



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
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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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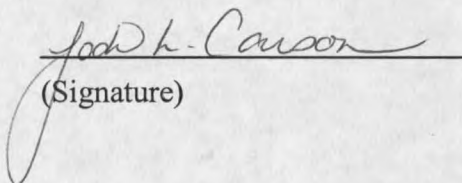
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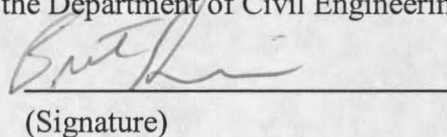
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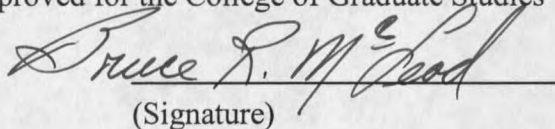
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TABLE OF CONTENTS

1. INTRODUCTION	1
BACKGROUND.....	2
REPORT PURPOSE AND CONTENTS	5
2. LITERATURE REVIEW	8
OPERATIONS	8
Delay.....	8
Traffic Calming.....	12
Environmental Impacts	14
Legal Considerations	15
System Considerations.....	16
Roundabout Signalization.....	16
Interchanges	16
At-Grade Rail Crossings	17
Arterial Network Considerations	17
SAFETY	19
Points of Conflict.....	20
Vehicle Conflicts	20
Pedestrian Conflicts	24
Bicycle Conflicts.....	25
Observed Safety Improvements	27
Crash Frequency and Severity	27
Collision Types	31
Crash Involvement.....	34
ECONOMICS	37
Safety Benefits	37
Crash Costs	38
Operational and Environmental Benefits.....	39
Capital and Construction Costs.....	39
Operations and Maintenance Costs.....	40
OTHER CONSIDERATIONS.....	41
Planning Process	41
Design	42
IMPLICATIONS FOR THIS EFFORT.....	42

TABLE OF CONTENTS - CONTINUED

3. METHODOLOGY	43
STUDY AREA	43
DATA COLLECTION	49
MEASURES OF EFFECTIVENESS	51
Crash Reduction	52
Delay	52
Queue Length and Stops	53
MODEL SELECTION	53
SimTraffic	54
Paramics	54
CORSIM	54
Integration	55
VISSIM	55
SIMULATION	56
Verification	57
Traffic Flow Characteristics	57
Driver Behavior	60
Multiple Runs	61
4. DATA ANALYSIS AND RESULTS	63
CRASH REDUCTION	63
DELAY	65
Higgins/Hill/Beckwith	69
Huffine/Cottonwood	70
QUEUE LENGTH AND STOPS	71
POTENTIAL SOURCES OF MODEL INACCURACIES	71
5. CONCLUSIONS AND RECOMMENDATIONS	73
REFERENCES	78

LIST OF TABLES

Table	Page
1. Average Annual Crash Frequencies and Severities at Converted Roundabouts	28
2. Crash Frequencies and Severities at Converted Roundabouts by Control Type	29
3. Mean Roundabout Crash Reductions from Various Countries.....	30
4. Roundabout Crash Types.....	31
5. Collision Types at Roundabouts	32
6. Crash Involved User Types at Roundabouts.....	34
7. Crash Reduction by Mode at Converted Roundabouts.....	35
8. Crash Rates for Two-Wheeled Vehicles at Roundabouts and Signalized Intersections in Britain	35
9. Crash Rates for Two-Wheeled Vehicles at Roundabouts and Signalized Intersections in France.....	36
10. Costs by Crash Severity	38
11. Crash Severity at Roundabouts.....	38
12. Crashes at the Case Study Sites	49
13. Higgins/Hill/Beckwith – Field Data Statistics.....	50
14. Huffine/Cottonwood – Field Data Statistics	51
15. Crashes at the Case Study Sites	63
16. Delay and Queue Results – Higgins/Hill/Beckwith with TWSC	66
17. Delay and Queue Results – Higgins/Hill/Beckwith with Traffic Signal	67
18. Delay and Queue Results – Higgins/Hill/Beckwith with Roundabout.....	67
19. Delay and Queue Results – Huffine/Cottonwood with TWSC	68

LIST OF TABLES - CONTINUED

20. Delay and Queue Results – Huffine/Cottonwood with Roundabout.....	68
21. Comparative Delay Costs	70

LIST OF FIGURES

Figure	Page
1. Circle Components Comparison - Roundabout vs. Traffic Circle.....	3
2. Traffic Control Preference - European vs. U.S.....	5
3. Average Delay per Vehicle at the MUTCD Peak Hour Signal Warrant	11
4. Delay Savings - Roundabout vs. Signal (50% Volume on Major Street).....	13
5. Delay Savings - Roundabout vs. Signal (65% Volume on Major Street).....	13
6. Vehicle-Vehicle Conflict Points for Three-Leg, T-Intersections and Roundabouts with Single-Lane Approach	21
7. Vehicle-Vehicle Conflict Points for Four-Leg Intersections and Roundabouts with Single-Lane Approach	21
8. Double-Lane Roundabout - Improper Lane-Use Conflict.....	23
9. Double-Lane Roundabout - Improper Turn Conflicts	23
10. Vehicle-Pedestrian Conflicts at Signals.....	24
11. Vehicle-Pedestrian Conflicts - Single-Lane Roundabouts	25
12. Vehicle-Bicycle Conflicts at Conventional Intersections	26
13. Vehicle-Bicycle Conflicts at Roundabouts.....	26
14. Graphical Depiction of Roundabout Collision Types.....	33
15. Urban Study Area Vicinity Map – Higgins/Hill/Beckwith	45
16. Urban Study Area Aerial Map – Higgins/Hill/Beckwith.....	46
17. Rural Study Area Vicinity Map – Huffine/Cottonwood.....	47
18. Rural Study Area Aerial Map – Huffine/Cottonwood.....	48
19. VISSIM Driving Behavior Parameters	61

ABSTRACT

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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).

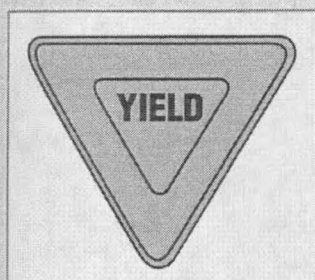
Roundabouts are being effectively used throughout Europe and the rest of the world with favorable results related to both safety and efficiency. However, several impediments include unfamiliarity, a lack of design guidelines, differences in interchanges/intersections and traffic control preferences and 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.



Yield-at-Entry

Modern Roundabout

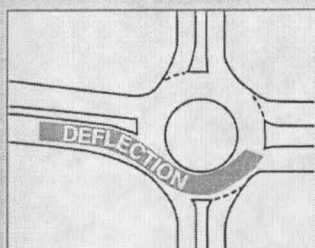
Entering traffic yields to circulating traffic.

- Circulating traffic always keeps moving.
- Works well with very heavy traffic.
- No weaving distance necessary. Roundabouts are compact.

Nonconforming Traffic Circle

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.



