts are most often considered as isolated intersections. However, with roundabout use increasing, there may be the need to incorporate roundabouts into a network of intersections or consider their interaction with surrounding infrastructure. Such system considerations include signalized metering at roundabouts, use as interchanges, and the inter-relation of roundabouts with at-grade rail crossings, and signals in an arterial network.

Roundabout Signalization. Roundabouts have been signalized by metering one or more entries, or signalizing the circulatory roadway at each entry. It is recommended however, that roundabouts should not be planned for metering or signalization due that it defeats the general operation of the roundabout (1). Signal use at roundabouts may "lock" traffic on the roundabout if vehicles queue back to the next upstream exit. Signalization should only be considered when unexpected demand dictates the need following installation and there is sufficient space for queuing between entries (3).

Interchanges. Roundabout use at interchanges would potentially reduce the queue length on the off-ramps over use of a traditional signal. Regarding on-ramp performance, a roundabout would likely supersede that of a traditional signal if the roundabout is operating within capacity; the headway between vehicles moving from the roundabout to the on-ramp is often more random than at signals allowing for smoother merging behavior and higher performance at the freeway merge area as compared with platooned signal traffic (1).

Lastly, the increased capacity and reduced delay at roundabouts can save in bridge/overpass construction costs. At a traffic signal, traffic may be required to stop, necessitating an additional lane of storage each direction on the bridge/overpass. The most expensive element of an interchange is the structure; fewer lanes required with a roundabout at the intersections would reduce interchange cost to a fraction of the cost of a signalized diamond interchange (3). For example, the State of Maryland will save approximately $10 million with the installation of a diamond interchange with roundabouts while reducing the delay to one-tenth, and accidents to one-half of the alternative signalized intersection design (6).

At-Grade Rail Crossings. While locating an intersection near an at-grade railroad crossing is not recommended, rail transit and their stations, have been successfully incorporated into roundabouts. The increased spatial footprint of roundabouts allow sufficient room for the tracks to pass through the central island and external radii. The *Guide* gives recommendations on how to effectively lay out such an intersection and recommends reviewing such sources as the MUTCD and the FHWA *Railroad-Highway Grade Crossing Handbook* (1).

Arterial Network Considerations. One of the most important issues in considering a roundabout is how well it will operate in a roadway system with signals or other intersection types. Doing so requires an understanding of a roundabout's arrival and departure characteristics and how they interact with other intersections.

As can be expected, a roundabout is affected by its proximity to signalized intersections. If the two are close, vehicles enter the roundabout in closely spaced platoons resulting in regular periods when no vehicles enter and providing an opportunity for minor street traffic to enter the major street. Since the critical gap is larger than the follow-up time, a roundabout actually becomes more efficient when the vehicles are handled as platoons versus individual vehicles.

When a roundabout and signal are separated by some greater distance, the arrival patterns include fewer closely spaced platoons, resulting in reduced performance. If arrival speeds are moderate, infrequent but longer gaps allow more motorists to enter a roundabout than a larger number of shorter gaps. If arrival speeds are low, more opportunities exist for priority-reversals (circulating vehicles yield to vehicles entering) and priority sharing (entering and circulating vehicles alternate) within the roundabout.

Roundabout departure rates tend to be more random than that of a traffic signal, affecting the performance of other unsignalized intersections or accesses downstream. This effect may be localized; as traffic travels further downstream from the roundabout, the proportion of platooning increases. If a roundabout is to be used in a coordinated network of signals closely grouped platoons may be difficult to maintain and hence, the use of roundabouts in a coordinated network of signals needs to be carefully evaluated. Further, roundabouts do not respond to street hierarchy and may cause greater delay to the major leg then would be experienced at a signal (1).

Nonetheless, roundabouts can be advantageous as an alternative to signal control at a critical signalized intersection within a coordinated network. Such intersections are usually the bottlenecks and determine the necessary cycle lengths. If a roundabout, operating within its capacity, is installed at a critical intersection, system cycle lengths may be reduced resulting in reduced delay and shorter queues at other intersections.

Roundabouts as part of an arterial network system support access management. Left-turn movements at minor entrances may experience long delays and require two-stage left-turn movements. If roundabouts are incorporated into such a network, the same movement can be provided through a right turn, followed by a U-turn at the next roundabout (1).

Safety

Safety is one of the major reasons roundabouts are often chosen as an option for new intersections and up-grades of existing intersections. The increased safety level at roundabouts is in part, explained through the following:

- Conflict points at roundabouts are fewer than at signalized intersections; roundabouts eliminate the potential for the more hazardous conflicts, such as right angle and left turn head-on crashes.
- Roundabouts require lower speeds to negotiate the geometry giving drivers more time to react to the potential conflicts that exist.
- Roundabout geometry encourages most motorists to drive at the same relative speed throughout the intersection; the lower relative speeds result in reduced crash severity as compared to other convential intersections.

- At roundabouts, pedestrians need only cross one direction of traffic at a time at each approach and the entry and exit speeds of motorists in a roundabout are reduced, resulting in less severe accidents. Since the movement of pedestrians is based on gap acceptance, the challenge for certain handicaps is still present (visually impared) (1).

Points of Conflict

The frequency of crashes at intersections is related to the number of conflict points, as well as the magnitude of traffic flows at each conflict point. These conflict points occur where one vehicle path crosses, merges or diverges with, or queues behind, the path of another vehicle, pedestrian, or bicycle. In addition to these cited conflicts with other road users, roundabout design results in a potential geometric conflict with the central island.

Vehicle Conflicts. For single lane roundabouts, the potential for vehicle-vehicle conflicts is reduced when compared to that of traditional three-leg, T-intersections and four-leg intersections. The vehicle-vehicle conflict points decreases from nine at three-leg, T-intersections to six at roundabouts (see Figure 6). For four-leg intersections the reduction is more significant. The vehicle-vehicle conflict points decreases from thirty-two at four-leg intersections to eight at roundabouts (see Figure 7). These figures do not take into account the ability to separate conflicts in space through the use of turning lanes and time through the use of traffic control devices (1).

Vehicle-vehicle conflicts can be divided into three categories, each with varying levels of severity. First, queuing conflicts occur when a vehicle runs into the back of a vehicle queue waiting at an approach. These types of accidents are usually the least

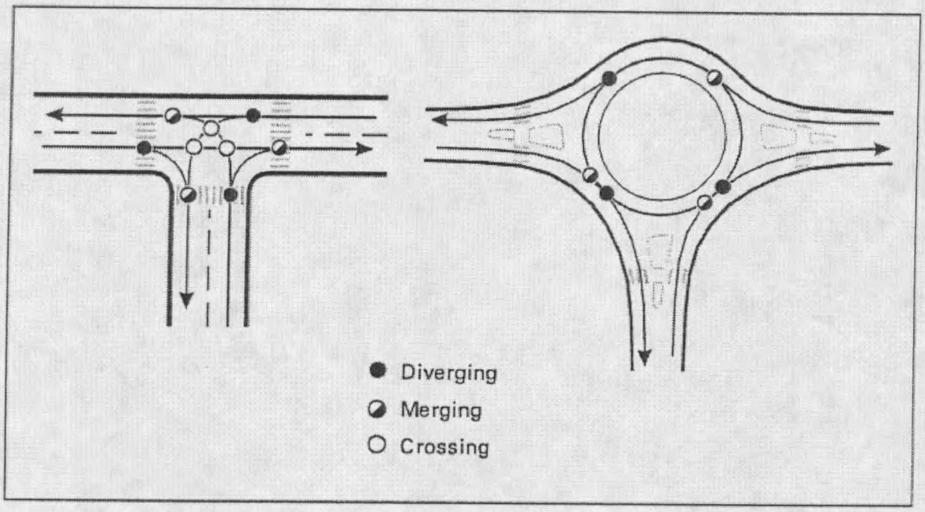


Figure 6. Vehicle-Vehicle Conflict Points for Three-leg, T-Intersections and Roundabouts with Single-lane Approach (1)

