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A computer simulation model for single-lane roundabouts

Hesham Roshdy Elbadrawi
Florida International University

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FLORIDA INTERNATIONAL UNIVERSITY

Miami, Florida

A COMPUTER SIMULATION MODEL FOR SINGLE-LANE ROUNDABOUTS

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by

Hesham Roshdy Elbadrawi

2000

To: Dean Gordon Hopkins
College of Engineering

This dissertation, written by Hesham Roshdy Elbadrawi, and entitled A Computer Simulation Model for Single-Lane Roundabouts, having been approved in respect to style and intellectual content, is referred to you for judgment.

We have read this dissertation and recommend that it be approved.

Albert Gan

Sylvan C. Jolibois, Jr.

Osama A. Mohammed

Fang Zhao

L. David Shen, Major Professor

Date of Defense: September 21, 2000

The dissertation of Hesham Roshdy Elbadrawi is approved.

Dean Gordon Hopkins
College of Engineering

Interim Dean Samuel S. Shapiro
Division of Graduate Studies

Florida International University, 2000


سورة الفاتحة ١
بسم الله الرحمن الرحيم ١
الحمد لله رب العالمين ٢ الرحمن
الرحيم ٣ مالك يوم الدين ٤
إياك نعبد وإياك نستعين ٥
اهدنا الصراط المستقيم ٦ صراط
الذين أنعمت عليهم غير المغضوب
عليهم ولا الضالين ٧
وآياتها سبع

In the name of Allah, the Beneficent, the Merciful

Praise be to Allah, Lord of the Worlds,

The Beneficent, the Merciful:

Owner of the Day of Judgment,

Thee we worship; Thee alone we ask for help.

Show us the straight path,

The path of those whom Thou hast favored; Not of those who earn

Thine anger nor of those who go astray.

DEDICATION

I dedicate this dissertation to my wife, my daughter, my parents, my brothers, and my sister. Without their patience, understanding, support, and most of all their love, the completion of this work would not have been possible.

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Last but not least, I would like to thank ProModel Corporation for providing the Service Model simulation package.

ABSTRACT OF THE DISSERTATION

A COMPUTER SIMULATION MODEL FOR SINGLE-LANE ROUNDABOUTS

by

Hesham Roshdy Elbadrawi

Florida International University, 2000

Miami, Florida

Professor L. David Shen, Major Professor

During the past three decades, the use of roundabouts has increased throughout the world due to their greater benefits in comparison with intersections controlled by traditional means. Roundabouts are often chosen because they are widely associated with low accident rates, lower construction and operating costs, and reasonable capacities and delay.

In the planning and design of roundabouts, special attention should be given to the movement of pedestrians and bicycles. As a result, there are several guidelines for the design of pedestrian and bicycle treatments at roundabouts that increase the safety of both pedestrians and bicyclists at existing and proposed roundabout locations. Different design guidelines have differing criteria for handling pedestrians and bicyclists at roundabout locations. Although all of the investigated guidelines provide better safety (depending on the traffic conditions at a specific location), their effects on the performance of the roundabout have not been examined yet.

Existing roundabout analysis software packages provide estimates of capacity and performance characteristics. This includes characteristics such as delay, queue lengths, stop rates, effects of heavy vehicles, crash frequencies, and geometric delays, as well as fuel consumption, pollutant emissions and operating costs for roundabouts. None of these software packages, however, are capable of determining the effects of various pedestrian crossing locations, nor the effect of different bicycle treatments on the performance of roundabouts.

The objective of this research is to develop simulation models capable of determining the effect of various pedestrian and bicycle treatments at single-lane roundabouts. To achieve this, four models were developed. The first model simulates a single-lane roundabout without bicycle and pedestrian traffic. The second model simulates a single-lane roundabout with a pedestrian crossing and mixed flow bicyclists. The third model simulates a single-lane roundabout with a combined pedestrian and bicycle crossing, while the fourth model simulates a single-lane roundabout with a pedestrian crossing and a bicycle lane at the outer perimeter of the roundabout for the bicycles. Traffic data was collected at a modern roundabout in Boca Raton, Florida.

The results of this effort show that installing a pedestrian crossing on the roundabout approach will have a negative impact on the entry flow, while the downstream approach will benefit from the newly created gaps by pedestrians. Also, it was concluded that a bicycle lane configuration is more beneficial for all users of the roundabout instead of the mixed flow or combined crossing. Installing the pedestrian crossing at one-car length is more

beneficial for pedestrians than two- and three-car lengths. Finally, it was concluded that the effect of the pedestrian crossing on the vehicle queues diminishes as the distance between the crossing and the roundabout increases.

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INTRODUCTION

1.1 Background

Being recognized of their benefits in comparison with traditionally controlled intersections, the use of roundabouts in the world has increased during the past three decades. In addition, roundabouts are often the traffic control method of choice because of their low accident rates, low construction and operating costs, and reasonable capacities and delay.

Unlike nonconforming traffic circles, roundabouts conform to modern roundabout guidelines (Ourston and Bared, 1995). Among other important new features, roundabout approaches have yield-at-entry, deflection, and flared entries. A description of the features of roundabouts, as well as a comparison between these features of roundabouts and traffic circles, are provided in **Table 1.1**.

Yield-at-entry is the most important operational element of a modern roundabout. Yield-at-entry, or "priority rule", requires entering vehicles to yield to drivers in the circulating roadway. The priority rule was adopted in the 1960s, and since that time, many other countries have adopted this practice (Flannery et al, 1998).

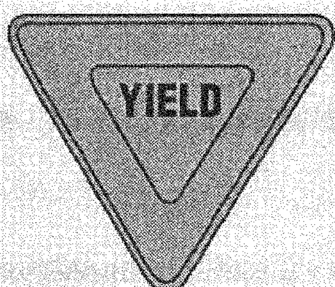
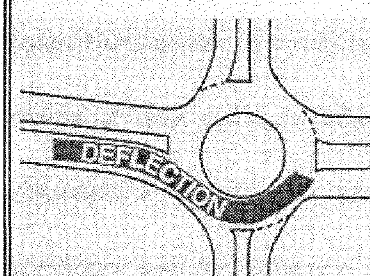
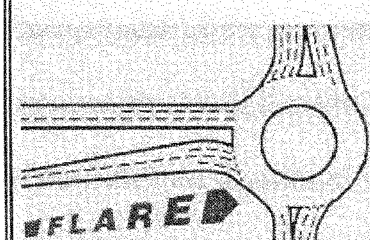
Deflection is the second element that is unique to roundabouts. Research conducted at the

Transport and Road Research Laboratory (TRRL) found that the capacity of roundabouts was increased if traffic entering the roundabout yielded to traffic on the circulating lane(s) of the roundabout (Blackmore, 1963). This rule not only increased the capacity of the roundabout but also had the additional benefit of preventing roundabout gridlock, which had become a serious problem at most heavily used roundabouts. Deflection is a design technique applied to the entries of roundabouts that helps to smooth the transition between straight approaches and circulating roadways of roundabouts. This transition helps alert drivers to a change in the roadway ahead and slow the entry of vehicles. Deflection is often enhanced through the use of splitter islands on the approaches. Splitter islands can be stripped areas, areas defined by raised reflector buttons, or raised concrete islands. Splitter islands provide drivers with more clues to the changing roadway, and alert them to take appropriate actions. Splitter islands also serve as refuge islands for pedestrians crossing an approach of a roundabout.

The final design element that is sometimes applied to roundabouts is flared entries. Flared entries are used to increase capacity at the roundabout by increasing the number of entering lanes to the roundabout. Flared approaches are often associated with British design techniques. Comparing single-lane entering roundabouts to flared approach roundabouts, the number of conflict points increases in the latter design. For this reason, Florida and Maryland have decided not to allow flared approaches on their roundabouts (Myers, 1994 and Flannery et al, 1998).

The other contributing factor in reducing the number of accidents at roundabouts is a lower number of conflict points at roundabouts, as shown in **Figure 1.1**. For a two-lane signalized intersection, there are 32 vehicle-to-vehicle conflict points and 24 vehicle-to-pedestrian conflict points. On the other hand, for a single-lane roundabout there are only eight vehicle-to-vehicle conflict points and eight vehicle-to-pedestrian conflict points.

Table 1.1 - Roundabouts Versus Traffic Circles

Features	Roundabouts	Traffic Circles
YIELD-AT-ENTRY 	**Entering Traffic Yields to Circulating Traffic.** - Circulating traffic always keeps moving. - Works well with very heavy traffic. - No weaving distance necessary. Roundabouts are compact.	**Entering Traffic Cuts off Circulating Traffic.** - Circulating traffic comes to a dead stop when the circle fills with entering traffic. - Breaks down with heavy traffic. - Long weaving distances for merging entries cause circles to be large.
DEFLECTION 	**Entering Traffic Aims at the Center of the Central Island and is Deflected Slowly Around it.** - Slows traffic on fast roads. - 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 multi-lane roads between circles, wasting pavement, land, and bridge area.