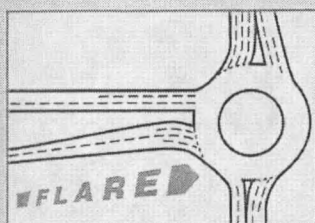
Deflection

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

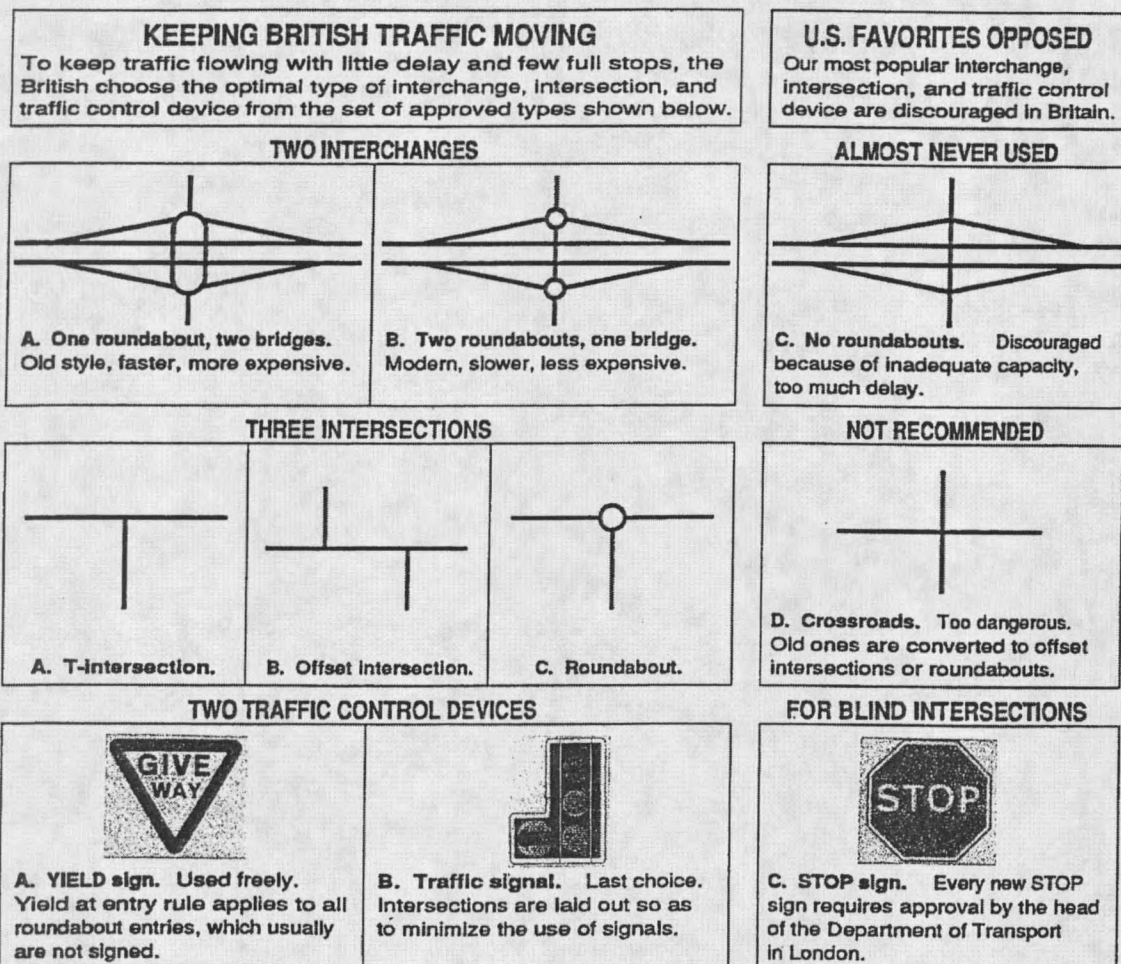


Figure 2. Traffic Control Preference – European vs. U.S. (3)

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

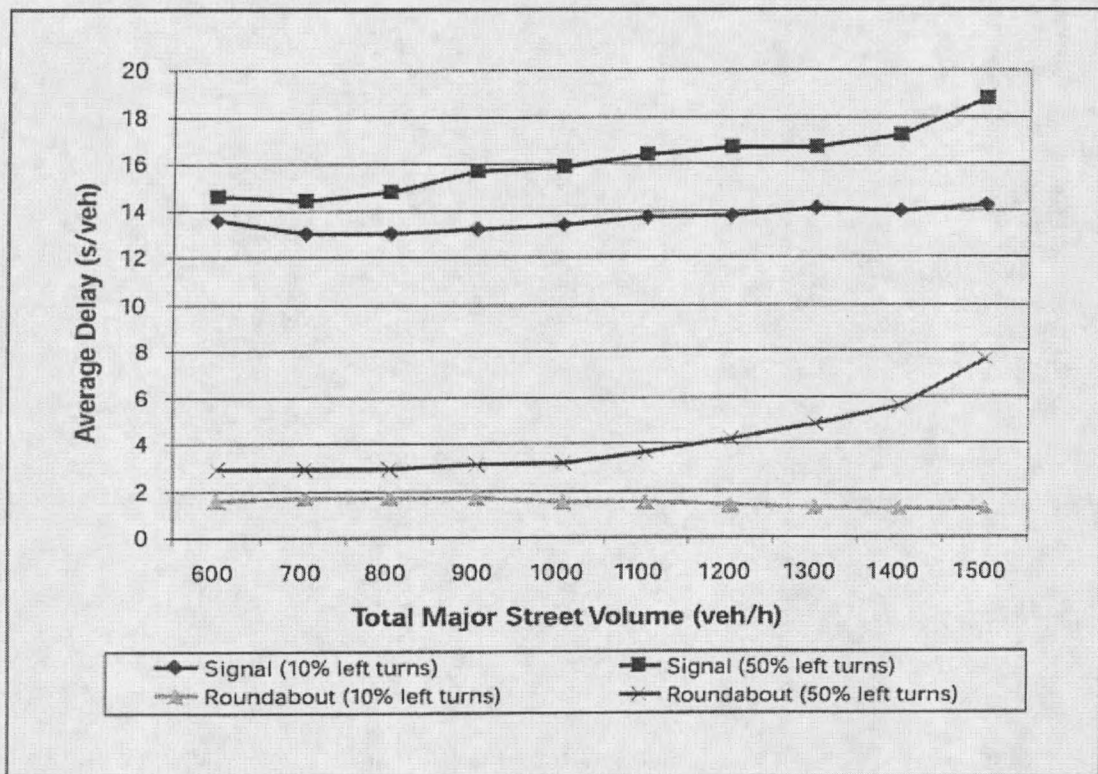


Figure 3. Average Delay per Vehicle at the MUTCD Peak Hour Signal Warrant (1)

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

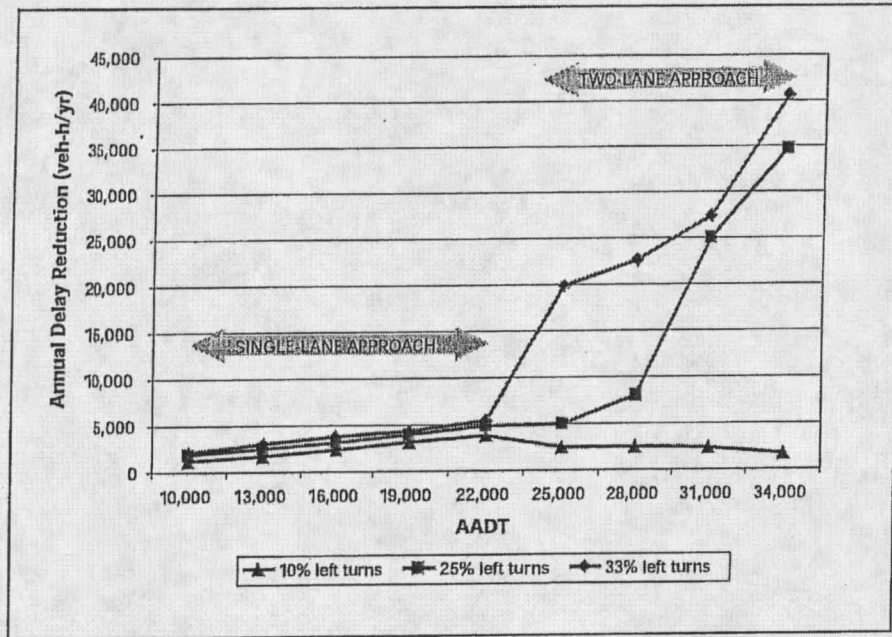


Figure 4. Delay Savings – Roundabout vs. Signal (50% Volume on Major Street) (1)

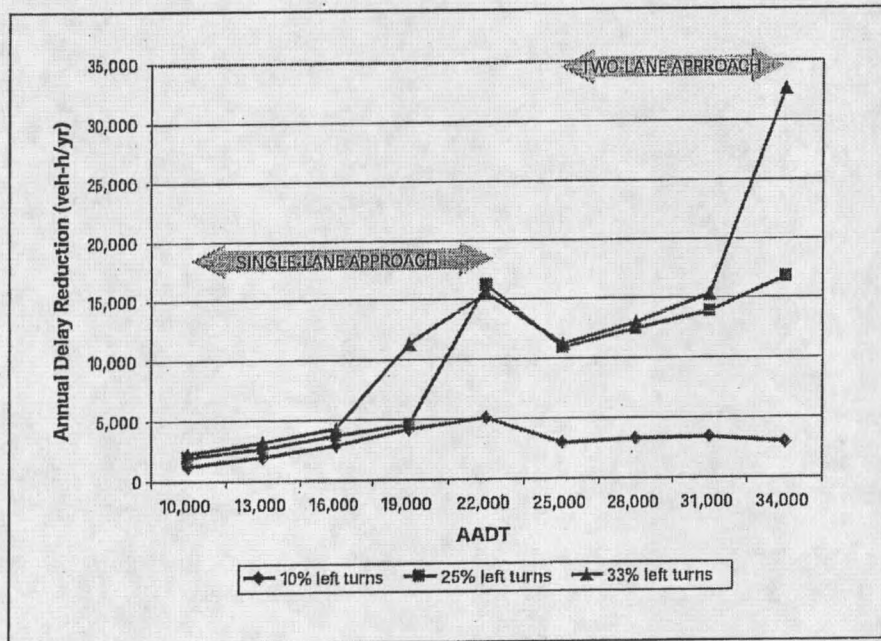


Figure 5. Delay Savings – Roundabout vs. Signal (65% Volume on Major Street) (1)

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 than 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 conventional 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 impaired) (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

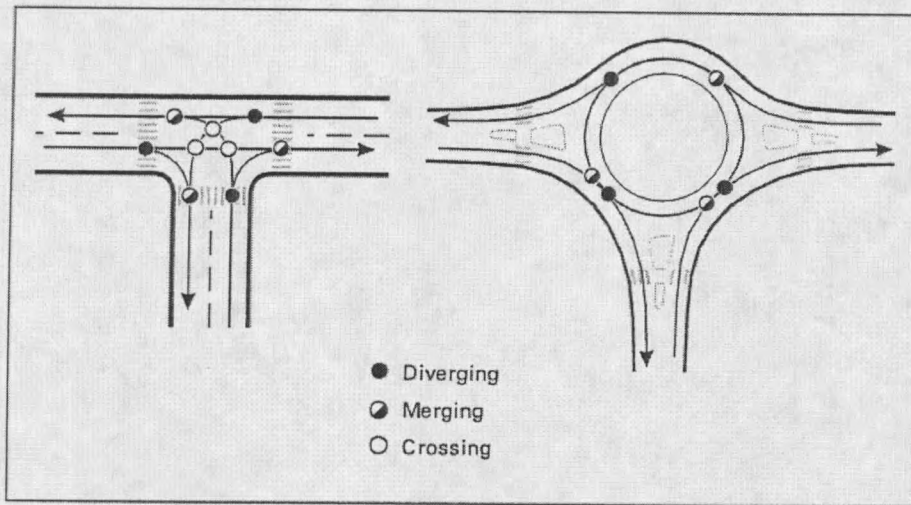


Figure 6. Vehicle-Vehicle Conflict Points for Three-leg, T-Intersections and Roundabouts with Single-lane Approach (1)