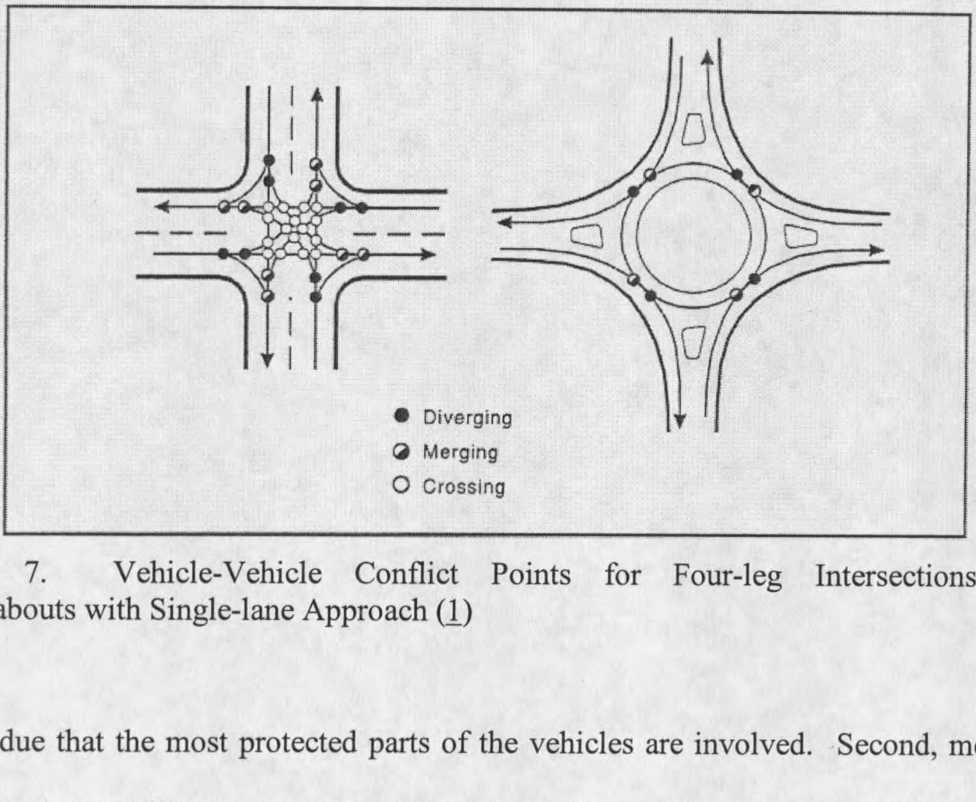


Figure 7. Vehicle-Vehicle Conflict Points for Four-leg Intersections and Roundabouts with Single-lane Approach (1)

severe due that the most protected parts of the vehicles are involved. Second, merging and diverging conflicts are caused by the joining and separating of two traffic streams. In merging accidents, the most common type of crashes are sideswipes and rear-ending. Merging accidents can be more severe then the diverging due to the greater probability of side collision with merging. Third, crossing conflicts occur with the intersection of two traffic flows. Such accidents are the most severe and most often involve injury or fatality. Typically the crashes are right angle or head-on and associated with signalized or TWSC intersections (1).

Two-lane roundabouts have similar safety characteristics as single-lane roundabouts, but introduce additional conflicts when drivers use the incorrect lane or make a turn improperly. Figure 8 and 9 depict these potential vehicle-vehicle conflicts. These additional conflicts are generally low- speed sideswipe conflicts that are lower severity then those experienced at alternative intersections. However, according to a study conducted in the United Kingdom, increasing roundabouts from one to two lanes can increase injury crashes by 25 percent (assuming a 10,000 entering ADT) (1).

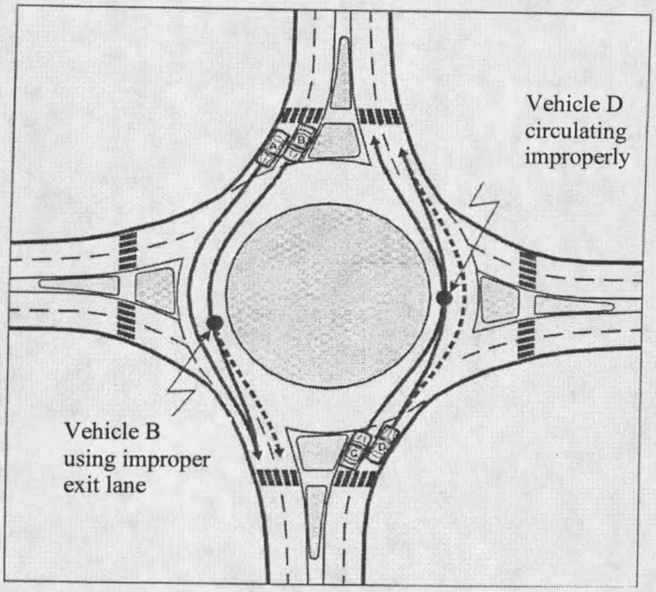


Figure 8. Double-Lane Roundabout – Improper Lane-Use Conflict (1)

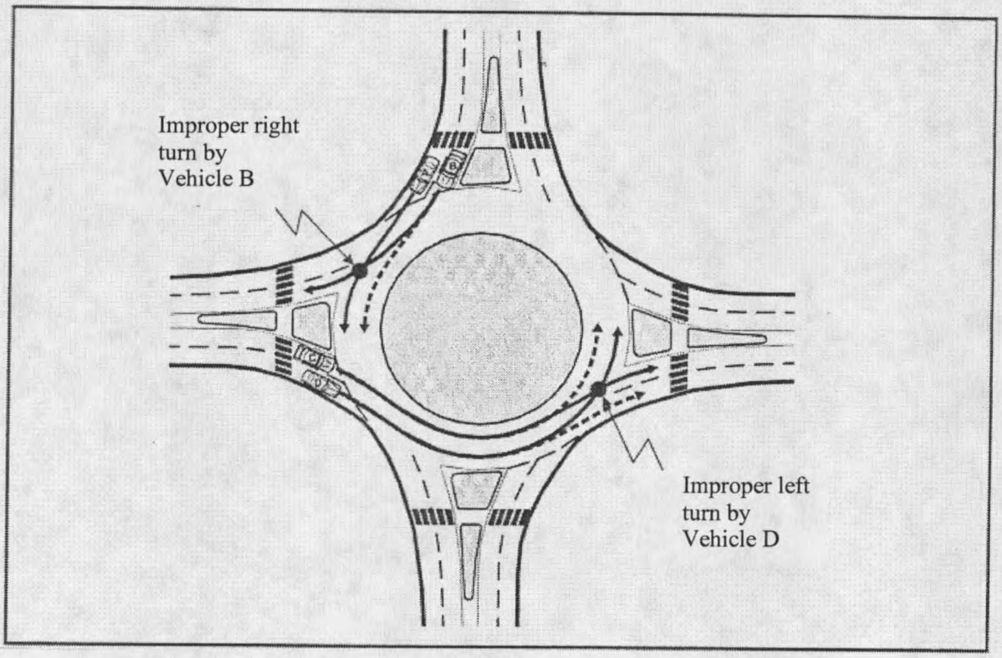


Figure 9. Double-Lane Roundabout – Improper Turn Conflicts (1)

Pedestrian Conflicts. Vehicle-pedestrian conflicts can exist at any intersection. At signalized intersections signal phasing is used to reduce the likelihood that such a conflict would occur. At the signalized intersection the pedestrian is confronted with four potential conflicts with vehicles, each from a different direction (see Figure 10):