Source: Ourston and Bared, 1995.

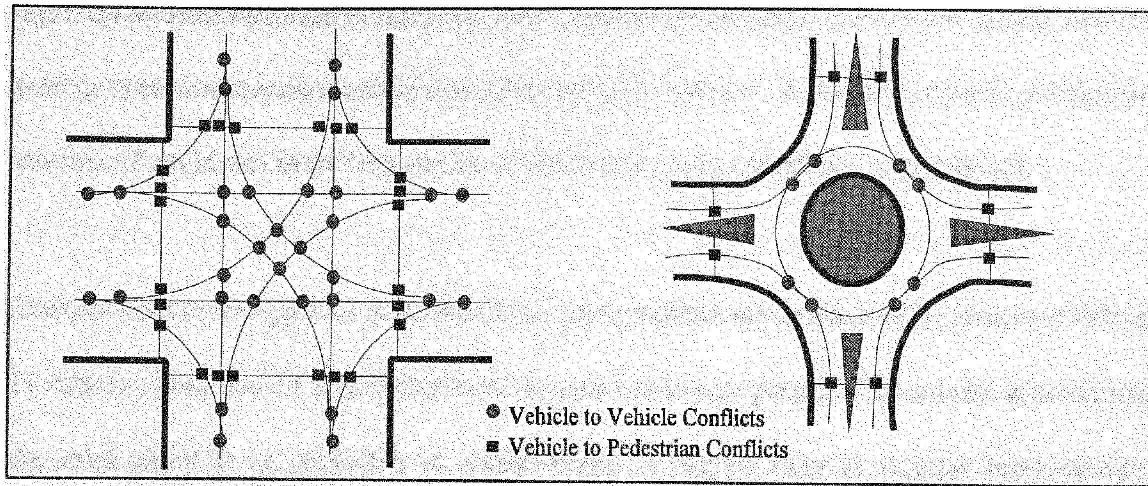


Figure 1.1 - Comparison Between Conflict Points at a Regular Intersection and a Single-Lane Roundabout

1.2 Safety Benefits of Roundabouts

Roundabouts have been in existence for many years. Existing roundabouts are in areas near shopping centers, schools and recreational facilities where high volumes of bicycles and pedestrians exist. A study conducted by Jordan (1985) at 36 roundabout locations, over a period of four years, concluded that the introduction of roundabouts led to a 95 percent reduction in right angle accidents per year, a 68 percent reduction in annual casualty accidents, a slight reduction in pedestrian accidents, and an increase in bicycle accidents. A traffic safety study performed by Jorgensen (1994) at 82 urban roundabouts in Denmark showed that bicyclists accounted for approximately 60 percent of all injured users. Conflicts between circulating bicyclists and approaching and departing traffic contributed to 45 percent of the accidents (Kjemtrup, 1993).

A study conducted by Alphand et al in 1991 concluded that 54 percent of the seriously injured accidents occurred in suburban areas, and the remaining accidents are equally divided among open countryside, residential areas and city centers. It was also concluded that the number of accidents involving personal injuries is twice that of the roundabouts.

Comparative investigations at intersections and roundabouts conducted by Brilon (1991) at 14 roundabouts, and 14 other intersections over a two-year period. The results showed that the total number of accidents at roundabouts is higher than at regular intersections. However, accidents at roundabouts are less severe than those at regular intersections. Moreover, the accident rates are higher at traffic circles than roundabouts. In addition, almost no accidents occurred at small roundabouts and accidents with personal injuries are less likely to occur at all types of roundabouts, due to low speed.

Ploeger and Oenema (1991) studied 46 roundabout locations in the Netherlands, and it was found that during the one year period after the construction of the roundabouts, the number of injuries decreased by 86 percent, the number of bicyclist injuries also decreased by 74 percent, and no fatalities were reported at the selected locations. A study conducted by Johannessen in 1984 concluded that the introduction of roundabouts in Norway reduced personal injury accidents by 30-40 percent, compared to signalized intersections. Another study conducted by Seim in 1991 at 59 roundabouts indicated 32 accidents involving personal injury. Only one of these accidents involved a pedestrian. On the other hand, 36 percent of the accidents involved bicycles. The same study by Seim concluded that single-lane roundabouts are safer for pedestrians than other types of intersections, as the geometric design of roundabouts forces motorists to reduce speed.

Although roundabouts have a good overall safety record in comparison with other types of intersections, bicyclg traffic has relatively high accident involvement rates (Allot and Lomax, 1991). In Great Britain, 70 percent of bicycle accidents occur mainly at T-intersections, crossroads, roundabouts, and private driveways. Out of this proportion, 22 percent take place at small roundabouts, and another 22 percent at roundabouts (Layfield and Maycock, 1986). Although the preceding percentages are above average, roundabouts and small roundabouts have a relatively low portion of fatal or serious accidents (15 percent and 18 percent, respectively).

Layfield and Maycock (1986) concluded that 68 percent of the bicycling accidents involved circulating bicyclists, where 50 percent were hit mainly by entering motor vehicles, and 18 percent were between exiting bicycles and circulating vehicles. Bicyclists approaching the roundabout accounted for 14 percent of the bicycle accidents where bicyclists were mainly hit from behind by motor vehicles. Bicyclists entering and exiting the roundabout each accounted for 7 percent of the bicycle accidents.

Modern American roundabouts have produced remarkable safety records. Reports of accidents have decreased considerably in areas where modern roundabouts have been built. In Summerline, Las Vegas, Nevada, only four accidents were reported in a five-year period at the two existing roundabouts. In Santa Barbara, California, the conversion of a five-approach two-lane intersection regulated by stop signs to roundabout reduced the accident rate from 4 to 2.1 accidents per year (Ourston and Bared, 1995).

In Maryland, the introduction of a roundabout replaced a lightly traveled four-leg intersection regulated by a flashing beacon, which resulted in reduction of personal injury accident rate, from eight to one per year. By April 1993, roundabouts at approximately 25 intersections had been considered, and three were in the final design process. There have been no reported accidents at those intersections since the roundabouts were installed, and the community has been satisfied with the improvement (Myers, 1994).

By converting the old nonconforming Long Beach (California) traffic circle to a modern roundabout, the overall rates accidents decreased 36 percent, and accidents with injuries by 20 percent. In Seattle, Washington, the introduction of roundabouts reduced the number of collisions by 94 percent (Sarkar et al, 1998). Moreover, the reduction of injuries was even more dramatic due to the reduction in speed, which enabled drivers to have better control over the stopping distance of their vehicles. A Maryland study by Walter (1994), showed that the 85^{th} percentile speed dropped from 40 mph to 20-22 mph. Another study conducted in Boulder, Colorado in 1996 indicated a 20 percent drop in vehicular speed at roundabouts.

Garder (1998) investigated accidents at the first roundabout in Maine, which was inaugurated in July 1997. In Maine, the accident rate was reduced by 50 percent after converting a stop-sign controlled intersection into a roundabout. None of the four reported accidents involved bicycles or pedestrians.

1.3 Problem Statement

Several guidelines for the design of pedestrian and bicycle facilities at roundabouts exist. The aim of these design guidelines is to increase the safety of both pedestrians and bicyclists at existing and proposed roundabout locations. Different design guidelines have different criteria for handling pedestrians and bicyclists at roundabout locations. For example, there is a debate about the optimum location of the pedestrian crossings at roundabouts. The locations of the pedestrian crossings can range from one-car length to five-car lengths from the yield line of the roundabout. Similarly, bicyclists can either be mixed with general traffic, use the same pedestrians' path outside the roundabout, or a bicycle lane may be installed at the outer perimeter of the roundabout. Although all of the investigated guidelines provide better safety depending on the traffic conditions at a specific location, their effects on the performance of the roundabout have not yet been examined.

There are several powerful traffic analysis packages capable of analyzing roundabouts. These software packages provide estimates of capacity and performance characteristics such as delay, queue lengths, stop rates, effects of heavy vehicles, accident frequencies, and geometric delays, as well as fuel consumption, pollutant emissions and operating costs for roundabouts. However, these software packages are not yet capable of determining the effects of various pedestrian crossing locations and the effects of various types of bicycle treatments on the performance of roundabouts.

There is a need to develop a simulation model capable of determining the effect of different pedestrian and bicycle considerations at single-lane roundabouts. The proposed models are capable of determining the number of served vehicles, as well as the average vehicle waiting time at each approach before entering the roundabout. The number of queued vehicles and the queue lengths can also be determined.

1.4 Research Objectives

The objectives to be achieved through this dissertation are described as follows:

- To understand the interaction among different groups of users of the roundabouts.
- To investigate the capability of existing roundabout models in determining the effect of pedestrians and bicycles on the performance of single-lane roundabouts.
- To develop simulation models capable of estimating the effects of different pedestrian and bicycle treatments at single-lane roundabouts.