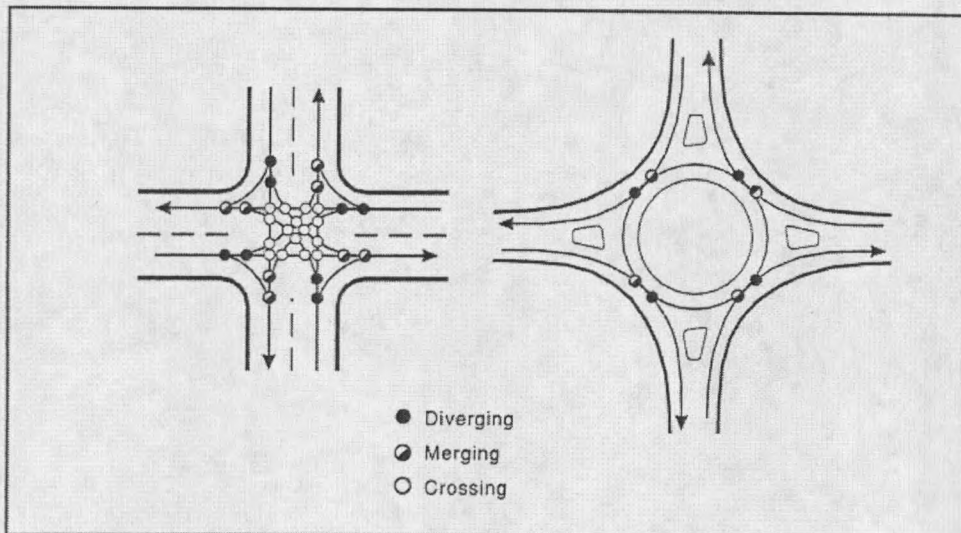


Figure 7. Vehicle-Vehicle Conflict Points for Four-leg Intersections and Roundabouts with Single-lane Approach (1)

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 than 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 than 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).

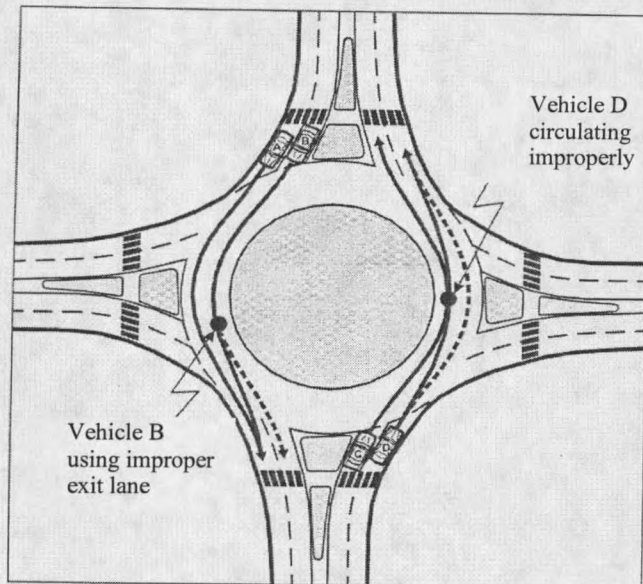


Figure 8. Double-Lane Roundabout – Improper Lane-Use Conflict (1)

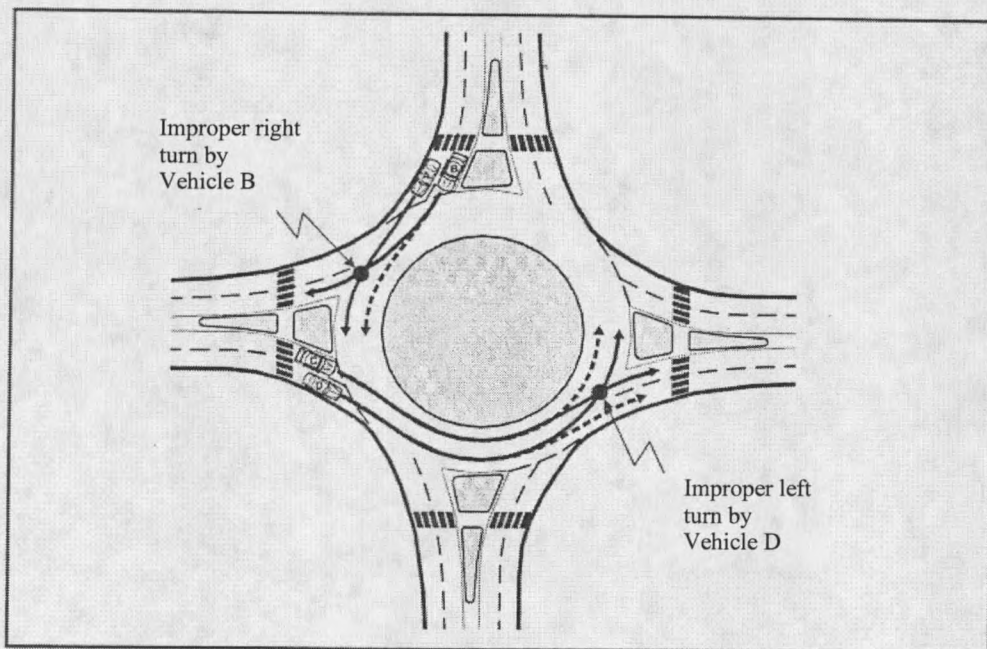


Figure 9. Double-Lane Roundabout – Improper Turn Conflicts (1)

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):

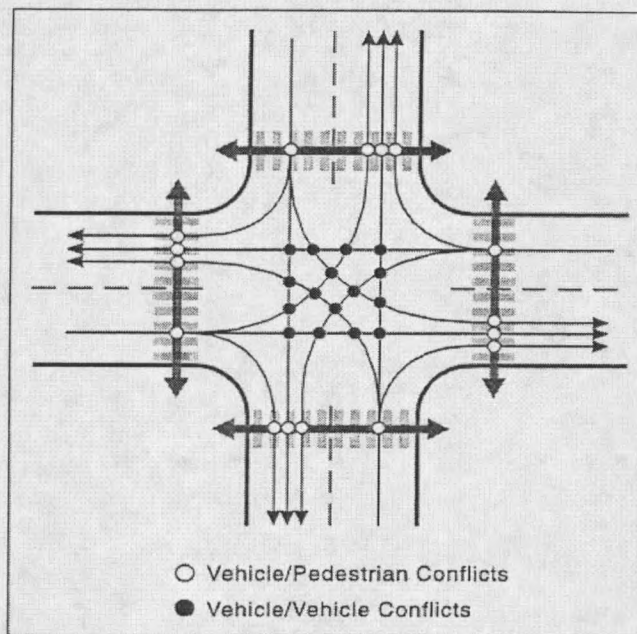


Figure 10. Vehicle-Pedestrian Conflicts at Signals (1)

- 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.

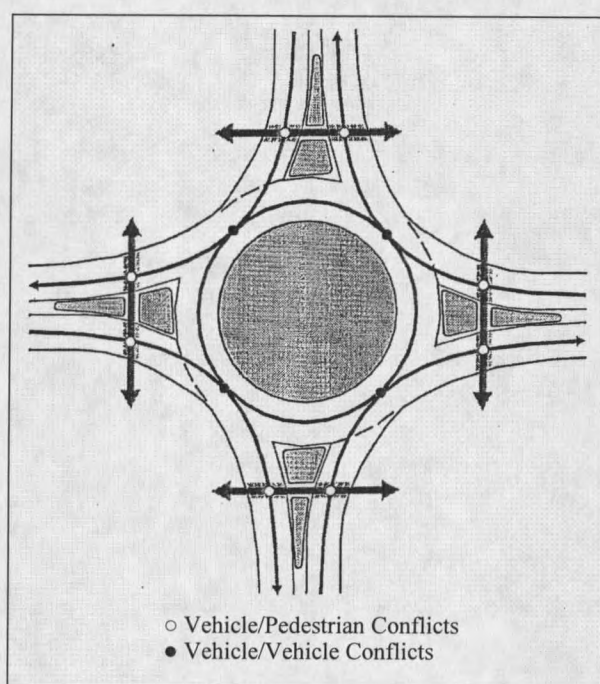


Figure 11. Vehicle-Pedestrian Conflicts – Single-Lane Roundabouts (1)