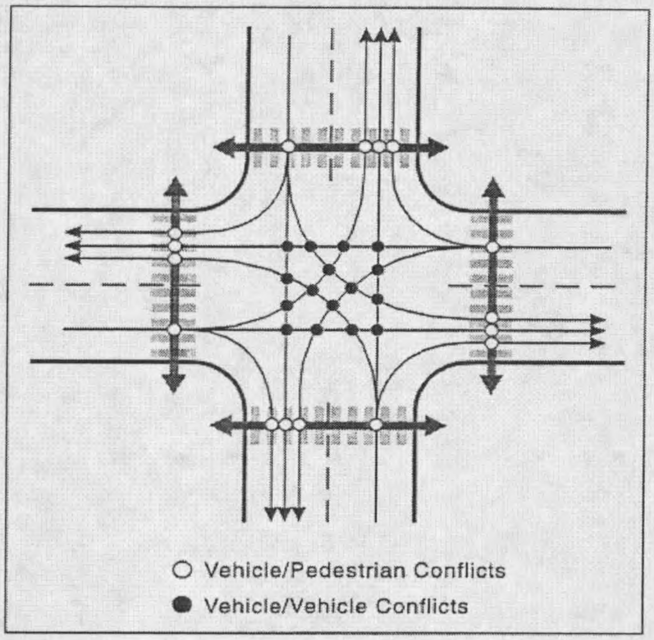


Figure 10. Vehicle-Pedestrian Conflicts at Signals (1)

- Crossing movements on red (usually high-speed, illegal)
- Right turns on green (legal)
- Left turns on green (legal for protected-permitted or permitted left turn phasing)
- Right turn on red (usually legal)

An intersection with four single-lane approaches results in a total of 16 pedestrian-vehicle conflicts (1).

Comparatively, Figure 11 shows the pedestrian-vehicle conflicts present at a roundabout. For this design, the pedestrian has two conflicting vehicle movements on each approach, entering and exiting vehicles resulting in eight potential points of conflict. As with signalized intersections, roundabouts incur additional conflicts as the number of approach lanes increases; one additional conflict for each additional lane the pedestrian must cross.

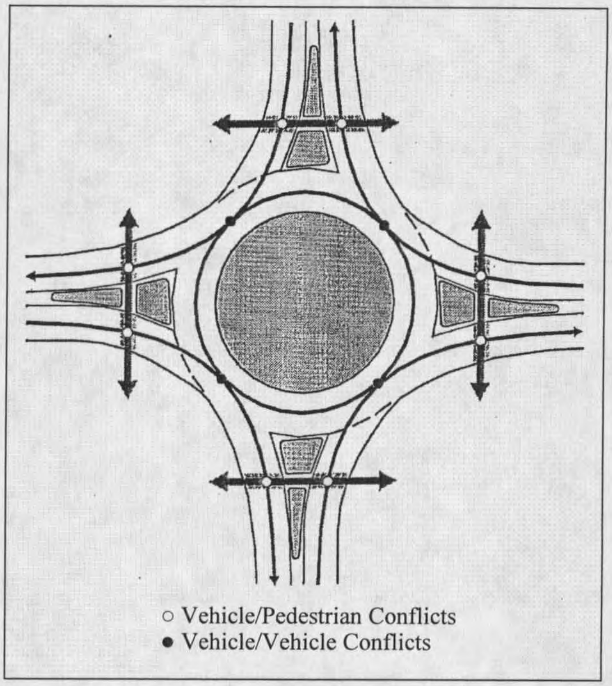


Figure 11. Vehicle-Pedestrian Conflicts – Single-Lane Roundabouts (1)

Bicycle Conflicts. Bicyclists experience similar conflicts as vehicles at traditional intersections (see Figure 12). However, the conflicts experienced by bicyclists at a roundabout are dependent on whether they negotiate their path as a vehicle or a

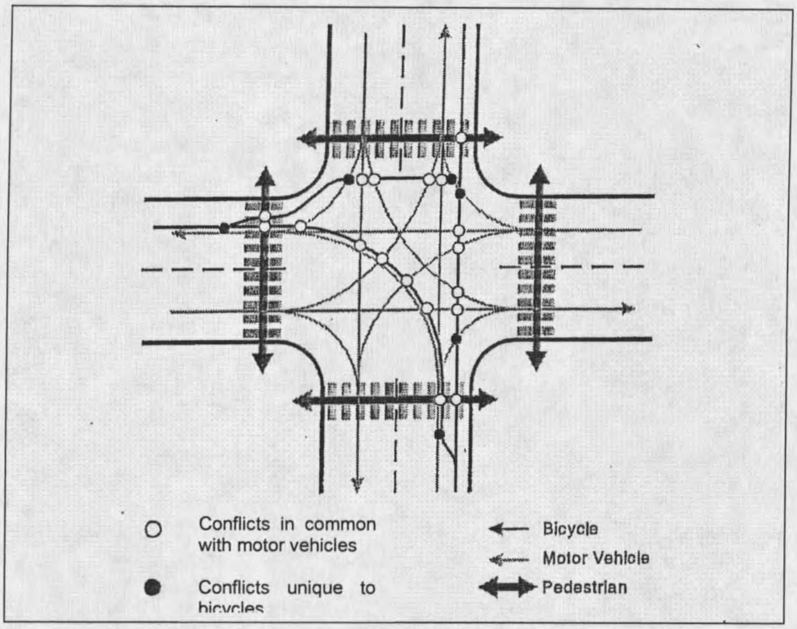


Figure 12. Vehicle-Bicycle Conflicts at Conventional Intersections (1)

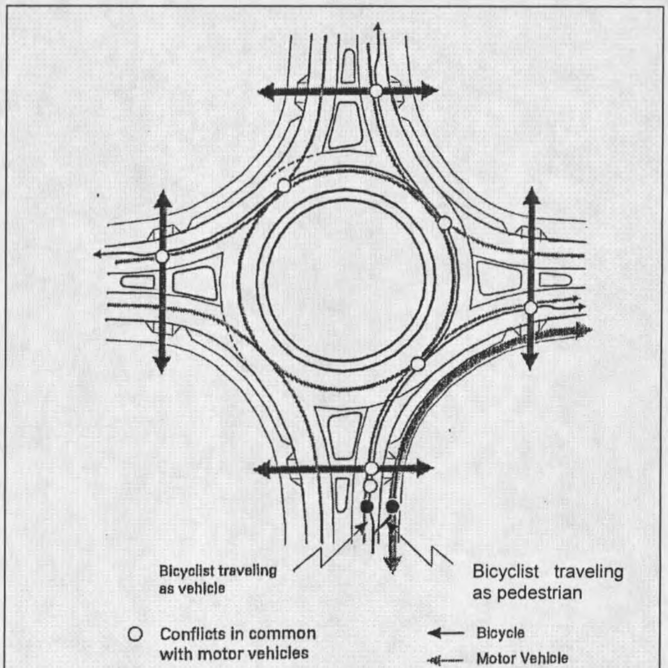


Figure 13. Vehicle-Bicycle Conflicts at Roundabouts (1)

pedestrian (see Figure 13). If the bicyclist chooses to negotiate the roundabout as a vehicle, an additional conflict occurs at the point where the bicycle merges into the traffic stream. For multi-lane roundabouts, bicyclists face a potential conflict with vehicles trying to exit when the bicyclists are continuing to circulate around the roundabout. In a study conducted in the Netherlands, it was found that a number of bicyclists riding along a marked bike lane within the circulatory roadway were killed when they ran into exiting trucks. Since the occurrence of these accidents, recommendations have been made to eliminate the bike lanes within the circulatory roadway (7). Bicycles are also more vulnerable to the merging and diverging conflicts at these multi-lane roundabouts due to their lack of visibility.