1.5 Research Methodologies

To achieve the research objectives, the following research tasks were completed:

- Study of various design considerations provided by various transportation agencies around the world to achieve maximum safety for pedestrians and bicyclists at roundabouts.

- Review of different methods that are used to measure the performance of roundabouts and identify the capabilities of each method.
- Use of a stochastic, event-based simulation package (Service Model) to develop the proposed models.

1.6 Report Organization

Chapter 1 includes the introduction and the problem statement of this dissertation. The literature review of the current bicycle and pedestrian considerations at roundabout and different analysis models to measure the performance of roundabouts are presented in **Chapter 2**. Traffic data used to run the developed models is presented in **Chapter 3**. **Chapter 4** contains the process of developing the computer simulation models. Simulation results are shown in **Chapter 5**. The model verification and validation are performed in **Chapter 6**. Finally, **Chapter 7** summarizes the findings and suggests some potential future research areas.

CHAPTER 2

LITERATURE REVIEW

2.1 Bicycle and Pedestrian Considerations at Roundabouts

A general comparison of casualty numbers at intersections before and after conversion to a roundabout showed that accident numbers at roundabouts were lower (TRL 302, 1998). The main reduction was to vehicle and pedestrian accidents, while the number of accidents involving bicycles has not changed, yet in some situations, increased. Bicyclists' problems can be divided into those encountered by inexperienced and/or recreational bicyclists in taking control at small roundabouts, as well as those encountered by all bicyclists when turning left at medium-sized roundabouts at the same time that motor vehicles are traveling through (Wisdom, 1992). The problems encountered by inexperienced and/or recreational bicyclists at roundabouts are as follows (Wisdom, 1992):

- On roundabouts with narrow entries, some bicyclists do not feel comfortable taking control of the approach by riding in the middle of the approach lane.
- On roundabouts with wider entries, bicyclists are frequently squeezed by vehicles entering the roundabout.
- Within the roundabout, the main problem occurs when left-turning bicyclists conflict with vehicles traveling straight.
- At roundabout exits, bicyclists must be aware of conflict with exiting vehicles

because drivers often try to go in a straight path, which may result in squeezing the bicyclists.

Watkins (1982) concluded that a roundabout is the type of intersection treatment that bicyclists most commonly try to avoid as they see themselves at the mercy of motorists. In addition, Layfield and Maycock (1986) concluded that a significant portion of bicycle accidents at roundabouts involve a circulating bicyclist, who has priority, being hit by a vehicle entering the roundabout. Moreover, numerous investigations of special bicycle facilities, including complete or partial bicycle lanes on the circulating lanes, peripheral bicycle tracks and give-way crossing at the entry/exit approaches, have failed to demonstrate any statistically significant reductions in bicycle accident numbers at roundabouts. However, there is a statistically significant reduction in the severity of bicyclist injuries at roundabouts when compared with other intersection treatments (TRL 302, 1998).

At the present, no explicit provision is made for bicyclists in most of the existing roundabout design guides. The following section includes a review of bicycle and pedestrian considerations at roundabouts, presented in different design guidelines and recommendations of several countries such as Australia, the Netherlands, United Kingdom, and the United States.

2.1.1 Guide to Traffic Engineering Practice, Part 6 - Roundabouts, Australia

In most circumstances, roundabouts can be designed to provide a satisfactory level of safety for both pedestrians and bicyclists (Austroad, 1986 and Austroad 1993). The provision of pedestrian crossings at roundabouts does not necessarily influence the geometric design from that required for other intersection treatments. However, Griffiths (1981) found that the ability of a vehicle to enter and exit a roundabout can be severely affected by a pedestrian crossing. Thus, Griffiths recommended not to provide painted pedestrian crossings at approaches of roundabouts. Also, it is stated in Austroad (1986) and Austroad (1993) that it is important not to give pedestrians a false sense of security by painting crossing lines across the entries and exits of roundabouts, but rather to encourage pedestrians to identify and to accept gaps in entering and exiting traffic flows, and to cross when it is safe to do so. Providing priority crossing for pedestrians should be considered when there is either a high pedestrian volume or there is a high proportion of young, elderly or disable citizens experiencing a long waiting time to cross the approaches of a roundabout.

The provision of providing special bicycle facilities to achieve an adequate level of safety for bicyclists depends on the proportion of bicyclists in the total traffic stream, as well as the functional classification of the roadway and the overall traffic management strategies for specific locations. The increased risk to bicyclists should be weighed against the pros and cons of adopting a roundabout as an intersection treatment at a particular location.

In attempts to enhance bicyclist safety at roundabouts, Jordan (1985) recommended that where bicycle volumes are high and space permits, one or more of the special provisions for bicyclists should be investigated (see **Figure 2.1**).

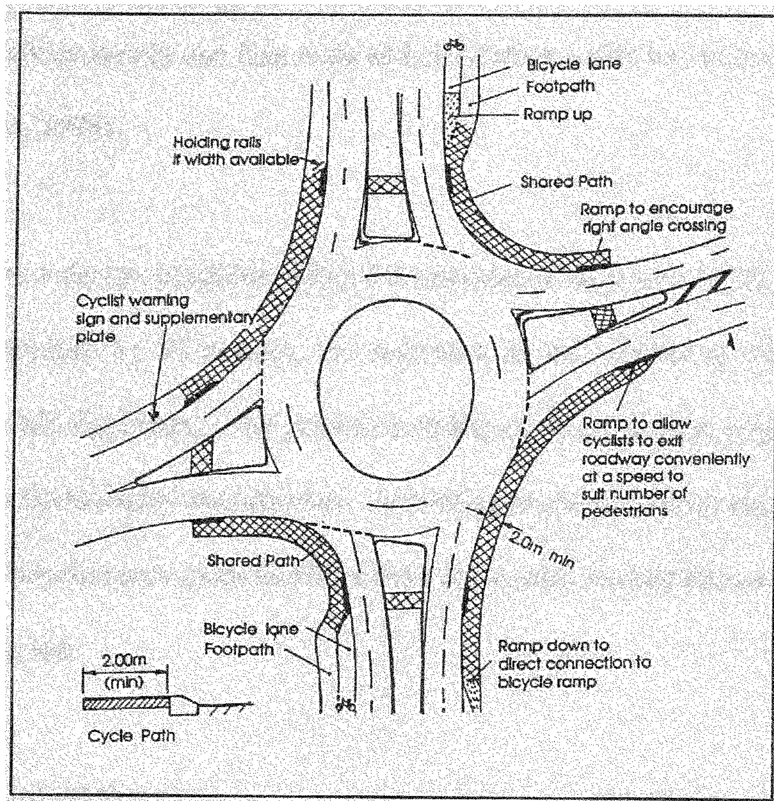


Figure 2.1 - Provision for Cyclists at Multi-lane Roundabouts

Source: Guide to Traffic Engineering Practice: Roundabouts, Part 6

2.1.2 Sign Up for the Bike, Design Manual for a Cycle-Friendly Infrastructure, Netherlands

In 1985, the roundabout designs in the Netherlands changed considerably (van Minnen, 1994). Before 1985, the roundabout layout in the Netherlands was similar to the layout roundabouts in Britain, with splayed entries, which allowed vehicles to enter the roundabout almost tangent to the circulating lanes having two or more traffic lanes. In the new design, entries are not flared and vehicles enter the roundabout along a radius. Moreover, the circulating roadway is only one lane wide and circulating traffic has priority over entering traffic (Morgan, 1998).