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

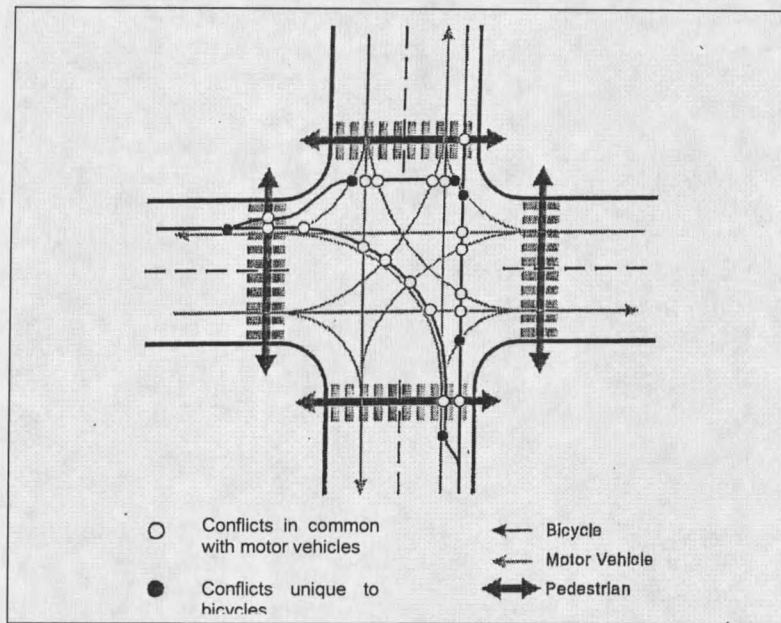


Figure 12. Vehicle-Bicycle Conflicts at Conventional Intersections (1)

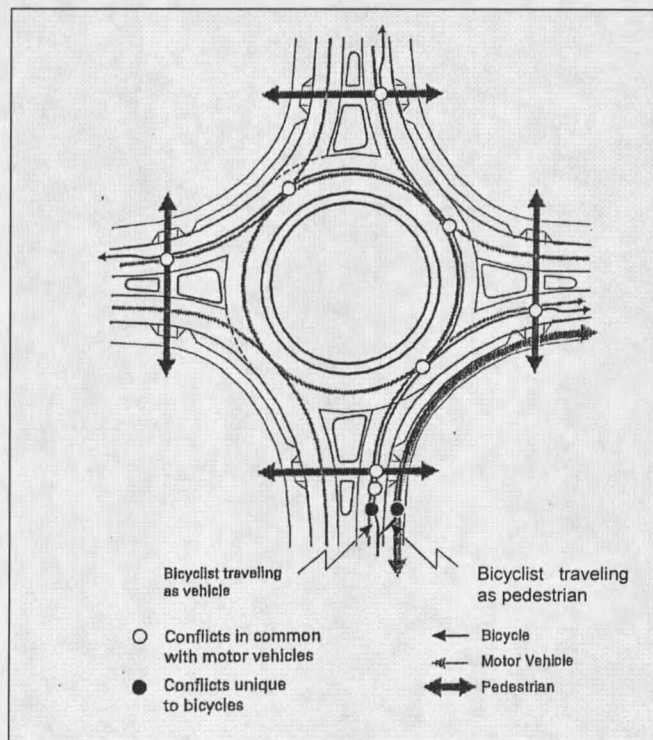


Figure 13. Vehicle-Bicycle Conflicts at Roundabouts (1)

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											
Jurisdiction	Year Opened	Control Before*	Single or Multilane	AADT		Months		Crash Count			
				Before	After	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)

Country	Mean Reduction (%)	
	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)

Country	Crash Description	Type of Roundabout	Type of Crash ¹		
			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)

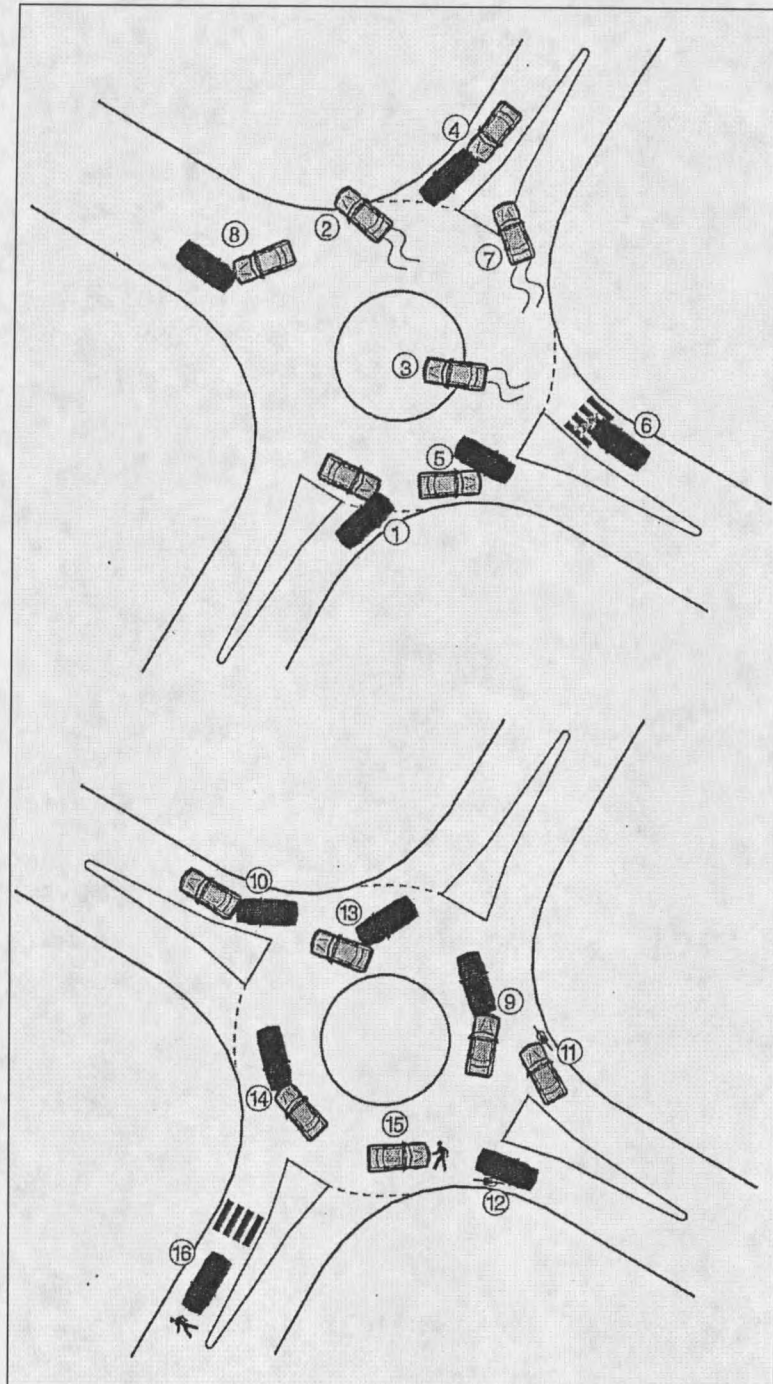


Figure 14. Graphical Depiction of Roundabout Collision Types (1)

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 convey 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 than 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 separately 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 than 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