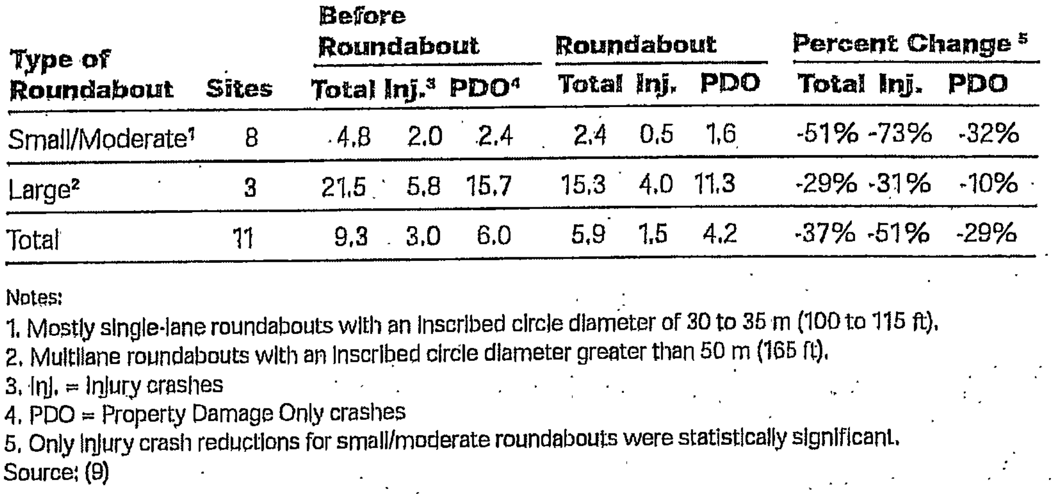
In the event the bicyclist chooses to negotiate the roundabout as a pedestrian, an additional conflict point occurs at the point where the bicycle reaches the sidewalk. This presents new hazards and conflict points for pedestrian-bicycle interaction (1).

Observed Safety Improvements

A number of studies conducted in Europe, Australia and, to a lesser extent, the United States have confirmed noted safety improvements attributable to roundabouts when compared to traditional two-way stop controlled and signalized intersections prevalent in the United States. These improvements relate to crash frequency and severity, collision types and crash involvement.

Crash Frequency and Severity. Tables 1 and 2 summarize observed crash frequencies and severities at U.S. intersections that were converted to roundabouts. In nearly every

Table 1. Average Annual Crash Frequencies and Severities at Converted Roundabouts (1)



Type of Roundabout	Sites	Before Roundabout			Roundabout			Percent Change [5]		
		Total	Inj.[3]	PDO[4]	Total	Inj.	PDO	Total	Inj.	PDO
Small/Moderate[1]	8	4.8	2.0	2.4	2.4	0.5	1.6	-51%	-73%	-32%
Large[2]	3	21.5	5.8	15.7	15.3	4.0	11.3	-29%	-31%	-10%
Total	11	9.3	3.0	6.0	5.9	1.5	4.2	-37%	-51%	-29%

Notes:
1. Mostly single-lane roundabouts with an inscribed circle diameter of 30 to 35 m (100 to 115 ft).
2. Multilane roundabouts with an inscribed circle diameter greater than 50 m (165 ft).
3. Inj. = Injury crashes
4. PDO = Property Damage Only crashes
5. Only injury crash reductions for small/moderate roundabouts were statistically significant.
Source: (9)

instance, roundabouts showed a reduction in total injury and property damage only crashes after installation. Due to the low number of roundabouts in the U.S., the data sample is sufficiently small to preclude statistical significance for all findings except the injury crash reduction for small and moderate roundabouts (1). When injury crash rates per roundabout are compared to those of Australia (0.15 crashes), France (0.6 crashes), and the United Kingdom (3.31 crashes), it is found that the injury crash frequency in the United States can be high, ranging from 0.5 to 4.0 injury crashes per roundabout (1). This may be explained in part by the unfamiliarity of the general public regarding roundabout operations in the U.S.

Expressed in terms of injury crashes per million vehicles entering, observed injury crash rates are 0.08 crashes in the U.S., 0.045 crashes in France, and 0.275 crashes in the United Kingdom (1).

Table 2. Crash Frequencies and Severities at Converted Roundabouts by Control Type (8)

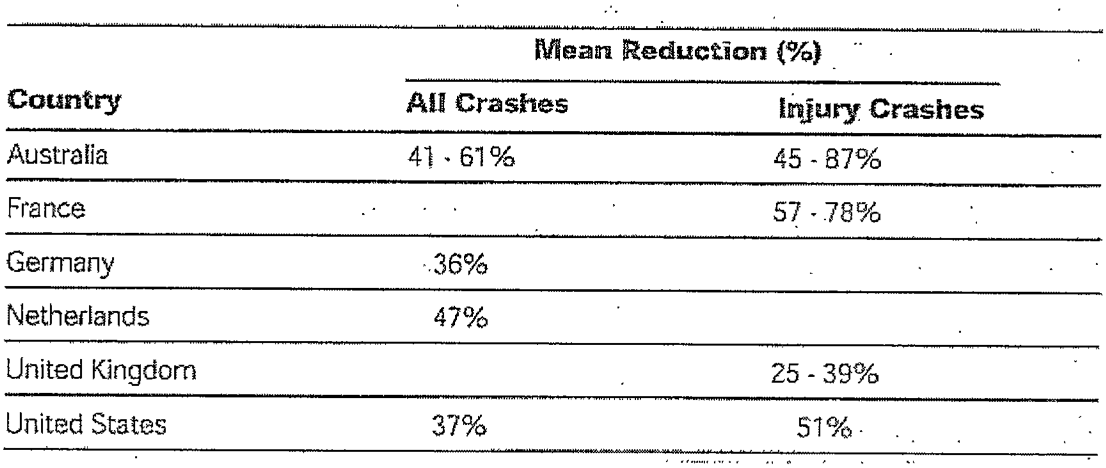
Details of the Sample of Roundabout Conversions

								Crash Count			
	Year	Control	Single or	AADT		Months		Before		After	
Jurisdiction	Opened	Before*	Multilane	Before	After	Before	After	All	Injury	All	Injury
Anne Arundel County, MD	1995	1	Single	15,345	17,220	56	38	34	9	14	2
Avon, CO	1997	2	Multilane	18,942	30,418	22	19	12	0	3	0
Avon, CO	1997	2	Multilane	13,272	26,691	22	19	11	0	17	1
Avon, CO	1997	6	Multilane	22,030	31,525	22	19	44	4	44	1
Avon, CO	1997	1	Multilane	18,475	27,525	22	19	25	2	13	0
Avon, CO	1997	6	Multilane	18,795	31,476	22	19	48	4	18	0
Bradenton Beach, FL	1992	1	Single	17,000	17,000	36	63	5	0	1	0
Carroll County, MD	1996	1	Single	12,627	15,990	56	28	30	8	4	1
Cecil County, MD	1995	1	Single	7,654	9,293	56	40	20	12	10	1
Fort Walton Beach, FL	1994	2	Single	15,153	17,825	21	24	14	2	4	0
Gainesville, FL	1993	6	Single	5,322	5,322	48	60	4	1	11	3
Gorham, ME	1997	1	Single	11,934	12,205	40	15	20	2	4	0
Hilton Head, SC	1996	1	Single	13,300	16,900	36	46	48	15	9	0
Howard County, MD	1993	1	Single	7,650	8,500	56	68	40	10	14	1
Manchester, VT	1997	1	Single	13,972	15,500	66	31	2	0	1	1
Manhattan, KS	1997	1	Single	4,600	4,600	36	26	9	4	0	0
Montpelier, VT	1995	2	Single	12,627	11,010	29	40	3	1	1	1
Santa Barbara, CA	1992	3	Single	15,600	18,450	55	79	11	0	17	2
Vail, CO	1995	1	Multilane	15,300	17,000	36	47	16	n/a	14	2
Vail, CO	1995	4	Multilane	27,000	30,000	36	47	42	n/a	61	0
Vail, CO	1997	4	Multilane	18,000	20,000	36	21	18	n/a	8	0
Vail, CO	1997	4	Multilane	15,300	17,000	36	21	23	n/a	15	0
Washington County, MD	1996	1	Single	7,185	9,840	56	35	18	6	2	0
West Boca Raton, FL	1994	1	Single	13,469	13,469	31	49	4	1	7	0

*1 = four-legged, one street stopped; 2 = three-legged, one street stopped; 3 = all-way stop; 4 = other unsignalized; 6 = signal

Despite the country to country variation in observed crash rates, it is important to note that in all locales, including the United States, the reduction in crashes after installation of a roundabout is quite significant. Table 3 summarizes the safety improvements attributable to roundabouts for the various countries.