Although the new design standards reduced the number of accidents by 50 percent and the number of casualties by 70 percent, the reduction in the number of casualties among bicyclists was still significant. The provision of bicyclists remains an important point for attention at the Netherlands' roundabouts. According to the functional level of the bicycle route, the five bicyclist provisions that have been taken into consideration at roundabouts in the Netherlands are:

- mixed flow
- bicycle lanes with physical separation
- bicycle lanes separated by narrow curb
- separate bicycle track with bicyclists not having the right-of-way
- separate bicycle track with bicyclists having the right-of-way

The three main categories are described below (see **Figure 2.2**):

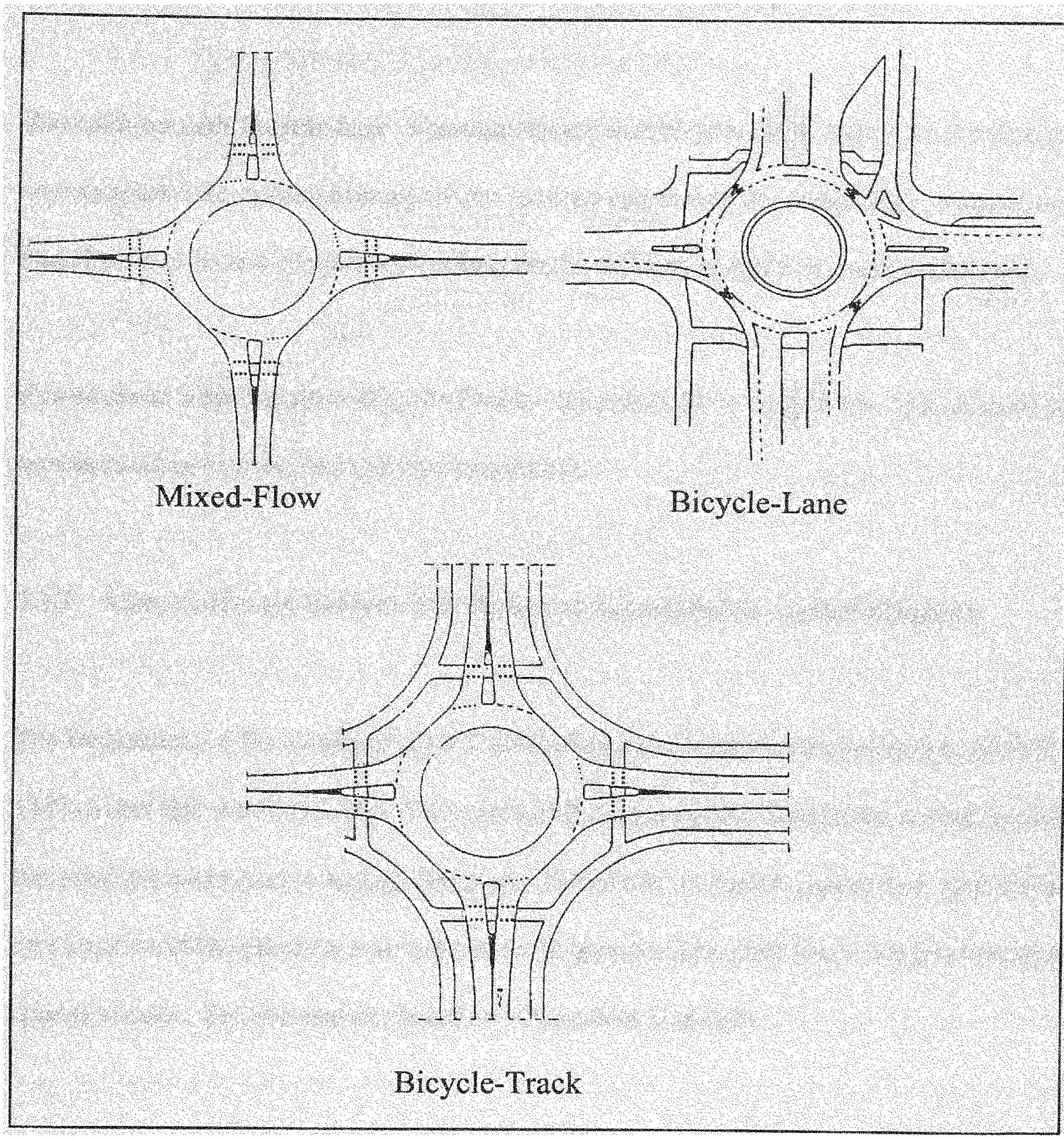


Figure 2.2 - Different Bicycle Treatments for Roundabouts in the Netherlands

Roundabout with Mixed Flow - On roundabouts with mixed flow, vehicle and bicycle traffic make joint use of the circulating roadway of the roundabout. This solution is often selected to allow bicyclists to benefit from the right-of-way rule at roundabouts and to achieve a minimum number of conflict points at roundabouts. Despite the low speed at roundabouts, bicyclists feel threatened as motorists often do not yield to the right-of-way.

Roundabout with Bicycle-lane - On roundabouts with bicycle lanes, bicyclists crossing an approach have the priority over all drivers entering and exiting the roundabout. In this case, bicyclists may have a considerable impact on the capacity and delays at the roundabout.

Roundabout with Separate Bicycle Track - Bicyclists have to give the right-of-way to motorists when crossing the exit of a roundabout.

2.1.3 State-of-the-art Review: The Design of Roundabouts, United Kingdom

The Department of Environment in the United Kingdom (Technical Memorandum, H.7/71, 1971) noted that the conversion of a signalized intersection to a roundabout would require the need for pedestrian crossing facilities. Generally, in flared approaches, pedestrian crossings should be placed at two- to three-car lengths from the yield line in conjunction with splitter islands. Splitter islands should be at least four feet wide.

In addition, the British Roundabout Design Guidelines (TD.16, 1993) advised that pedestrian crossing facilities should be placed away from the flared entries to roundabouts, i.e., where the widths of the approaches are less and vehicular movements are more straightforward. When this is not practical, the following facilities should be considered:

- unmarked crossing with a splitter island if possible

- zebra crossing with or without a splitter island
- controlled crossing with or without a splitter island
- pedestrian subways or footbridges.

The use of different types of pedestrian crossing facilities at the same roundabout is not recommended, as this may lead to confusion for both pedestrians and drivers (DMRB, 1993). If a signalized pedestrian crossing is provided, splitter islands should be provided to avoid excessive delays at the exit points, because the "blocking back" mechanism may cause queues to extend onto the circulating lane (Brown, 1995).

British DOT guidelines on the geometric design of roundabouts (TD.16, 1993) also observed that roundabouts are of a particular hazard for bicyclists. The operational performance and safety factors have been monitored at a number of experimental schemes aimed at improving bicyclist safety at roundabouts. These have included the use of bicycle lanes around the circulatory roadway, the conversion of peripheral pedestrian paths to joint bicyclist/pedestrian facilities, shared use of pedestrian subways, and signposting alternative bicycle routes away from the roundabout. Evaluation of these options concluded that once a bicyclist enters the roundabout, it is difficult to reduce the risk, and that the use of a shared facility depends on the volume of pedestrians and bicyclists. Nevertheless, it is important to consider bicycle facilities that take bicyclists out of the circulating lanes of roundabouts by the application of the following:

- shared-use by pedestrians and bicyclists of a peripheral bicycle/footway

- signposted alternative routes away from the roundabout
- full grade separation for bicyclists and pedestrians, e.g., by a combined pedestrian/ bicyclist subway system

If the volume of bicyclists is significant and high enough to justify providing a separate bicycle facility, consideration should be given to signalizing the roundabout or given to an alternative form of intersection control. Signalized bicycle crossings may be appropriate where there are no pedestrian requirements, but roundabout approaches may intersect a bicycle track.

2.1.4 Florida Roundabout Guide, United States

According to the Florida Bicycle Facilities Planning and Design Manual (1996), no special markings or lanes are needed on the roundabout to accommodate bicyclists at roundabouts. On approaches with bicycle lanes, lanes should end and permit bicycles to merge with general traffic during the last 70 to 100 feet of the approach.

For pedestrians, the roundabout guide emphasizes that no special crossing facilities are necessary and a well-designed splitter island of a sufficient size should be installed on the approach of roundabouts, which help secure the pedestrians. The reason for not providing a priority crossing is that priority crossing might give pedestrians a false sense of security. Rather than painting pedestrian crossing lines across the entrances and the exits of the roundabouts, it is better to encourage pedestrians to identify and accept gaps within the traffic flow and to cross when it is safe to do so. When pedestrian crossings are provided at areas with a high population of youngsters and the elderly, it is recommended that the crossings be installed at one-car length back from the yield line at the entrances and exits of roundabouts.

2.1.5 State of Maryland Roundabout Design Guidelines, United States

When planning and designing roundabouts, special attention should be given to pedestrian movement. While, conventional intersections, pedestrian crossings should be located at the holding line of the intersection, at roundabouts, pedestrian crossing should be 20 to 25 feet from the yield line. Also, pedestrian crossing lines should not be painted on the entrances and exits of roundabouts, as they may place pedestrians at high risk by giving them a false sense of security. In addition, painted crosswalks may cause drivers' confusion with yield lines. Priority pedestrian crossings should be provided where high pedestrian volume exists with a high portion of young, elderly or infirm citizens, or where pedestrians are experiencing difficulty in crossing. In such cases, it is desirable to place pedestrian crossings at least 75 feet back from the yield line of the roundabout (and possibly augmented by a pedestrian signal).

The Maryland Roundabout Design Guidelines also recommended that no special bicycle lanes are required at roundabouts, as bicyclists would be able to proceed through the roundabout in the travel lane(s) and use the roundabout in a similar manner as motor vehicles. If a high volume of bicycle traffic exists, a special bicycle/pedestrian facility could be constructed.

Table 2.1 presents a summary of pedestrian and bicycle considerations from selected roundabout guides.