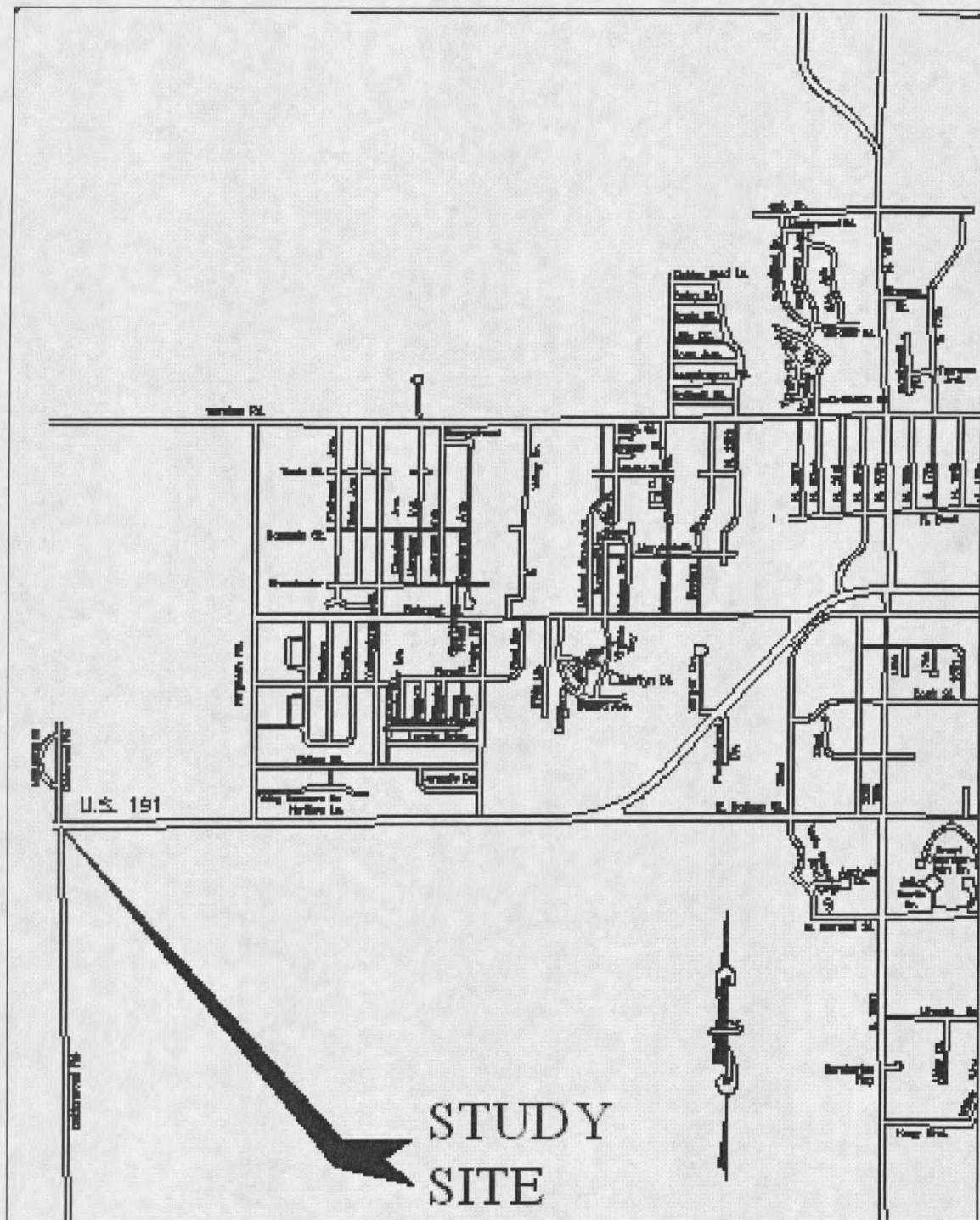


Figure 17. Rural Study Area Vicinity Map – Huffine/Cottonwood



Figure 18 – Rural Study Area Aerial Map – Huffine/Cottonwood

Data Collection

Two types of data were collected as part of this investigation: (1) safety-related data and (2) operational performance data. Safety related data, including crash count by severity and maneuver, was obtained from the Montana Department of Transportation's (MDT) Safety Management Section. For the Higgins/Hill/Beckwith intersection, three years of crash data were obtained (July 1, 1998 – June 30, 2001) from Keith Avenue one block north of the subject intersection through the intersection with Mount Avenue/Evans Avenue one block to the south (no mile-marker post designations are provided along this roadway). For the Huffine/Cottonwood intersection, three years of crash data were obtained (October 1, 1996 through September 30, 1999) between Mile Post 85.8 and 85.9. This data is only based on crashes reported to local authorities. The local jurisdictions then forward the accident report data to the Montana Department of Transportation for inclusion in the Transportation Information System (16). This data was reviewed to determine what, if any, accidents could be reduced through the installation of a roundabout. Descriptive statistics characterizing existing safety conditions are provided in Table 12.

Table 12. Crashes at the Case Study Sites (16)

	Total	Injury	Property Damage Only	Rear End	Left Turn Oncoming	2-Vehicle Right Turn	Angle
Higgins/Hill/ Beckwith	12	3	9	4	3	1	4
Huffine/ Cottonwood	7	3	4	1	1	1	4

Data to support the operational performance comparison included directional per lane volumes, turning movements, speed distributions, vehicle classification and traffic composition. This data was from four primary sources: (1) Montana Department of Transportation's machine and manual counts, (2) City of Missoula's machine counts, (3) conventional short duration tube counts, and (4) limited field studies (i.e. signal phasing times, headway timing, speed monitoring). Descriptive statistics characterizing existing operational conditions are provided in Tables 13 and 14.

Table 13. Higgins/Hill/Beckwith – Field Data Statistics

Location: Higgins Avenue & Beckwith Avenue & Hill Street													
Date Field Work Performed: P.M. – Thursday, 1/31/02													
Traffic Count Summary													
Hour Beginning	Eastbound			Westbound			Northbound			Southbound			15-Min Totals
	L	T	R	L	T	R	L	T	R	L	T	R	
5:00	3	6	1	6	28	20	2	99	10	12	180	4	371
5:15	4	3	0	11	16	18	2	95	18	5	162	7	341
5:30	1	8	1	11	21	13	0	109	18	12	146	3	343
5:45	3	12	0	3	22	16	2	98	17	10	135	9	327
Vehicle Classification (Bus and Truck)													
Hour Beginning	Eastbound			Westbound			Northbound			Southbound			15-Min. Totals
	L	T	R	L	T	R	L	T	R	L	T	R	
5:00		1B						1B	1B				3B
5:15												1B	1B
5:30				1B				1B	1B		1B		4B
5:45												1B	1B
Miscellaneous Field Data (based on 10 field measurements)													
Speed Distribution: mean speed = 33 mph, range = 24 – 37 mph													
Headway Timing (seconds)	L from Hill or Beckwith: mean = 6.5, range = 5.5 – 8.0												
	T from Hill or Beckwith: mean = 6.5, range = 6.0 – 8.0												
	R from Hill or Beckwith: mean = 6.0, range = 5.0 – 7.5												
	L from Higgins: mean = 6.0, range = 5.5 – 6.5												
Note: L = Left, T = Through, R = Right, B = Bus, no trucks noted in counts													

Table 14. Huffine/Cottonwood – Field Data Statistics

Location: Huffine Lane & Cottonwood Road													
Date Field Work Performed: P.M. – Thursday, 9/16/99													
Traffic Count Summary													
Hour Beginning	Eastbound			Westbound			Northbound			Southbound			15-Min. Totals
	L	T	R	L	T	R	L	T	R	L	T	R	
4:15	6	227	1	6	295	11	7	1	9	3	0	5	571
4:30	5	211	2	6	248	5	5	0	8	14	1	14	519
4:45	5	200	2	7	212	5	10	1	9	5	0	9	465
5:00	5	175	5	10	313	4	2	0	6	5	0	19	544
Vehicle Classification (Bus and Truck)													
Hour Beginning	Eastbound			Westbound			Northbound			Southbound			15-Min. Totals
	L	T	R	L	T	R	L	T	R	L	T	R	
4:15	1T	4T			5T								10T
4:30		7T			11T								18T
4:45		8T			4T	1T							13T
5:00		2T		1T	8T								11T
Miscellaneous Field Data (based on 10 field measurements)													
Speed Distribution: mean speed = 69 mph, range = 56 – 72 mph													
Headway Timing		L from Cottonwood: mean = 8.0, range = 8.0 – 9.0											
		T from Cottonwood: mean = 8.5, range = one observation											
		R from Cottonwood: mean = 6.0, range = 5.5 – 8.0											
		L from Huffine: mean = 6.5, range = 5.5 – 7.0											
Note: L = Left, T = Through, R = Right, T = Trucks, no buses noted in counts													

Measures of Effectiveness

The measures of effectiveness (MOEs) include those factors which are deemed necessary to adequately compare the different intersection forms. For this investigation, three critical measures of effectiveness were identified: (1) crash reduction, (2) delay and (3) queue length and stops. Measures of effectiveness were captured for base case conditions at each intersection and following intersection redesign to include a roundabout.

Crash Reduction

The reduction of crashes is an evident measure of effectiveness concerning the safety attributes of an intersection. An intersection type that consistently reduces the number of crashes following implementation would be deemed an improvement upon safety. This cost in crash savings can be combined with other costs such as construction and design to produce a benefit-cost ratio indicative of an intersection's overall effectiveness. For this analysis, three years of crash records from MDT's Safety Management Section were reviewed for each of the intersections. The data was analyzed to determine if historic accident types could be prevented by implementing either a roundabout or traffic signal.

Delay

The overall delay through a corridor can be effectively used in comparing the benefits of one intersection type over another. Delay can also be utilized to determine the optimal arrangement of intersection types to provide optimal performance. Delay was measured by placing counters in the model up and down stream of the intersections. The points were chosen so as to ensure uniformity between the intersection types.

The *Highway Capacity Manual* (17) identifies delay as the overall primary measure of effectiveness for both signalized and unsignalized intersections (including roundabouts) because it is used to define the intersection level-of-service. It can therefore be ascertained that this analysis of the delay between a signal and roundabout will serve as the primary measure in this intersection comparison. Simulation software packages report delay in a variety of forms including: (1) average total delay per vehicle in seconds, (2) average stopped delay per vehicle in seconds, (3) number of stops per

vehicle, (4) vehicle throughput, (5) average total person delay in seconds and (6) person throughput (18).

Queue Length and Stops

Queue length is important when analyzing the adequacy of a roundabout's geometric design, as well as that of other intersection forms. The average queue length is proportional to the vehicle-hours of delay per hour on an identified approach. The average queue length, maximum queue length, and number of vehicles stopped at an identified location were used in the simulation as a measure of effectiveness.

Model Selection

To support the determination of the various measures of effectiveness related to delay and queuing, simulation was used to estimate effects following roundabout installation. Simulation, compared to direct analysis, was thought to more accurately demonstrate the potential for operational benefits of roundabouts not yet constructed. Because available simulation models represent different underlying data or theories, and will therefore produce different results, a cursory review of simulation options was first conducted.

More limited simulation options exist for exploring safety-related MOEs. Crash prediction models have been created for signalized intersections in the U.S., but not for roundabouts. Many of the crash prediction models are based on generalized linear regression. The goodness of fit for the models is expressed in terms of scaled deviations that are only moderately reliable. Some of the models are only valid for certain

geometric layouts as well (i.e., four-leg); small changes in geometry can drastically change the results (1).