Table 3. Mean Roundabout Crash Reductions from Various Countries (9)



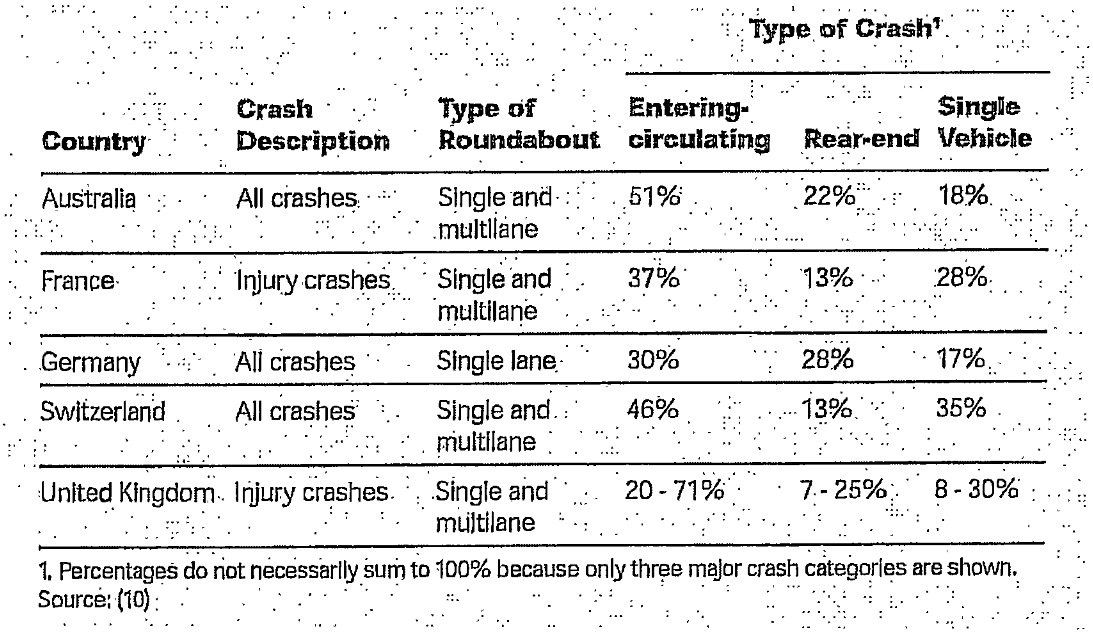
	Mean Reduction (%)	
Country	**All Crashes**	**Injury Crashes**
Australia	41 - 61%	45 - 87%
France		57 - 78%
Germany	36%	
Netherlands	47%	
United Kingdom		25 - 39%
United States	37%	51%

In some cases, a range of crash reduction is reported to account for variations in the data sample not captured in the level of detail reported here. A study from the Insurance Institute for Highway Safety found that roundabouts reduced the numbers of fatal and incapacitating injury crashes by up to 90 percent. This reduction was attributed to two primary factors: (1) reduced traffic speeds and (2) elimination of conflicts that occur frequently at angular intersections (8).

Several studies also show that the crash reduction for roundabouts is more prominent in rural areas than urban (1). It should be noted when interpreting these findings in totality that these crash reductions are generally reported for sites where there was an initial problem. As such, they do not represent a universal safety comparison with all other types of intersections.

Collision Types. Tables 4 and 5 summarize the various collision types occurring at roundabouts. The most common types of roundabout collisions involve a motorist failing to yield at entry, running off the road or losing control (single vehicle) or rear ending another vehicle. Figure 14 depicts these and other roundabout collision types.

Table 4. Roundabout Crash Types (1)



			Type of Crash[1]		
Country	**Crash Description**	**Type of Roundabout**	**Entering-circulating**	**Rear-end**	**Single Vehicle**
Australia	All crashes	Single and multilane	51%	22%	18%
France	Injury crashes	Single and multilane	37%	13%	28%
Germany	All crashes	Single lane	30%	28%	17%
Switzerland	All crashes	Single and multilane	46%	13%	35%
United Kingdom	Injury crashes	Single and multilane	20 - 71%	7 - 25%	8 - 30%

1. Percentages do not necessarily sum to 100% because only three major crash categories are shown.
Source: (10)

Table 5. Collision Types at Roundabouts (1)

Collision Type	**France**	**Queensland (Australia)**	**United Kingdom**[1]
1. Failure to yield at entry (entering-circulating)	36.6%	50.8%	71.1%
2. Single-vehicle run off the circulatory roadway	16.3%	10.4%	8.2%[2]
3. Single vehicle loss of control at entry	11.4%	5.2%	[2]
4. Rear-end at entry	7.4%	16.9%	7.0%[3]
5. Circulating-exiting	5.9%	6.5%	
6. Pedestrian on crosswalk	5.9%		3.5%[4]
7. Single vehicle loss of control at exit	2.5%	2.6%	[2]
8. Exiting-entering	2.5%		
9. Rear-end in circulatory roadway	0.5%	1.2%	
10. Rear-end at exit	1.0%	0.2%	
11. Passing a bicycle at entry	1.0%		
12. Passing a bicycle at exit	1.0%		
13. Weaving in circulatory roadway	2.5%	2.0%	
14. Wrong direction in circulatory roadway	1.0%		
15. Pedestrian on circulatory roadway	3.5%		[4]
16. Pedestrian at approach outside crosswalk	1.0%		[4]
Other collision types		2.4%	10.2%
Other sideswipe crashes		1.6%	

Notes:
1. Data are for "small" roundabouts (curbed central islands > 4 m [13 ft] diameter, relatively large ratio of inscribed circle diameter to central island size)
2. Reported findings do not distinguish among single-vehicle crashes.
3. Reported findings do not distinguish among approaching crashes.
4. Reported findings do not distinguish among pedestrian crashes.
Sources: France (12), Australia (13), United Kingdom (1)