Table 2.1 - Summary of Pedestrian and Bicycle Considerations at Roundabouts

Guide	Pedestrians	Bicycles
Traffic Engineering, Part 6, Australia	- No painted crossing - Priority crossing where high pedestrian volume - Splitter islands should be as large as the site allows	- Depends on proportion of bicycles in total volume - Bicycle facility where bicycle volumes are high - Reroute bicycle facility to avoid roundabout sites
Netherlands	N/A	- Mixed flow bicycle where bicycles are treated as vehicles - Bicycle lanes at the outer perimeter of the circulating lanes of the roundabout - Bicycle track outside the roundabout
United Kingdom	- Unmarked crossing with splitter islands - Zebra crossing with or without splitter islands - Pedestrian subways and foot-bridges	- Shared use of pedestrian/bicycle crossing - Alternative route away from the roundabout - Full grade separation
Florida Roundabout Guide, USA	- No special crossing - Well-designed splitter islands should be provided - Priority crossing where high pedestrians volume exists - Pedestrian crossing should be placed at least one-car length from the yield line of the roundabout	- No special markings of lanes for bicyclists - Mixed flow where vehicles and bicycles have the same priority - Bicycle lanes should end 70 - 100 feet before the roundabout
Maryland, USA	- No special crossing - Well-designed splitter islands should be provided - Priority crossing where high pedestrians volume exists - Pedestrian crossing should be placed at least one-car length from the yield line of the roundabout	- No special markings of lanes for bicyclists - Mixed flow where vehicles and bicycles have the same priority - At high bicycle traffic, special facility outside the roundabout may be provided

2.2 Capacity and Performance Analysis Models for Roundabouts

Prior to 1966, there was no defined priority at roundabouts between entering and circulating traffic (Brown, 1995). The basis of roundabout operations was that entering traffic had to merge with circulating traffic along a weaving section downstream of the entry, and the capacity was governed by the capacity of the weaving sections.

After the introduction of the priority rule roundabouts in Great Britain in 1966, roundabout entries functioned in the same concept as a series of one-way T-intersection. Consequently, the priority rule allowed for the development of smaller and more efficient roundabouts. This made it feasible to use roundabouts much more extensively and in tighter spaces. Changes were made to entry geometry by having deflected traffic paths, oblique entry, and often at extra lanes at entries. As a result, capacity estimation became a two-stage process:

- Entry capacity is determined as a function of the flow in the priority stream crossing each entry.
- The entering flow from each entry must be calculated. Since the entry flow depends on the priority flow, which in turn comes from the previous entries, the problem of predicting the average balance of entering flows from all the entries is an interactive manner.

2.2.1 Theories of Capacity and Delay

Theories of capacity and delay fall into four groups:

- Deterministic Theories
- Statistical Theories
- Probabilistic Theories
- Simulation Models

Deterministic Theories

Deterministic ideas are not commonly used. These are simply the opinions of practitioners laid down as rules. For example, roundabouts should be used only on routes of certain traffic flow and be of a certain minimum size, roadway width, etc. Although these rules may involve invalid assumptions of traffic behavior, they can be useful in the absence of a theory based on systematic collection of data, and validated by measured observation. However, in the design process, many details which cannot be satisfactorily modeled are often determined by "what is reasonable", or by appearance.

Statistical Theories

The development of statistical theories depends on a pre-existing stock of roundabouts from which satisfactory sample data can be drawn. Thus, in countries with a few number of roundabouts, more reliance is placed on other theories. The statistical approach is based on measuring operational and geometric variables from a sample of roundabouts to determine the relationships between them, and then to use these relationships as predictors. The most significant variable to be explained is usually capacity. However, waiting times, delays, queue lengths, and accident frequencies can also be estimated in the same manner (Louah, 1988). The statistical approach to roundabout capacity estimation is widely used in the United Kingdom. Also, statistical theories are currently used or being investigated in France, Germany, Israel, Norway, and Switzerland (Brown, 1995).

Probabilistic Theories - "Gap Acceptance"

The gap-acceptance technique was mainly applied to non-roundabout intersections, but more recently, has been applied to roundabouts. When the "gap acceptance" theory is applied to roundabouts, the circulating flow is considered to be the major flow, in which randomly spaced gaps occur. On the other hand, the entering flow is considered as the minor flow. Gap-acceptance theory assumes that approaching drivers enter the roundabout when there is a gap between circulating vehicles greater than the critical gap (Troutbeck, 1990). Gap acceptance is intrinsically passive in the sense that circulating traffic is assumed not to react in the presence of entering traffic.

At roundabouts, unlike other intersections, the entry process is more interactive than what the gap-acceptance assumptions normally allows. In other words, when congestion occurs, entering drivers might accept shorter gaps than the critical gap. This phenomenon is called "*gap-forcing*." With the gap-forcing and priority reversal aspects, it is difficult to determine whether the gaps are naturally occurring or modified for, or by, the entering vehicles. Therefore, although gap-acceptance is an important element, it is unlikely to be a complete and sufficient determinate of capacity (Kimber, 1980).

The two main parameters for gap-acceptance are the critical gaps in the major flow, and the follow-up time in minor flow. Critical-gap values may vary depending on the maneuver type to be made, as well as the size of the intersection. They also vary with size of urban or rural areas, gradient, traffic flow, and drivers' behavior. For example, heavy vehicles need greater gaps and greater follow-up times. Corrections are usually made to account for these factors. The critical gap is also influenced by vehicle type, dimensions, weight, engine capacity, and acceleration ability. Gap-acceptance methods of roundabout capacity estimation, delay and risk analysis are used in Australia and Sweden. In addition, they are used, or have been investigated, in others countries including the United States, Czechoslovakia, France, Israel, Germany, and Great Britain (Brown, 1995).

Simulation Models

In an attempt to overcome the multiplicity of theoretical problems inherent in gap-acceptance approaches, simulation methods are becoming more popular to model traffic streams and drivers' behavior at intersections. With the general availability of powerful computers, the simulation models of entry capacity, delay and accident risk, are changing from instruments of scientific research to practical tools for the traffic engineer.

Although, a number of countries are using simulation to model the drivers' behavior at non-signalized intersections, few have been adapted for roundabout analysis. Roundabout simulation models have been either developed or investigated in Australia, France, Germany, United Kingdom, and Switzerland.

Simulation Model Development in Australia - INSECT is a microscopic (vehicle-by-vehicle) simulation model used mainly for modeling roundabouts, as well as other types of unsignalized intersections. The model is based on a vehicle-by-vehicle simulation technique, where vehicle movements are governed by rules and constraints. This model monitors the movement of each vehicle throughout the intersection and is used to indicate the performance of unsignalized intersections under variable demands. The model may be used with a variety of arrival conditions. INSECT is regarded as one of the better simulation programs (Traffic Engineering, Part 6).

Simulation Modeling in France - OCTAVE, a capacity and delay simulation model developed by Service d'Etudes Techniques des Routes et Autoroutes (SETRA), has been used for roundabout analysis (Louah, 1988). The model uses several algorithms to simulate drivers' behavior. Moreover, it includes rules for vehicle arrivals, entering process, and queuing process. The model also includes factors for gap-acceptance and follow-up times.

Simulation Modeling in Germany - The simulation model KNOSIMO was developed at the Ruhr University, Bochum, Germany. The model is used to simulate different traffic streams at unsignalized intersection. The model deals with individual vehicle platoons throughout the stages of arrival, queuing, entering, critical gaps, and headways (Brown, 1995).

Simulation Modeling in Great Britain - SIMRO is a simulation model, developed at Southampton University, England, to simulate traffic at roundabouts. It uses eight behavioral mechanisms to model the microscopic movement of vehicles at roundabouts. The model input includes traffic flows, traffic compositions, turning movement proportions, as well as geometric data. Validation of the model showed that it accurately represents the observed situations and provides comparable results with other empirical formulae.

Simulation Modeling in Switzerland - The Swiss Federal Institute of Technology in Lausanne developed a simulation model for the analysis of roundabouts. The model is capable of simulating the observed traffic situations in terms of the maximum entry flow. The model includes the following four sub-models:

- vehicle kinematics
- vehicle generation (both for entry and conflicting flows)
- vehicle leaving generation
- gap determination and gap acceptance

2.3 Capacity and Delay Formulae for Roundabouts

The introduction of the priority rule contributed significantly in increasing the efficiency of roundabouts. With the priority operation, roundabout entries were governed by the ability of entering drivers to detect and utilize gaps within the circulating flow. Thus, the entry width and the number of circulating lanes became two major parameters that affect the capacity of roundabouts. This led to a series of experiments and research in several countries, in order to develop capacity and delay models for roundabouts.