Simtraffic

Simtraffic is a simulation model closely related to the signal timing software Synchro. Simtraffic has the capability to model unsignalized intersections and therefore may be suitable for modeling roundabouts. However, no publications to date have demonstrated the accuracy of Simtraffic in modeling of roundabout operations (1).

Paramics

Developed in Scotland, Paramics has been used internationally for a wide range of simulation projects. It has been used in the United Kingdom for a number of actual roundabout evaluations. The model has a coding feature to automatically code a roundabout intersection at a generic node, which may then be edited. The model uses a steering logic on the circulatory roadway to track a vehicle from an entrance to an exit through a roundabout intersection (1).

CORSIM

CORSIM is a North American microscopic, stochastic traffic simulation model with a scope covering urban streets and freeways. It was developed by the Federal Highway Administration (FHWA) and combines a street simulator (NETSIM) with a freeway simulator (FRESIM) (19). The FHWA is currently investigating modifications that may allow CORSIM to adequately model stop and yield controls at roundabouts using gap

acceptance logic. Presently, the roundabouts have been modeled as a circle of four yield-controlled T-intersections (1).

Integration

Integration is a second North American microscopic simulation model with a scope that includes urban streets and freeways. It has documented gap acceptance logic for permitted movements at signal-, yield- and stop-controlled intersections. Similar to CORSIM, this software requires that roundabouts be coded as a series of short links and nodes with yield control at the entrances (1).

VISSIM

VISSIM is a German based microscopic time-step and behavior-based simulation model. It models design alternatives including signalized and stop-controlled intersections, as well as roundabouts and grade-separated interchanges. Networks can also be overlaid on aerial photography using VISSIM. The output files include travel time and delay, queue length, signal timing information, detector actuation, time space diagrams, speed profiles, and environmental indicators. Other key features include 3-D modeling, dynamic routing, and traffic calming (20).

VISSIM was selected as the simulation model of choice for this investigation because of its extensive features and recent application in the United States and use internationally. The *Guide* notes that when selecting a model, analysts should consider if the model input requirements are sufficient, and how can they be provided or estimated (1). The data inputs available with VISSIM are substantial and include the network

layout (number of lanes, widths, gradients, intersection controls, speed zones, etc.), vehicle characteristics (acceleration/deceleration, speed distributions, type/classifications, etc.), traffic compositions and volumes, routing decisions/turning movements, priority rules (involving gap times and minimum headways), and driver behavior (reaction times, gap acceptance, headway distances, acceleration/deceleration, etc.), among others. The *Guide* also notes that the types of output should be considered (animated, graphical, or tabular). VISSIM allows for extensive review of the model through animation and the 3-D modeling feature. The data is output in tabular form. The VISSIM user manual also specifically addresses the modeling of a roundabout and notes extensive validation of the model in European applications. A number of such models are included with the VISSIM program to reference as examples of relevant past projects (18).

Simulation

For traditional simulation applications, three basic steps are recommended prior to finalizing any analysis results: (1) calibration, (2) validation, and (3) conducting of multiple runs (because VISSIM is stochastic) (21). Further, a sensitivity analysis should be performed by changing some of the parameters and observing the results. In the event that a parameter is found to significantly affect the outcome, more attention can be directed towards its accurate representation and calibration. Because the purpose of this investigation was to provide a comparative analysis among three alternatives (i.e., TWSC, signalized and roundabout intersections) rather than predicting MOEs for each, full calibration/validation procedures were not undertaken. Any model inaccuracies

would be applied to all three alternatives equally. Instead the model's reasonableness was verified through the following process.

Verification

Two components of a simulation model that require verification are (1) traffic flow characteristics and (2) driver behavior. Verification requires that any field data observations are reasonably close to VISSIM model outputs.

Traffic Flow Characteristics. Input data for the VISSIM model can come from various sources including saturation flow rate studies, gap acceptance studies, delay and queue length studies, as well as turning movement counts and 24-hour tube counts (18). For this investigation, field data comprised 24-hour tube counts for at least one complete weekday (Tuesday through Thursday). While tube counts were obtained for the Huffine/Cottonwood intersection from Thursday, September 16 to Tuesday, September 21, 1999, only the Thursday and Tuesday counts were utilized. For the Higgins/Hill/Beckwith intersection, tube counts were obtained from February 20 to February 22, 2002. Peak morning and afternoon hours were derived from this tube count data, allowing for manual traffic counts and turning movements to be obtained during those peak hour periods (7:30 – 8:30 a.m. and 4:15 – 5:15 p.m. for the Huffine/Cottonwood intersection and 8:00 – 9:00 a.m. and 5:00 – 6:00 p.m. for the Higgins/Hill/Beckwith intersection). Traffic volumes and turning movements observed during the field data collection are summarized in Tables 13 and 14.

These traffic counts were used to develop the VISSIM model. Fifteen-minute time periods during the peak hour helped to characterize the peak distribution. Vehicle types

were coded as one of three vehicle types; passenger vehicle, transit bus, and large truck. The number of vehicle type categories could be expanded to more accurately represent actual conditions. For example, UPS delivery trucks were coded as passenger vehicles instead of large trucks. While their operations may more closely resemble a passenger vehicle, they have parameters that, if coded separately in a model, may alter the results. The accuracy of the peak hour traffic data could further be increased, to ensure the most representative sample of the system, by conducting multiple counts of the peak hour time period throughout various times of the year. Only one peak hour traffic count was obtained for each case study and used for the field data input into the VISSIM models. Additional peak hour counts were not collected for this investigation. Instead, the different intersection alternatives were compared at a specific snapshot in time, which was thought sufficient for a comparative analysis.

Limited travel runs were also conducted through each of the case study areas to verify average speeds. Ten travel runs through each of the case study areas, using a car-following technique, were conducted as part of the data collection effort. The range of travel speeds was used in coding the models.

Headway times were also measured at the Higgins/Hill/Beckwith intersection and on a facility similar to Huffine Lane (Highway 93 near Lolo, Montana) to provide a basis for coding in the models. While these measurements were limited, they did provide a basis for coding the priority rules. Headway distances for the roundabouts were based solely on VISSIM default values since no constructed facilities exist in the area. A review of

the models indicated that the coded headway times were providing results similar to those in the field with regards to vehicle movements (see Tables 13 and 14).

There were no actual field measurements of queue length conducted for either of the case study areas. Each site was a TWSC intersection with the majority of the traffic on the major through leg. Given this small volume of traffic on the minor legs controlled by the stop signs it was felt that the variability would not necessarily aid the verification of the model.

To replicate the modeled infrastructure network to scale, base maps were imported from aerial photos of both case study areas. These base maps were then scaled using known distances and used to exactly trace the existing base case network in VISSIM. While actual designs have not been completed for the roundabout and signal options for the Higgins/Hill/Beckwith intersection, preliminary designs are complete enough to provide accurate layout dimensions for both a signal and roundabout. The Huffine/Cottonwood intersection roundabout was dimensioned based on recommendations from the *Guide* (50 km/h entry speed, 60 m inscribed circle diameter) (1).

In the absence of a completed signal design for the Higgins/Hill/Beckwith intersection, timing configurations of two neighboring signals along Beckwith Avenue were examined. The intersections are similar in traffic volumes and associated signal timing. A fixed-time signal control was developed based on the average of these two adjacent signals (Beckwith/Brooks and Beckwith/Arthur). Tentative plans of the municipality include coordinating signals along this corridor, assuring common cycle

times for each signal. Averaging the timing plans of adjacent signals better addressed these plans for coordination than designing a new timing plan for this intersection in isolation. This estimated signal timing could be considered a largely variable condition in this analysis.

All of the intersection alternatives considered in this investigation – TWSC, traffic signal and roundabout - were each coded with priority rules designating the right-of-way for conflicting movements (i.e., the location where a vehicle should yield for other vehicles).

Driver Behavior. Driver behavior parameters were based solely on VISSIM default values and the psychophysical driver behavior model developed by Wiedemann. Periodical field measurements and their resulting updates of model parameters ensure that changes in driver behavior and vehicle improvements are accounted for (18). Relying on these default values assumes that the demographics of the model are similar to that encountered for the case scenarios. These default values can vary on an intersection-by-intersection basis, and could result in erroneous delays, queue lengths and level of service (LOS) estimates (21). Figure 19 depicts the default driving behavior parameters used for all the case studies.

Driving Behavior Parameters

Urban

Average Standstill Distance: 2.00 m

Max. Deceleration (negative): -9.99 m/s²

Additive Part of Desired Safety Distance: 2.00

Multipl. Part of Desired Safety Distance: 3.00

Lane Change

Waiting time before diffusion: 60.00 s

Min. Headway (front / rear): 0.50 m

To slower lane if collision time above: 11.00 s

Reaction to Amber Signal

Probability Factor Alpha: 1.58858105

Probability Factor Beta 1: -0.2619807

Probability Factor Beta 2: 0.26945295

Formula for determination of stop probability at start of amber time:

$$p = 1 / (1 + \exp [-\text{Alpha} - \text{Beta1} * v - \text{Beta2} * dx])$$

Number of observed preceding vehicles: 2

Freeway

CC0: 1.50 m

CC1: 1.30 s

CC2: 4.00 m

CC3: -12.00

CC4: -0.25

CC5: 0.35

CC6: 6.00

CC7: 0.25

CC8: 2.00 m/s²

CC9: 1.50 m/s²

Default

OK

Cancel

Figure 19. VISSIM Driving Behavior Parameters (18)

Multiple Runs

The third step in the simulation process involves conducting multiple runs of the simulation model. Because VISSIM is based on stochastic algorithms that describe driver behavior and traffic operations, it is necessary to conduct multiple runs of the models to have a reasonable data pool from which to conduct analysis.