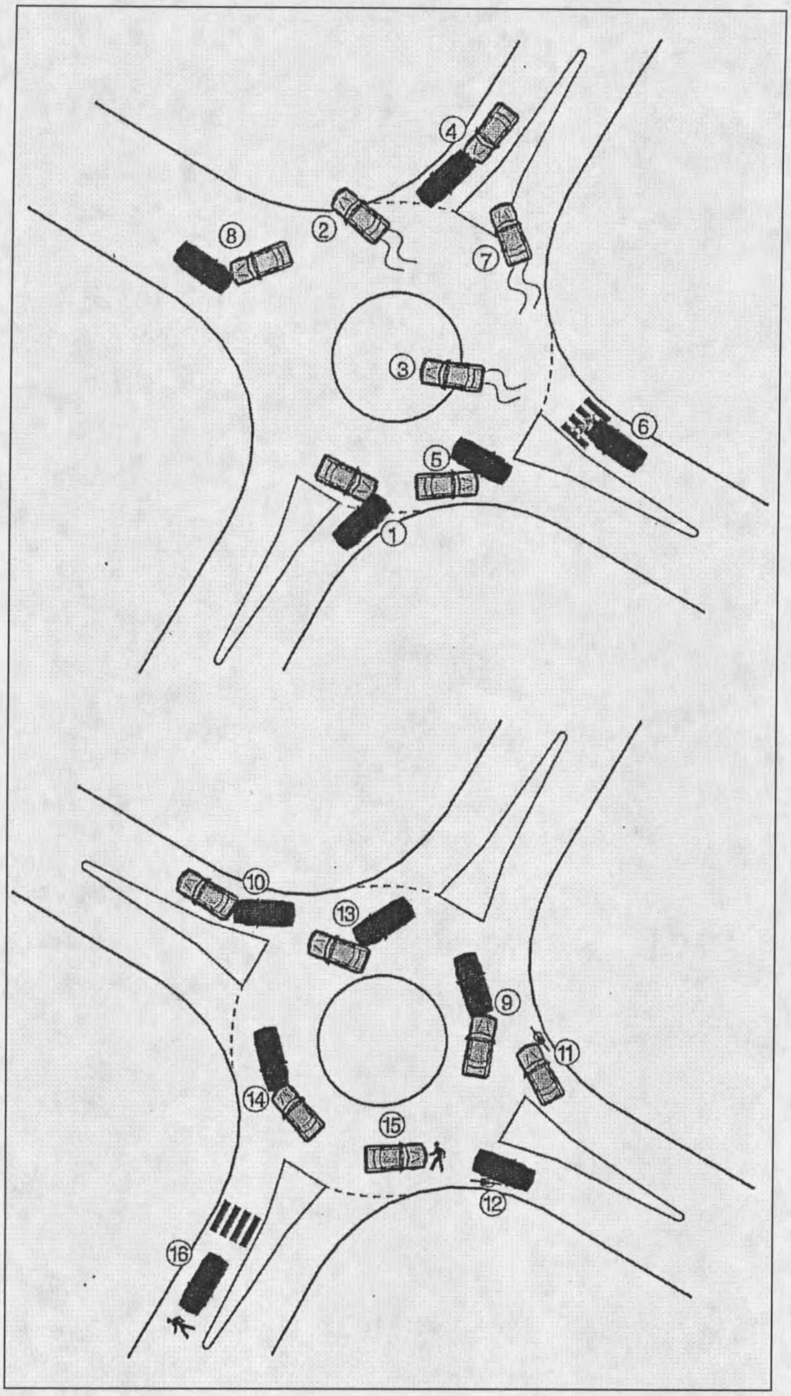
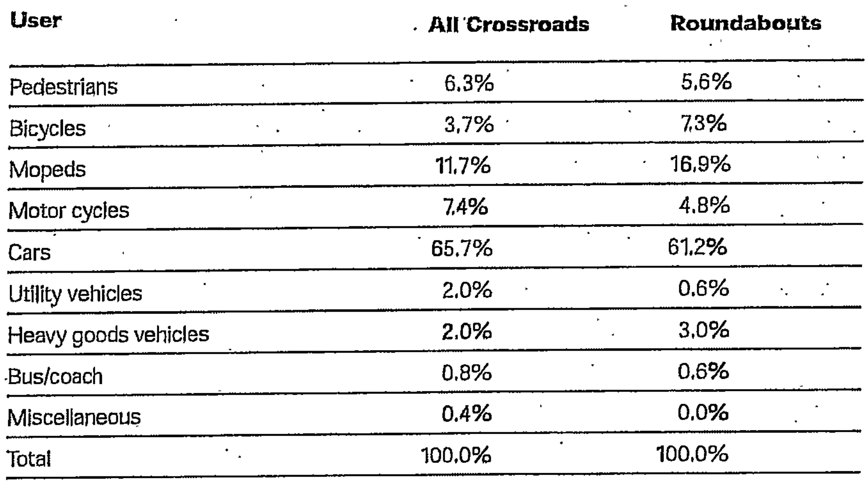


Figure 14. Graphical Depiction of Roundabout Collision Types (1)

Crash Involvement. Crash involvement at traditional intersections and roundabouts is compared in Table 6. Note that crash involvement at roundabouts decreased for every motorist type except bicycles, mopeds and heavy goods vehicles.

Table 6. Crash Involved User Types at Roundabouts (1)



User	**All Crossroads**	**Roundabouts**
Pedestrians	6.3%	5.6%
Bicycles	3.7%	7.3%
Mopeds	11.7%	16.9%
Motor cycles	7.4%	4.8%
Cars	65.7%	61.2%
Utility vehicles	2.0%	0.6%
Heavy goods vehicles	2.0%	3.0%
Bus/coach	0.8%	0.6%
Miscellaneous	0.4%	0.0%
Total	100.0%	100.0%

Similar crash involvements and corresponding safety improvements were observed in a Dutch study of 181 intersections that were converted to roundabouts (see Table 7).

There have been no known studies that have focused on the safety of visually impaired pedestrians at roundabouts or pedestrians with disabilities. While these issues require additional research, it can be noted that many of the challenges that exist with conventional intersection safety for pedestrians also conveys to roundabouts, including crosswalk location, identification and acceptance of a safe gap and crossing multiple lanes where pedestrian movement can be masked to vehicles in adjacent lanes.

Table 7. Crash Reduction by Mode at Converted Roundabouts (1)

Mode	**All Crashes**	**Injury Crashes**
Passenger car	63%	95%
Moped	34%	63%
Bicycle	8%	30%
Pedestrian	73%	89%
Total	51%	72%

Bicycle safety is one area that traditional signalized intersections are either equal or superior to roundabouts with respect to performance. Two studies conducted in Britain and France, respectively report crash statistics for bicycles at roundabouts as compared to signalized intersections (see Tables 8 and 9, respectively).

Table 8. Crash Rates for Two-wheeled Vehicles at Roundabouts and Signalized Intersections in Britain (1)

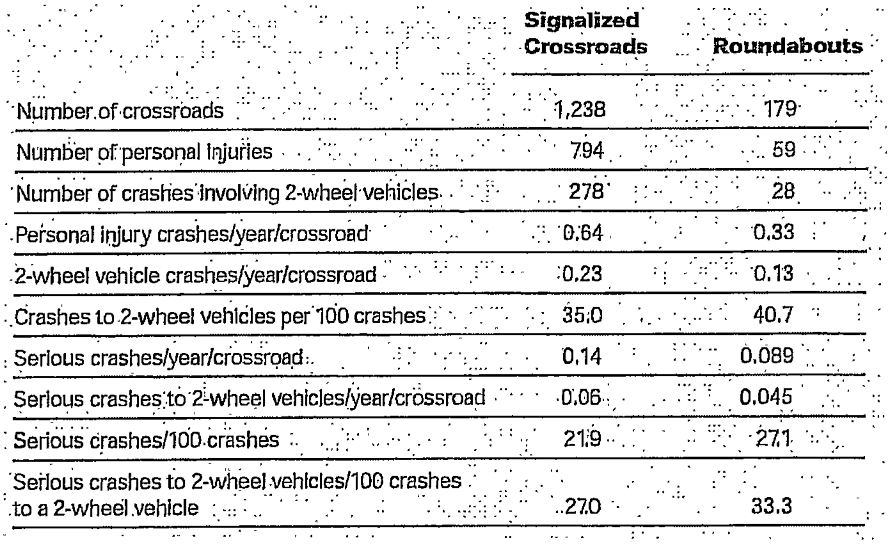
Intersection Type	**Bicyclists**	**Motorcyclists**
Mini-roundabout	3.11	2.37
Conventional roundabout	2.91	2.67
Flared roundabout	7.85	2.37
Signals	1.75	2.40

French researchers drew the following conclusions:

- Two-wheel vehicles were 16 percent more likely to be involved in any type of crash at roundabouts then signalized intersections.

- Total injury crashes numbered twice as many at signalized intersections as at roundabouts;
- Two-wheel vehicles were involved in 77 percent more injury crashes at signalized intersections.

Table 9. Crash Rates for Two-Wheeled Vehicles at Roundabouts and Signalized Intersections in France (1)



	Signalized Crossroads	Roundabouts
Number of crossroads	1,238	179
Number of personal injuries	794	59
Number of crashes involving 2-wheel vehicles	278	28
Personal injury crashes/year/crossroad	0.64	0.33
2-wheel vehicle crashes/year/crossroad	0.23	0.13
Crashes to 2-wheel vehicles per 100 crashes	35.0	40.7
Serious crashes/year/crossroad	0.14	0.089
Serious crashes to 2-wheel vehicles/year/crossroad	0.06	0.045
Serious crashes/100 crashes	21.9	27.1
Serious crashes to 2-wheel vehicles/100 crashes to a 2-wheel vehicle	27.0	33.3

To promote bicycle safety at roundabouts, policies regarding placement of bicycle lanes, mixing of bicycles and vehicles depending on traffic flows, and separate bicycle facilities have been established in many European countries.