2.3.1 British Models

In 1976, Kimber and Semmens carried out a full scale experiment to improve the capacity formula and to provide entry-by-entry capacity calculations of roundabouts for the purpose of design and economic assessment (Kramer, 1977). The experiment aimed to investigated the relationship between the capacity of a roundabout entry and the geometric and traffic factors affecting it. The entry capacity was found to be linearly related to the flow of the circulating traffic across the entry. The entry capacity equation is shown below.

$$Q_e = F - f_c Q_c$$
$$f_c = 0.29 + 0.116e$$
$$F = 329e + 35u + 2.4D - 135$$

where

Q_e	= entry capacity
Q_c	= circulating capacity
f_c	= constant depends on the geometry of the circle (outside diameter)
F	= constant depends on the geometry of the entry
e	= the entry width
u	= the circulating width
D	= the roundabout size factor

Entry flaring was found to provide sizable traffic benefit, even for small circulating flows, increasing capacity by up to 45 percent. The circulating width and overall size of the roundabout had significant but small effects.

2.3.2 Australian Methods

The capacity of a roundabout is influenced by its geometry through the critical gap parameters. In 1989, Troutbeck produced several tables to calculate the follow-up time and the ratio of the critical gap-acceptance to the follow-up time at single-lane entries. The same tables for single-lane roundabouts can be used for multi-lane roundabouts after applying an adjustment factor. Further research by Troutbeck and Akcelik in 1991 proposed adjustment factor for wider circulating lanes. The research also suggested the application of adjustment factors if the roundabout is within the proximity of a nearby signalized intersection. The capacity of each entry lane is calculated from the entry lane gap acceptance parameters, using the following equation:

$$C = \frac{3600(1-\theta)q_c e^{-\lambda(t_a-\tau)}}{1-e^{-\lambda t_f}}$$

where

C	= capacity of an entry lane (vph)
θ	= proportion of bunched vehicles in the circulating stream
q_c	= flow of vehicles in the circulating stream (vps)
t_a	= critical gap acceptance between circulating vehicles
t_f	= follow-on headway between entering vehicles
τ	= minimum headway in the circulating traffic stream
λ	= parameter that depends on θ and circulating flow, defined as follows:

$$\lambda = \frac{(1-\theta)q_c}{1-\tau q_c}$$

It should be noted that the predicted capacity using the above formulae is the steady-state capacity, or the maximum entry flow rate, it is not the practical capacity.

There are two components of the delays experienced at roundabouts: queuing and geometric delay. Queuing delay is the delay to drivers waiting to accept a gap in the circulating traffic, while the geometric delay is the delay to drivers slowing down to the negotiation speed, proceeding through the roundabout, then accelerating back to normal operating speed. The geometric delay can also be the delay to drivers slowing down to stop at the end of the queue and, after accepting a gap, accelerating to the negotiation speed, proceeding through the roundabout and then finally accelerating further to reach the normal operating speed. The total delay is the sum of the geometric delay and the queuing delay.

To calculate the average queuing delay, first calculate the minimum delay for the entering traffic flow, using the following equation:

$$w_m = \frac{e^{\lambda(t_a-\tau)}}{(1-\theta)q_c} - t_a - \frac{1}{\lambda} + \frac{\lambda\tau^2 - 2\tau\theta}{2(\lambda\tau + 1 - \theta)}$$

The geometric delay for vehicles depends on whether the vehicles have to stop or not is based on the follwing formula (George, 1982):

$$d_g = P_s d_s + (1 - P_s) d_u$$

where

P_s = proportion of entering vehicles that must stop

d_s = geometric delay to vehicles that must stop

$(1-P_s)$ = proportion of entering vehicles that need not stop

d_u = geometric delay to vehicles that need not stop

The average entry queue length, n_w, under steady-state and saturated conditions is given by the product of the average queuing delay, w_m, and the entry lane flow, Q_m, as follows:

$$n_w = w_m Q_m$$

2.3.3 Swiss Models

The Swiss capacity formula resulted from the development of a microscopic simulation model (Tan, 1991). The model was used to study the entry capacity formula, as well as the influence of exiting vehicles on the entry capacity under different roundabout geometries. Based on several field observations, the following formulae were derived:

$$Q_e = k(1500 - (\frac{8}{9})Q_g)$$
$$Q_g = \beta Q_{cir} + \alpha Q_s$$

where

Q_e = entry capacity

Q_g = conflicting traffic volume

Q_s = traffic volume leaving the roundabout using the previous exit

Q_{cir} = circulating flow

α, β and κ = factors determined according to the roundabout geometry

In 1997, Tan estimated the queues and delays using two methods. The first is used to estimate the mean queue and delays without taking account for traffic flow variations, and the second is used to estimate variations in queue and delay, incorporating flow variations (Tan, 1997). The following formulae are used to estimate the queue length and delay based on flow variations.

$$L = 0.5(\sqrt{A^2 + B^2} - A)$$
$$A = (1-\rho)\lambda\mu t + (1 - \lambda L_o)$$
$$B = 4\lambda(L_o + (\frac{1}{\zeta} + \rho - 1)\mu t)$$
$$\rho = \frac{q}{\mu}$$
$$d = \frac{L}{q}$$

where

L = queue length (vehicles)

q = flow rate arriving at entries

μ = the entry capacity

t = the time interval

L_0 = queue at the beginning of time interval

λ = adjustment factor for deterministic equation

ζ = speed adjustment factor

ρ = ratio of capacity to real traffic flow

d = delay per arriving vehicle

Increasing the use of compact roundabouts in urban areas where there are pedestrians and bicyclists raise the need to qualify their influence on entry capacity. In 1994, Tan conducted field observations on six roundabouts to study the influence of pedestrians and bicycles on the entry capacity of roundabouts in Switzerland. The results of Tan's study showed that pedestrians at the entry side crosswalk may decrease the entry capacity, and pedestrians at the exit side crosswalk may cause exiting vehicles to queue, which may block the circulating road. Similarly, bicyclists may decrease the entry capacity, and circulating bicyclists may also result in exiting vehicles to queuing at the circulating roadway.

To estimate the influence of pedestrian on the entry capacity, Tan (1994) used Marlow's and Maycock's (1982). This equation is used to estimate the overall capacity of crosswalk/entry system:

$$Q_{ep} = Q_e P$$

where

P = the probability of vehicles waiting at the yield line for a useful gap

Q_e = the basic entry capacity (veh/hr)

The new formula is as follows:

$$Q_{vp} = \frac{3600 q_p}{q_p H(1 - e^{-q_p*(t+H)} + e^{-q_p*t-1})(1 - e^{-q_p*H})}$$

where

Q_{vp} = the vehicular capacity (vph) of crosswalk estimated by

q_p = the pedestrian flow rate (ped/sec)

t = the pedestrian crossing time (sec)

H = the mean time headway of vehicles passing over the crossing (sec) in the absence of pedestrians

Due to the fact that the exiting traffic flow may be stopped by pedestrians at the exit side crosswalk causing vehicles to queue near the exit, if the circulating roadway of the roundabout is blocked, the capacity of the previous entry is affected. Accordingly, Tan (1994) developed two formulae to estimate the block time and to determine the influence of the blockage on the entry capacity.

$$T_b = AQ_s - 10^{-4} BQ_S^{\,2} + 10^{-8} CQ_s^{\,3}$$

where

T_b = blocking time (sec/hr)

Q_s = length of blocking times (sec)

A, B and C are coefficients for each case of stocking capacity

When a circulating roadway is blocked, vehicles at the previous entry either cannot enter, or can only enter with low speed. This leads to a decrease in the entry capacity of the roundabout. The influence of the blockage on the capacity of the previous entry is determined quantitatively as follows:

$$Q_{cirb} = \frac{T_b}{2\beta}$$

where

β = factor determined according to the roundabout geometry

To determine the influence of bicycles on the entry capacity, several observations were made roundabouts in Switzerland. The study showed that exiting bicycles have no influence, and that entry bicyclists have very limited influence on entry capacity if circulating bicycles have no priority over exiting vehicles (Tan, 1994). On the other hand, circulating bicyclists have relatively strong influence on entry capacity. This is due to the fact that entry vehicles have to yield to circulating bicyclists. Moreover, if the circulating bicyclists have priority over exiting vehicles, exiting vehicles may be stopped at the circulating lane(s), which may cause a blockage. Accordingly, two cases were considered and a simulation program was used to determine the influence of bicyclists on the entry capacity. The first case assumed that vehicles can overtake circulating bicyclists, while the second case assumed that circulating vehicles cannot. The results of the simulation shown in **Figures 2.3** and **2.4** concluded that the more the circulating bicycles, the less the entry capacity, and that the influence of the circulating bicycles decreases when the circulating traffic volume increases. Case two shows that circulating bicycles (Q_{ccir}) have a relatively higher influence on the entry capacity (Q_e) when circulating vehicles (Q_g) cannot overtake circulating bicyclists.