VISSIM uses random number seeds to generate output results for each individual model execution. For each of the case studies, a random number seed group was

calculated using Excel. The same number seed group was used for the existing TWSC base case, proposed signal, and proposed roundabout for the Higgins/Hill/Beckwith case study site. A separate number seed group was used for the Huffine/Cottonwood case study, but the new seed group was used for both the existing TWSC base case and proposed roundabout. Using the same number seed groups for each model at the case study site allows for the same driver behavior and traffic operations to occur between the models and more accurate analysis of the different intersection types by allowing comparison of the actual traffic control without concern for varying behavior or traffic operations between the models.

VISSIM recommends anywhere from five to ten iterations be conducted to provide an adequate base line for analysis, depending on the complexity of the model (18). The iterative process described above was conducted five times for each case study, given that only individual intersections were modeled versus complete networks. Five iterations were thought to adequately capture random variations in the traffic flow. The averages for each movement were then calculated to ascertain a more representative value for the measure of effectiveness being evaluated. Further detail and accuracy could be attained in the analysis by conducting additional runs of the models to get a larger data pool from which to calculate the overall averages.

CHAPTER 4

DATA ANALYSIS AND RESULTS

Data related to vehicle crash reduction, delay and queue length and stops were analyzed to determine the effects of employing a variety of intersection traffic control measures at two case study sites. These traffic control measures included the base case two-way stop controlled intersection, a proposed signalized intersection and a proposed roundabout intersection. Results are detailed below.

Crash Reduction

As noted previously, reductions in crashes can be a primary measure of effectiveness when evaluating overall intersection safety. Crashes occurring within the milepost location, and within one-tenth of a mile of the subject intersections were reviewed.

Crashes were categorized by severity and type of crash. Table 15 lists the number and types of crashes that took place during the noted time periods by site location.

Table 15. Crashes at the Case Study Sites (16)

	Total	Injury	Property Damage Only	Rear End	Left Turn Oncoming	2-Vehicle Right Turn	Angle
Higgins/Hill/ Beckwith	12	3	9	4	3	1	4
Huffine/ Cottonwood	7	3	4	1	1	1	4

Because the signal and roundabout intersection options are only proposed, and not yet constructed, a valid before-after comparison cannot be made. Accident Investigator's Reports were provided with the Montana Department of Transportation accident data and provided insight into the cause of each crash. While weather can be a factor in the cause of any crash, most crashes reviewed here are due strictly to driver violation of traffic laws. Review of the Higgins/Hill/Beckwith data indicated that two of the crashes resulted from traveling too fast for conditions (1 rear end, 2 vehicle right turn), three resulted from following too close (rear end), and seven resulted from failure to yield the right-of-way (left turn oncoming and angle). For the Huffine/Cottonwood intersection only one crash resulted from traveling too fast for the conditions (rear end), with the remaining six resulted from failure to yield the right-of-way (left-turn oncoming, 2 vehicle right-turn and angle).

While before-after data is not available, the types of crashes and their causes were reviewed to determine if a signal or roundabout may be able to reduce crashes at the subject sites. Rear end crashes may be preventable with a traffic signal; a signal may be able to reduce the probability of an occurrence by separating left-turn traffic from the free flowing through traffic movement through the use of a dedicated left-turn bay. A roundabout may also reduce or eliminate rear end crashes by requiring all vehicles to enter the intersection with only right turns, removing stopped left-turn traffic from the travel-way.

Left-turn oncoming, two-vehicle right-turn and angle collisions are largely due to right-of-way violations. As noted in the literature, traffic signals may be able to reduce

these collision types by providing a definitive right-of-way indication to the motorists. Signals are not failsafe; with right-turn-on-red conflicts, left-turn traffic yielding to oncoming through traffic and racing to beat the red light accidents, motorists still experience crash risk. A roundabout fully prevents crashes involving left-turning vehicle conflicts with oncoming through traffic. Right-turn and angle collisions would experience a reduction in severity due to the configuration of the traffic flow; impact angles and reduced travel speeds, resulting in reduced property damage and personal injuries.

Crashes that result from following too closely or traveling too fast for the conditions will likely not see a reduction in frequency with any type of intersection control. The severity of injury and property damage crashes may however be reduced by providing dedicated right-of-way indications, separating traffic at grade or removing certain movements from the traffic stream.

Delay

Using VISSIM, the delay at the case study intersections was estimated for each base case and their proposed alternate intersection types (signal and/or roundabout). Each model was structured to allow for the same beginning and ending delay measurement points up and downstream of the subject intersections. For this analysis, VISSIM was used to determine the average total delay per vehicle in seconds. Passenger data was not recorded; it was assumed that each vehicle had only one occupant. While this is not necessarily realistic, it does offer a basis for equal comparison of intersection types.

There are no special generators in the area of either site that would indicate that the vehicle occupancy rate is dissimilar between east-west movements and north-south movements. Tables 16, 17 and 18 show the delay and queue results for the Higgins/Hill/Beckwith intersection assuming the base case TWSC and the proposed traffic signal and roundabout. Tables 19 and 20 show the delay and queue results for the Huffine/Cottonwood intersection assuming the base case TWSC and the proposed roundabout.

Table 16. Delay and Queue Results – Higgins/Hill/Beckwith with TWSC

Higgins/Hill/Beckwith Intersection Intersection Type: Two-Way Stop Control (Existing Base Case)			
Movement	Length of Travel Path (m)	Avg. Delay/Vehicle (sec.)	Avg. Queue Length (m)
SB Left	129.6	4.2	0.2
SB Thru	136.9	0.8	
SB Right	133.5	0.7	
EB Left	138.2	67.0	1.6
EB Thru	128.0	44.9	
EB Right	115.4	23.6	
NB Left	131.6	5.4	0.0
NB Thru	136.5	0.5	
NB Right	120.5	0.2	
WB Left	129.6	123.1	30.2
WB Thru	130.1	112.4	
WB Right	119.6	86.6	
Vehicle Total	185,343.7 (m) traveled	22,398.8 373.3 min.	

Table 17. Delay and Queue Results – Higgins/Hill/Beckwith with Traffic Signal

Movement	Length of Travel Path (m)	Avg. Delay/Vehicle (sec.)	Avg. Queue Length (m)
SB Left	134.7	7.0	0.0
SB Thru	140.9	4.8	2.8
SB Right	138.2	3.9	
EB Left	143.0	17.8	0.4
EB Thru	127.2	17.7	0.8
EB Right	97.8	16.0	
NB Left	120.5	7.2	0.0
NB Thru	139.5	4.4	2.2
NB Right	119.5	3.4	
WB Left	126.3	18.0	1.0
WB Thru	130.0	17.0	4.0
WB Right	118.1	20.0	
Vehicle Total	188,999.0 (m) traveled	9,491.4 158.2 min.	

Table 18. Delay and Queue Results – Higgins/Hill/Beckwith with Roundabout

Movement	Length of Travel Path (m)	Avg. Delay/Vehicle (sec.)	Avg. Queue Length (m)
SB Left	171.0	2.7	0.0
SB Thru	144.9	2.9	
SB Right	139.7	2.6	
EB Left	174.3	2.7	0.0
EB Thru	140.8	1.9	
EB Right	113.4	3.9	
NB Left	184.3	0.6	0.0
NB Thru	144.5	0.8	
NB Right	109.6	0.5	
WB Left	156.2	2.4	0.0
WB Thru	151.3	1.7	
WB Right	111.2	2.4	
Vehicle Total	197,792.9 (m) traveled	2,803.4 46.7 min.	

Table 19. Delay and Queue Results – Huffine/Cottonwood with TWSC

Movement	Length of Travel Path (m)	Avg. Delay/Vehicle (sec.)	Avg. Queue Length (m)
SB Left	422.2	272.6	12.2
SB Thru	281.6	300.2	
SB Right	430.6	23.0	1.2
EB Left	442.3	10.1	0.0
EB Thru	620.7	0.1	NA
EB Right	464.5	0.0	
NB Left	481.2	259.6	13.8
NB Thru	280.8	358.8	
NB Right	438.8	34.3	0.2
WB Left	450.7	9.6	0.4
WB Thru	620.1	0.2	NA
WB Right	406.4	0.1	
Vehicle Total	1,262,130.7 (m) traveled	17,574.9 373.3 min.	

Table 20. Delay and Queue Results – Huffine/Cottonwood with Roundabout

Movement	Length of Travel Path (m)	Avg. Delay/Vehicle (sec.)	Avg. Queue Length (m)
SB Left	482.3	6.9	0.0
SB Thru	296.1	2.8	
SB Right	411.7	8.2	
EB Left	499.8	1.0	0.0
EB Thru	629.8	1.0	
EB Right	447.0	0.9	
NB Left	536.8	7.0	0.0
NB Thru	296.2	4.5	
NB Right	425.0	6.3	
WB Left	510.7	0.9	0.0
WB Thru	630.0	1.2	
WB Right	390.5	0.9	
Vehicle Total	1,284,149.7 (m) traveled	3,126.3 52.1 min.	