Unlike bicycle safety effects, roundabouts have been observed to greatly enhance pedestrian safety. Roundabouts promote lower speeds, and as such, lower the risk of being in a severe collision. At 20 mph, only 5 percent of pedestrians are killed, other injuries are slight, and 30 percent of the pedestrians suffer no injury at all. At 30 mph, the death toll rises to 45 percent with an increased number of the survivors being seriously injured. When speeds reach 40 mph, 85 percent of involved pedestrians are killed (10). The lower number of conflict points also results in a reduced frequency of collision and the splitter island provides pedestrians with a safe haven to resolve conflicts seperately with vehicles entering and exiting.

Economics

Economic feasibility is an important part in any project. Usually the most appropriate method to use in this case is the benefit-cost analysis method. Benefits can be categorized as they relate to traffic safety, traffic operations and environmental benefits. Costs can include capital and construction, operations and maintenance costs.

Safety Benefits

Safety benefits are those savings to the public for a reduction in crashes and injuries. Table 10 gives estimated costs for a variety of severity levels. Even a small reduction in crash rates can be substantial. A British study found that the average accident cost at a roundabout is calculated to be about 50 percent lower than the average accident cost at all other intersection types. In the case of mid-block accidents, the average accident cost is 70 percent lower for roundabouts (11).

Table 10. Costs by Crash Severity (1)

Crash Severity	**Economic Cost (1997 dollars)**
Death (per death)	$980,000
Injury (per injury)	$34,100
Property Damage Only (per crash)	$6,400

Crash Costs

A Maryland study observed a significant reduction in the more severe and thus costly accidents for roundabouts as compared to traditional intersections (see Table 11).

Table 11. Crash Severity at Roundabouts (9)

ACCIDENT SEVERITY COMPARISON

Collision Type	**Before Roundabout**			**After Roundabout**		
	No. of Accidents	Average Accident Cost (1)	Total Accident Cost	No. of Accidents	Average Accident Cost (1)	Total Accident Cost
Angle	62	$125,971	$7,810,202	8	$125,971	$1,007,768
Rear-End	6	$80,231	$481,386	10	$80,231	$802,310
Sideswipe	2	$60,819	$121,638	1	$60,819	$60,819
Left Turn	11	$95,414	$1,049,554	1	$95,414	$95,414
Opposite Direction	1	$307,289	$307,289	0	$307,289	$0
Single Vehicle	3	$59,851	$179,553	20	$59,851	$1,197,020
Totals	**85**		**$9,949,622**	**40**		**$3,163,331**
Average Accident Cost (Before): $ 117,054						
Average Accident Cost (After): $ 79,083						

Operational and Environmental Benefits

Operational benefits are those attributable to the reduction in person-hours of delay. Delay at intersections results in lost productivity time to the public and therefore incurs a cost that should be accounted for. Directly related to reduced delay, environmental benefits include reduced fuel consumption and improved air quality. These benefits have not been well-quantified in prior studies.

Capital and Construction Costs

The costs of installing a roundabout vary from site to site and depend on the type of site conditions that exist. The U.S. Department of Transportation reports a wide range of costs related to roundabout implementation varying from $10,000 for a retrofit of an existing signal to $500,000 for a new roundabout at the junction of two State highways (1). A study by the National Cooperative Highway Research Program (NCHRP) reports average construction costs of $250,000 for 14 roundabouts constructed in the United States. It is important to note that none of these roundabouts were at an interchange and the costs did not include land acquisition (12).

At an existing unsignalized intersection it may be cheaper to install a signal rather than perform the additional pavement and curb modifications required with a roundabout. Where a new site exists, signalized intersections may require widening to provide additional lane width for storage. In this case, the cost of a roundabout may be comparable or even cheaper due to the ‘wide nodes and narrow roads’ concept that requires more pavement at the intersection, but less on the approaches into the intersection. This can result in a big cost savings at interchange ramp terminals where roundabouts can result in a narrower bridge structure.

If a substantial amount of realignment, drainage, or grading work is needed to accommodate a roundabout, the costs will generally exceed that of a traffic signal. The cost of traffic control during construction can also be high. Other items that add to the cost of roundabouts are landscaping, signing and lighting and the provision of curbs on all outside pavement edges (1).

Less easy to quantify are costs related to the engineering 'learning curve' resulting from the newness of roundabouts as a form of traffic control. Ourston Roundabout Interchanges, a private engineering firm, provides some average costs for their services: determination of roundabout site suitability – free, plan review - $3,600 per roundabout, feasibility study/study report - $12,500 per roundabout, and designs for contract plans - $4,000 per roundabout (13). Public education in the form of flyers, radio/TV broadcasts, and public meetings can also add to roundabout intersection costs.

Operations and Maintenance Costs

In terms of operations and maintenance (O&M) costs, roundabouts are generally more expensive then traditional TWSC and AWSC intersections, and less expensive than signalized intersections. Traffic signals require constant power, periodic light bulb and detector maintenance and signal timing updates. General O&M costs for signals average $3000 per year (1). Roundabouts do not incur these same costs, but require special maintenance for landscaping. Further, illumination and pavement marking costs for roundabouts are slightly higher than signals due to a higher prevalence. In the event of power failure, roundabouts suffer compromised visibility but maintain functionality. Traffic signals additionally lose functionality.

Roundabouts typically have a service life of approximately 25 years, while a typical traffic signal's life is 10 years (1). Life-cycle costs should be considered in any economic evaluation comparing roundabouts with traditional signalized intersections.

Other Considerations

Other considerations when comparing roundabouts to traditional TWSC or signalized intersections relate to incorporation in the transportation planning process and design issues. These items are not the focus of this thesis but are presented briefly as items that should be considered for any at-grade intersection control.

Planning Process

There are several planning-level steps to determine if a roundabout is a suitable alternative to a traffic signal at an intersection: (1) consider the context (i.e., policy considerations, site-specific/community impact); (2) define roundabout lane configuration and category; (3) identify the selection category (why would it be the preferred choice?); (4) analyze selection category (community enhancement, traffic calming, safety improvement, operational improvements); (5) determine spatial requirements; and (6) perform an economic evaluation. Included in this process is public involvement and education efforts (1).

Design

When comparing roundabouts and traffic signals, design issues must also be considered. Design areas that should be addressed include the following: (1) spatial requirements; (2) vehicle access (large vehicles, transit, emergency vehicles, railroad); (3) bicycle and pedestrian access, (4) driver considerations, and (5) aesthetics. While roundabouts are relatively new to the United States, there are numerous domestic and foreign design guides that can be referenced for design specifics (1).

Implications for this Effort

A review of previous evaluation studies and guidance documentation as presented here serves a twofold purpose; (1) provide general background information to the reader to familiarize roundabouts as an alternative means of traffic control and (2) to provide comparative findings related to the performance of roundabouts as a traffic control alternative to TWSC or signalized intersections that confirm the validity of the findings in this investigation.

CHAPTER 3

METHODOLOGY

The methodologies used in this investigation compare the operational efficiencies of roundabouts to that of (1) TWSC intersections and (2) signalized intersections in a rural and urban environment, respectively. Specifically, this Chapter (1) describes the study area, (2) data collection efforts, (3) measures of effectiveness, (4) simulation model selection, and (5) model development.

Study Area

Roundabouts can be implemented in either urban or rural environments. Urban implementations experience normally high peak hourly flows, apparent directional flow reversals and restrictions on right of way. Rural implementations are characterized by higher speeds with low directional flow reversals and few physical constraints. The two case studies for this investigation consider both types of installations.