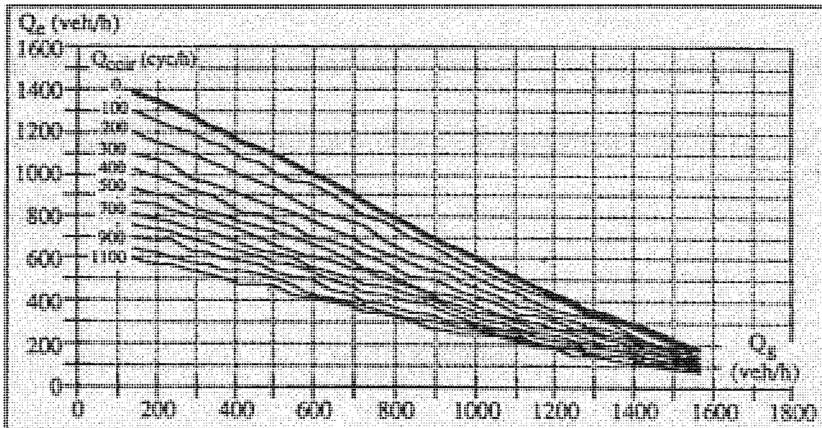


Figure 2.3 - Influence of Circulating Bicyclists on Entry Capacity - Case 1: Circulating Vehicles Can Overtake Circulating Bicyclists

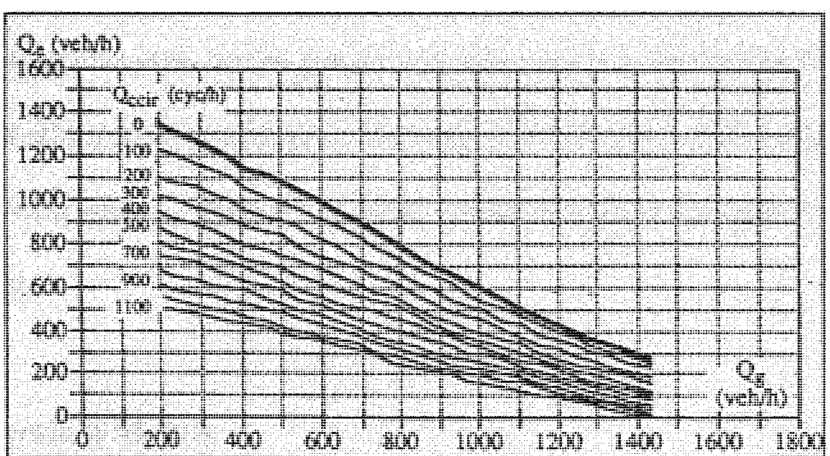


Figure 2.4 - Influence of Circulating Bicyclists on Entry Capacity - Case2: Circulating Vehicles Cannot Overtake Circulating Bicyclists

2.3.4 German Models

Several capacity models have been created and experimentally studied with gap-acceptance theory and linear regression techniques in Germany. Based on data collection on more than 100 roundabouts in Germany, the observed values of capacity were compared to those of circulating traffic that was observed upstream of the entrance, the following equation was derived (Brilon and Stuwe, 1990):

$$V_e = Ae^{\frac{-BV_c}{10000}}$$

where

V_e = maximum volume of entering traffic

V_c = circulating traffic

A, B = determining parameters

The capacities predicted using the previous equation seem to be notably lower than the values predicted by the British formulae. The range of the German results is between 0.7 and 0.8 of the British values. However, there is a good agreement between the French and German results.

2.3.5 Netherlands Models

Until recently, there was no satisfactory method available in the Netherlands to weigh one intersection type against another (de Leeuw et al, 1999). Also, there is only one capacity calculation method in the Netherlands that takes into account the influence of bicyclists on capacity (Van Arem and Traag, 1992).

As the influence of bicyclists on capacity cannot be ignored in the Netherlands, de Leeuw et al (1999) carried out the development of a new capacity model that takes into account the influence of bicyclists, and provides more accurate results than the previous model. The main purpose of the new model is to estimate capacity and average delay per entry.

In order to develop the new model, five submodels were taken into consideration. The main three submodels are:

Bicycle Lane - The reduction of capacity caused by crossing bicyclists is based on gap-acceptance, and presents the chance that the entry is not blocked by crossing bicyclists. The formula assumes random arrivals of slow traffic. This seems to be a realistic assumption, because in general, slow traffic does not platoon as much as motor vehicles (de Leeuw et al, 1999). The chance that the entry is not blocked by crossing bicyclists (P_{entry}) is:

$$P_{entry} = e^{-q_{cir} * t_0}$$
$$t_0 = t_{cir} - 0.5t_f$$

where

q_{cir} = volume of circulating bicyclists

t_{cir} = critical gap to bicyclists

t_f = minimum follow-up time entry traffic

Consequently, in the case of a cycle lane, the capacity of the entry ($C_{entry,clane}$) is:

$$C_{entry,clane} = C_{entry,h} F_{exit} P_{entry}$$

where

$C_{entry,h}$ = capacity of the entry due to main conflict

F_{exit} = reduction factor caused by downstream exit

P_{entry} = probability exit is not blocked by cyclists

Bicycle Path - The capacity increase caused by the extra space between bicycle path and roundabout can be modeled using a model of Brilon (1995), describing the process at two-stage priority intersections. At the entry of a roundabout the motor vehicles also have to yield to the conflicting flows in two phases. At first, the vehicles yield to crossing bicyclists, then they can use the space of five meters between conflicting flows, and then they yield to circulating vehicles. The capacity of the entry in the case of a bicycle path ($C_{entry,path}$) is:

$$C_{entry,path} = \frac{C_{entry,bic} C_{entry,w} - C^2_{entry,clane}}{C_{entry,bic} + C_{entry,w} - 2C_{entry,clane}}$$

$$C_{entry,bic} = p_{entry} 1500$$

$$C_{entry,w} = C_{entry,h} F_{exit}$$

where

$C_{entry,bic}$ = capacity of the entry due to crossing bicyclists only

$C_{entry,w}$ = capacity of the entry without crossing bicyclists

$C_{entry,clane}$ = capacity of the entry in case of a bicycle lane

F_{exit} = reduction factor caused by downstream exit

P_{entry} = probability exit is not blocked by cyclists

Delay - Only queuing delay is considered, not geometric delay. In this model, the queue length and the delay follow from the V/C ratio over a given time period, and the queue length at the beginning of the period. First, the queue length is calculated, and after that, the delay, by integrating the queue length over the time period.

The results of the new model are presented in **Figure 2.5**. The model calibration has shown that the model can predict real capacities and delays with sufficient accuracy. However, more validating field studies were recommended.

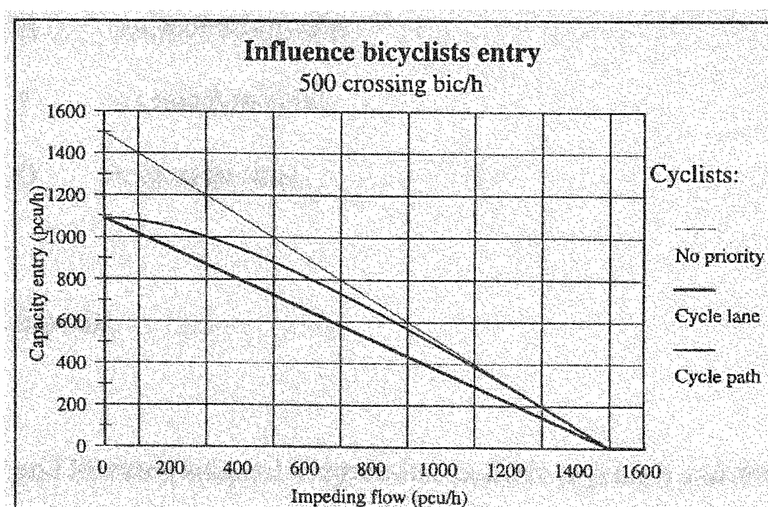


Figure 2.5 - Effect of Bicycle Traffic on the Capacity of Roundabout Entries

2.3.6 Danish Models

The Danish capacity model is based on two assumptions. First, roundabouts are regarded as a series of single T-intersections, where the traffic in the entrance lane has to yield to the circulating traffic. Second, the basis for calculations is the time-gap method, where the behavior of the drivers is described through the critical interval and the passage time (Kjemterup, 1993).