Higgins/Hill/Beckwith

At the Higgins/Hill/Beckwith site, a review of the delay and queue data indicates that both the eastbound and westbound movements (minor leg) are positively impacted by the implementation of either a signal or roundabout. Traffic signals provide dedicated right-of-way and roundabouts provide gaps and confine movement. However, the loss of continuous free flow movement introduced with either the signal or roundabout increases the delay to the north-south movements (major leg).

Implementation of either a signal or roundabout reduces the delay to the eastbound and westbound traffic (minor leg) but increases delay to the north-south movements. The increase in delay, from 2 to 4 seconds per vehicle for a traffic signal and 1 to 2 seconds for a roundabout, can be considered significant since the north-south orientation are the major approaches majority of traffic volumes.

Table 21 summarizes the delay impacts for each of the three intersection alternatives and attributes a cost value to this delay. The cost value assumes \$10/vehicle-hour and excludes costs associated with fuel consumption and emissions (21). These cost values were extrapolated to annual estimates of delay. Because this output is based on conditions during the peak hour, delay costs are overestimated but still afford a basis for comparison between the intersection alternatives.

Table 21. Comparative Delay Costs

Higgins/Hill/Beckwith		
Control Type	Delay	Delay (1) Cost/Yr.
	Vehicle Hours (Peak Hour)	
Two-Way Stop	6.2	\$545,047
Signal	2.6	\$204,721
Roundabout	0.8	\$68,153
Huffine/Cottonwood		
Two-Way Stop	4.9	\$427,663
Roundabout	0.9	\$76,037

(1) Based on peak hour estimates of delay.

Huffine/Cottonwood

Similar to the findings at the Higgins/Hill/Beckwith site, the delay to the northbound and southbound movements (minor leg) were decreased by the implementation of a roundabout. However, a similar increase in delay to the east-west movements (major leg) was also observed.

The northbound-southbound movements at Huffine/Cottonwood were greatly improved with respect to delay with the implementation of a roundabout. The roundabout gives right-of-way to certain vehicle movements including eastbound-westbound left turns, northbound-southbound left turns and through movements, that result in minor increased delay (an additional one second) to the major leg through traffic.

Queue Length and Stops

Average queue length provides a limited measure of effectiveness in this evaluation. The queue length is associated with the determination of delay, and is used here to primarily evaluate the basic adequacy of the design elements (i.e., lane configuration).

Analysis of the Higgins/Hill/Beckwith data indicates minimal to non-existent average queue lengths across most of the movements, although a 30.2 meter queue length is estimated for the westbound traffic at the two-way stop. Consistent with the analysis of delay, this leg experienced a large amount of wait time. The traffic signal alternative offers an improvement in the form of additional lanes and controlled right-of-way into the traffic stream. While the queue lengths increase other movements with a signal, the westbound traffic is reduced to an average queue length of 4.0 meters.

For both the Higgins/Hill/Beckwith site and the Huffine/Cottonwood site, the roundabout alternative reflected no queuing of vehicles. This is likely attributable to the significant differences in directional distribution; the Higgins/Hill/Beckwith site carries 84 percent on the major leg and Huffine/Cottonwood site carries 94 percent of the traffic on the major leg.

Potential Sources of Model Inaccuracies

During the simulation process, potential inconsistencies in simulated findings and field conditions were noted. Modeling the two-way stop controlled intersections resulted in unrealistic observations with regards to driver behavior. Several excessive delay times

(10+ minutes) were noted with eastbound and westbound traffic waiting for a gap in the north-south traffic stream. While the presence of these excessive times was rare, it does suggest room for improvement in the accuracy of the model. To avoid such an excessive delay time, a motorist will likely either choose a different route (right or left turn) or become more aggressive and reduce their acceptable gap tolerance to force their way into the traffic flow.

Another inconsistency observed at the Higgins/Hill/Beckwith site was the volume of traffic entering from the east. Each model run resulted in an error message; the link did not generate all the vehicles specified because the discharge rate was smaller than the input flow. Because these volumes were input directly from actual field data, it can be ascertained that even though the model could not move the volume of traffic along this leg, the link is able to in the field.

At the Huffine/Cottonwood site, field observations showed that minor leg left turning motorists entering the major leg were using the center left-turn lane as an on ramp, allowing them to address one direction of traffic at a time. This illegal driving maneuver is difficult to replicate accurately in the simulation model.

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

This report reviews the results of an evaluation of two-way stop controlled, signalized, and roundabout intersections in an urban and rural environment. The intersection of Higgins/Hill/Beckwith in Missoula, Montana served as the urban case study, while the intersection of Huffine Lane/Cottonwood Road in Bozeman, Montana served as the rural case study.

Measures of effectiveness (MOEs) used in the analysis include (1) crash reduction, (2) delay and (3) queue lengths. VISSIM, a German-based microscopic time-step and behavior-based simulation software, was used to model the various intersection types. Field data (peak hour 15-minute traffic volumes, vehicle type, gap timing and headway distance) was input into the model to calibrate the conditions. This field data was then utilized to validate the model performance and output. Multiple runs of the models were then conducted to provide a data pool from which to compile average values for the delay and queue.

Before-after crash data was only available for the two-way stop controlled intersections; the traffic signal and roundabout alternatives were not constructed but were based off preliminary design and on Federal Highway Administration guidelines. As such, existing crash types were reviewed for potential reduction in terms of frequency and severity should a signal or roundabout replace the two-way stop controlled intersection. The traffic signal alternative was found to have the potential to reduce rear

end crashes by separating the left turn traffic and reduce all crash types by providing definitive right-of-way indications. The roundabout alternative would remove the possibility for left turn crashes and conflicts with oncoming traffic, as well as reduce rear-end crashes. With the roundabout, right turn and angle crashes would experience reduced severity.

Delay was also estimated for each intersection alternative. For the urban case study, the roundabout minimized delay to the greatest extent. Installation of a signal did improve upon the operation of the intersection at TWSC, but not to the extent of the roundabout alternative. Given that the directional distribution at the urban site was largely skewed with 84 percent of the total traffic volume traveling on the major leg, the signal timing may be able to be adjusted to allow greater free flow movement on the major leg, resulting in shorter delay. The rural case study reflected the same pattern; delay estimated at the roundabout was approximately 20 percent of the delay of the TWSC. With delay being utilized as the primary factor in the determination of level-of-service, the roundabout provided notable results, demanding equal consideration in the evaluation of any intersection control.

With delay analyzed separately, the average queue length was used to further identify issues with the effectiveness of the design layout. The results indicated a problem area with the TWSC intersection at Higgins/Hill/Beckwith regarding the westbound traffic movement. The queue length was shortened through the implementation of a traffic signal and an additional lane. However, the roundabout alternative eliminated queuing altogether.

During the simulation process, inconsistencies were noted between the simulation results and the field observation. One such example was in the modeling of the urban TWSC base case. Error messages were recorded with each iteration, noting that the input traffic volume from one direction could not be attained because the discharge rate was smaller than the input flow. In conjunction with this finding was the estimation of several large, unrealistic delay times on the same link. Field data confirms these volumes suggesting a flaw in the underlying VISSIM assumptions related to most likely driver behavior.

Recommendations include the need for additional crash reduction analysis; crashes are a primary MOE for safety enhancements. As previously noted, a meaningful before-after comparison cannot be made without adequate data. While crash frequency and severity can be qualitatively reviewed for potential reduction, a more accurate assessment can be made with field data and predictive modeling techniques.

Municipalities and government agencies can require the analysis of an intersection to include the present before-after improvement comparison and a 20-year, future growth projected before-after improvement comparison to see how the intersection may function in the future. The life span operational characteristics of TWSC, traffic signals and roundabouts vary and may do so in a positive or negative way with projected future volumes and distributions. Growth factors should be applied to the data and incorporated into the models to provide this present-future comparison.

In addition to varied traffic volumes and distributions, one should also explore different configurations of the various intersection types to ascertain which aspects may

result in the most efficient traffic control. These can include such areas as multilane roundabouts, right-turn slip lanes, vehicle-actuated signals vs. fixed time signals, multiple left-turn lanes and two vs. four-phase signals, among others.

It is also recommended that purpose and need be clearly defined for an intersection analysis. The results of the urban intersection comparison show that the traffic signal alternative provides the greatest reduction in travel time, while the roundabout alternative minimizes delay. Which is of more importance for your specific circumstance?

The model is only as good as the quantity and quality of the data input. To further enhance the evaluation of the urban and rural case studies included here it is recommended to improve upon the data collection. With respect to a roundabout, additional data concerning gap timing and headway distances could be obtained for various diameter roundabouts with varying speed profiles. The evaluation of the roundabout may also offer more insight into their overall performance through review and modeling of a site with more equal directional distributions across all legs of traffic. For all the intersection control types explored here, driver demographics, as well as detailed delay and queue length field data could be obtained to further validate the models. Sites with increased volumes of pedestrians and bicyclists could also add insight into the comparison of the intersection traffic control.

In summary, it is believed that roundabouts should be treated like any other potentially viable traffic engineering solution. Present research strongly suggests that as the number of roundabouts increases, the evidence for their use will solidify and the design guidelines will become more regulatory. Roundabouts should receive objective

consideration in an equal standing with other traffic control measures, to include traffic signals, stop signs, grade-separation, etc.

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