The intersection of Higgins/Hill/Beckwith served as the urban site in a fully developed area of the City of Missoula, Montana and the intersection of U.S. Highway 191 and Cottonwood Road just to the west of Bozeman, Montana served as the rural site. At the urban site, Higgins Avenue is a two-lane principal arterial carrying approximately 15,000 AADT. Hill Street and Beckwith Avenue are both two-lane urban collector streets that carry an AADT in the range of 1700 and 4250 vehicles per day, respectively (14). Figures 15 and 16 depict the urban study area.

In the rural environment, Cottonwood Road is a two-lane collector that runs north/south with AADT in the approximate range of 750 vehicles per day (15). Traffic control at this intersection consists of two-way stop control, with stop signs on the Cottonwood legs. Figures 17 and 18 depict the rural study area.

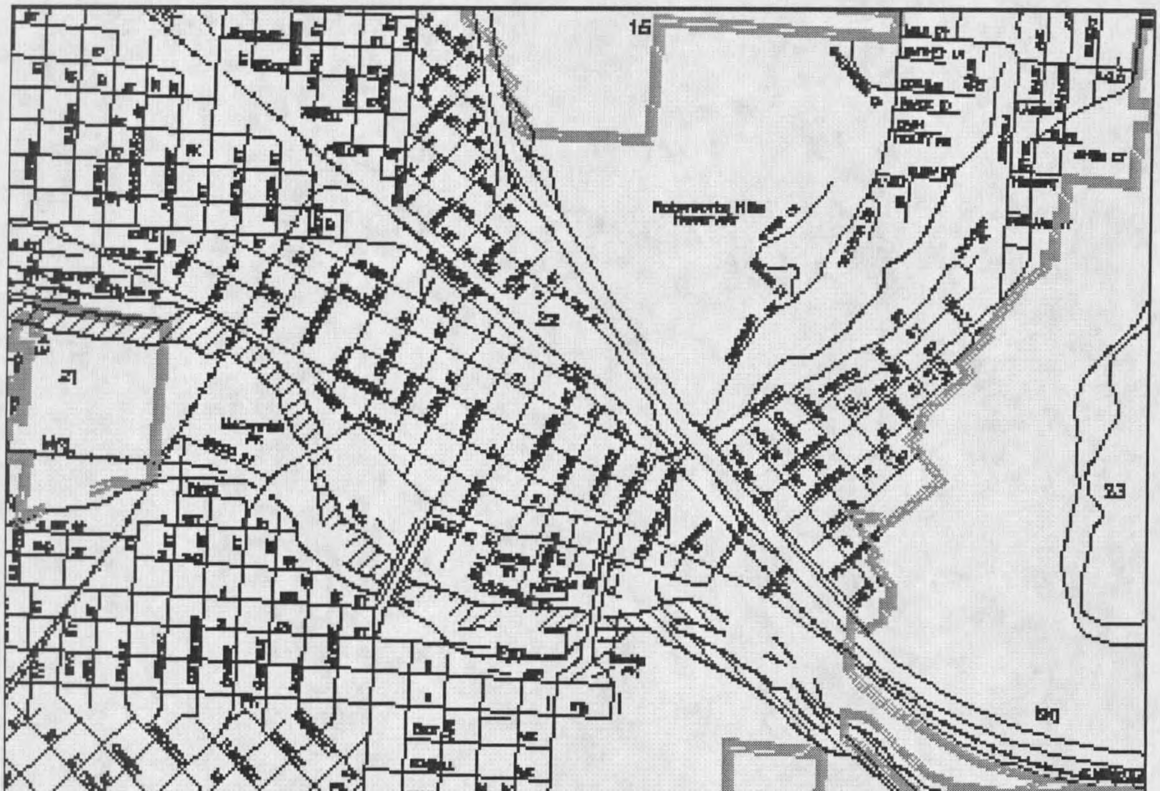


Figure 15. Urban Study Area Vicinity Map – Higgins/Hill/Beckwith

Figure 16. Urban Study Area Aerial Map – Higgins/Hill/Beckwith

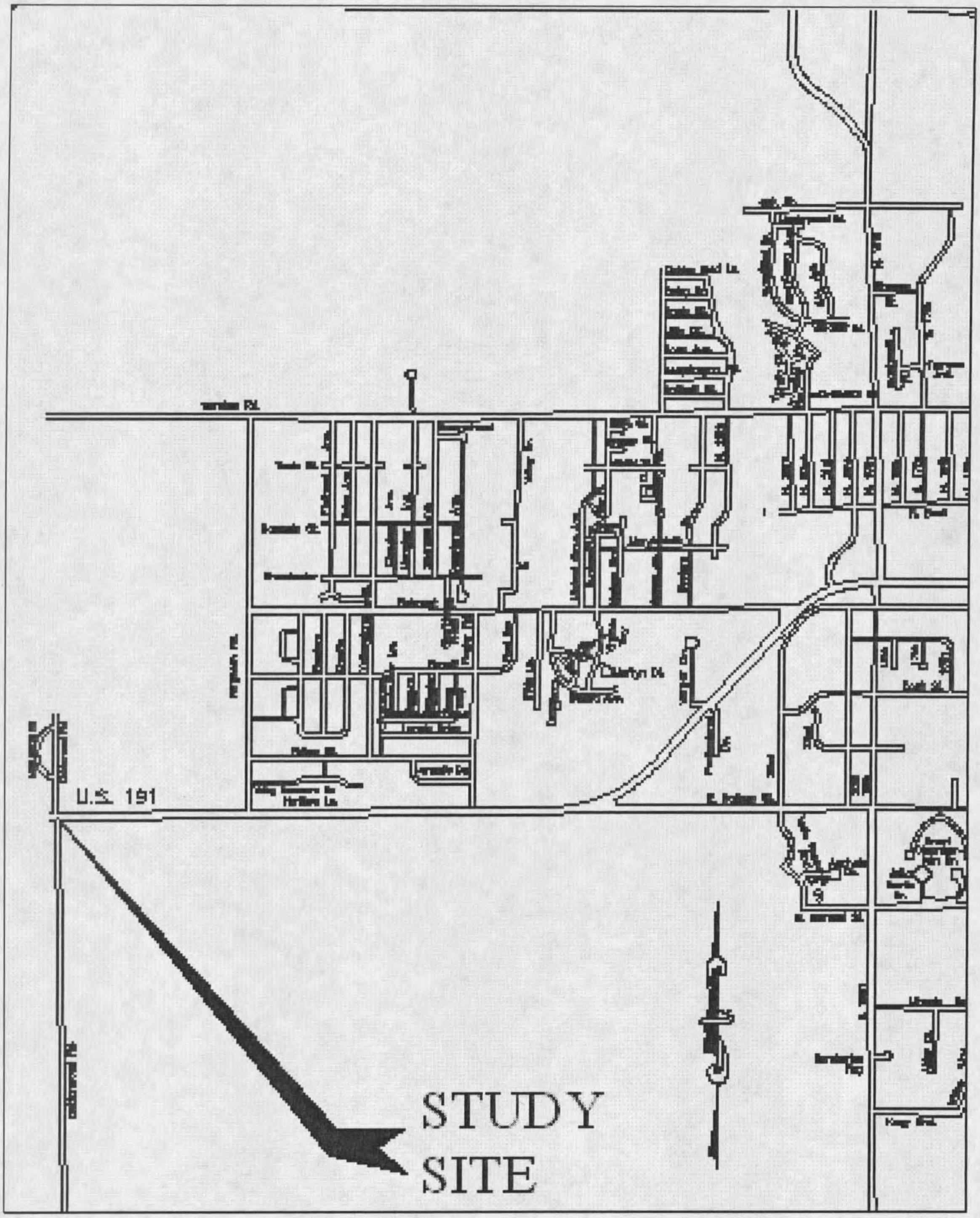


Figure 17. Rural Study Area Vicinity Map – Huffine/Cottonwood