Using the following formula, the maximum entry flow rate can be calculated as a function of the circulating traffic in front of the entrance.

$$N_{max} = H \frac{e^{-HT/3600}}{1 - e^{-HD/3600}}$$

where

N_{max} = entry traffic

H = circulating traffic

T = critical interval

D = passage time

2.3.7 Israeli Models

In 1997, Polus and Shmueli adopted a regression analysis approach and develop a separate regression model for each roundabout, rather than aggregate the data for all locations. This approach was taken into consideration as the geometric characteristics, especially the diameters of the central island, which were believed to have a significant impact on the intersection capacity. The general formula for the capacity is as follows:

$$V_e = Ae^{-BV_c}$$

where

V_e = the possible entry capacity for each circulating flow

V_c = circulating flow rate

B = parameter reflecting the curvature

A = parameter reflecting the entry capacity for a very low circulating flow

Using different circulating flow rates, the relationship between the entry capacity and the circulating flow rate is drawn (see **Figure 2.6**). Next, the entry capacity is determined using this relationship, and the general form of the entry capacity can be expressed as:

$$V_e = 394D^{0.31}e^{-0.0095V_c}$$

where

D = outside diameter

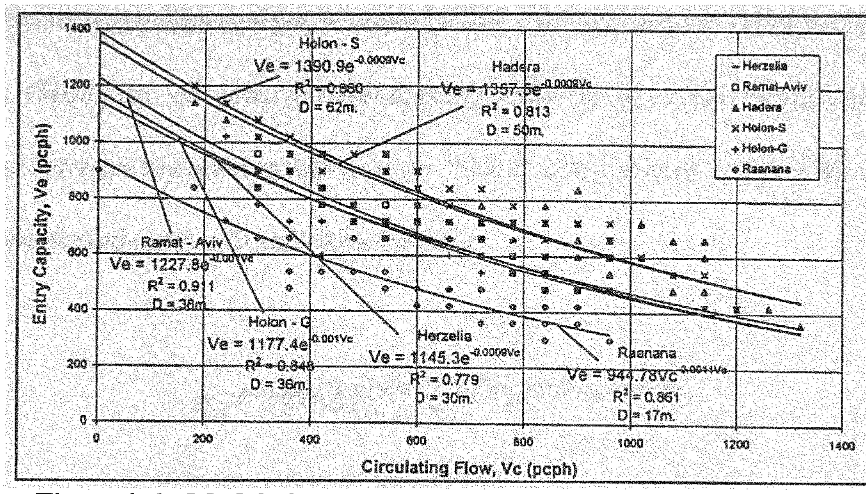


Figure 2.6 - Models for Entry Capacities Versus Circulating Flow

Source Polus and Shmueli, 1997

2.3.8 Jordanian Models

In Jordan, roundabouts are widely used in urban and suburban areas. Some of these roundabouts are subjected to high volumes of traffic and experience high levels of delay. For the analysis of roundabouts in Jordan, roundabouts are considered as a series of T-shaped entries into a one-way circular street (Al-Masaeid and Faddah, 1997).

Regression analysis was carried out to determine the best form of predictive equation by using entry-specific data. The following regression equation was developed for estimating the entry capacity.

$$q_e = e^{\frac{A - Bq_c}{10,000}}$$

Multiple variate regression analysis was conducted to develop a general entry-capacity model for Jordan. Geometric variables that had a strong effect on the estimated parameters of entry capacity model were included in the analysis. Based on the results, the following regression equation was found to best fit the capacity data:

$$q_e = 168.2 D^{0.312} S^{0.219} e^{0.017 E_w + 0.019 R_w}$$

where

D	= central island diameter (m)
S	= distance between the entry and near-side exit (m)
E_w	= entry width (m)
R_w	= circulating roadway width (m)

For practical applications of the models, the effect of roundabout geometry and traffic variables were taken into consideration. Thus, the general model for estimating the entry capacity was simplified as follows:

$$q_e = 168.2 f_d f_s f_{EW} f_{RW} e^{-0.56 q_c}$$

where

f_d	= represents the effect of central island diameter on estimated capacity (see **Figure 2.7**)
f_s	= represents the effect of the distance between entry and next downstream exit on estimated capacity (see **Figure 2.7**)

f_{EW} = represents the effect of entry width on the capacity (see **Figure 2.8**)

f_{RW} = represents the effect of circulating width on the capacity (see **Figure 2.8**)

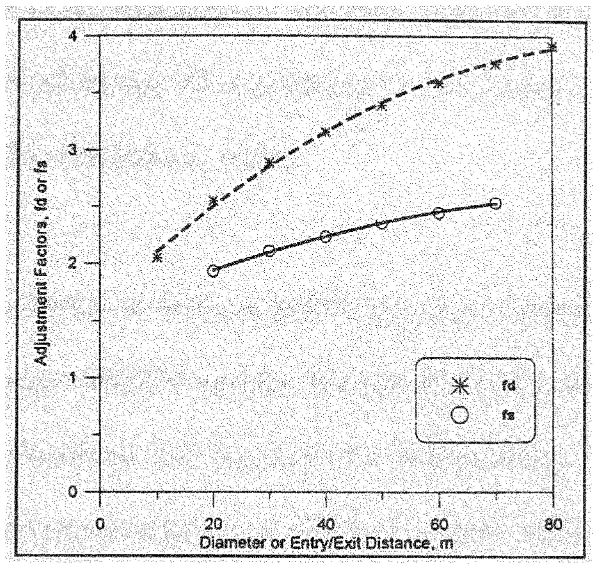


Figure 2.7 - Adjustment Factors for Effects of Diameter and Entry/Exit

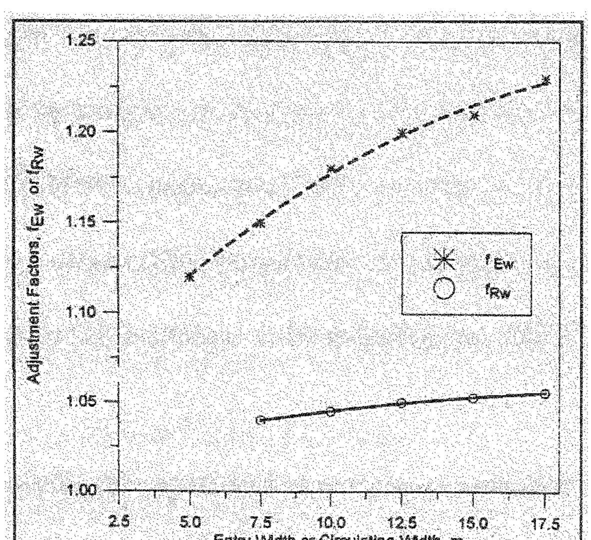


Figure 2.8 - Adjustment Factors for Effects of Entry Width and Circulating Lane Width

2.3.9 The United States Model

The Committee on Highway Capacity and Quality of Service of the Transportation Research Board (Committee A3A10) has recently included some guidance for predicting the performance and level of service of roundabouts in the United States in the Highway Capacity Manual (HCM) (Troutbeck, 1997).

The capacity of a roundabout can be estimated using gap-acceptance techniques with basic parameters of critical gap and follow-up time. It has generally assumed that the performance of each leg of a roundabout can be analyzed independently from the other legs. Consequently, most techniques tend to use information about only one leg in the analysis (Brilon and Stuwe, 1994).

As drivers make a right turn onto the roundabout, the gap acceptance characteristics of drivers are expected to be the same as or similar to those of drivers making right turns at a two-way stop control (TWSC) intersection. This concept is only suitable for single-lane roundabouts. There are other traffic interactions at multi-lane roundabouts that influence driver behavior and cause this technique to be inappropriate (HCM, 1997).

The equation for forecasting the capacity of an entry to a roundabout with one lane approach is as follows:

$$c_a = \frac{v_c e^{-v_c t_c / 3600}}{1 - e^{-v_c t_f / 3600}}$$

where

c_a = approach capacity

v_c = conflicting circulating traffic flow rate

t_c = critical gap

t_f = follow-up time

Limited studies of U.S. roundabouts, as well as comparisons with existing roundabout operations, indicated that a range of values of critical gap and follow-up time should provide a reasonable estimate of the likely capacity planned roundabouts. The recommended value ranges are shown in **Table 2.2**. The conflicting flow is calculated by evaluating the 150 min volumes of vehicles passing in front of the entering vehicles.

Table 2.2 - Critical Gap and Follow-up Time for U.S. Model

	Critical Gap (sec)	Follow-up Time (sec)
Upper-bound solution	4.1	2.6
Lower-bound solution	4.6	3.1

The comparison of the studied roundabout models presented in **Table 2.3** shows that although most take into consideration gap acceptance and follow-up time to determine the capacities and delays, few take into account pedestrians and bicyclists. Moreover, all the models, with the exception of the Netherlands', do not take into account the different bicycle treatments at roundabouts.

Table 2.3 - Comparison of Selected Roundabout Models

Model		Gap-Acceptance	Follow-up Time	Pedestrians	Pedestrian Crossing Location	Bicycles	Bicycle Treatments
British	Old	No	No	No	No	No	No
	New	Yes	Yes	Yes	Yes	No	No
Australian		Yes	Yes	No	No	No	No
Swiss		Yes	Yes	Yes	Yes	Mixed Flow	No
German		Yes	Yes	No	No	No	No
Netherlands		Yes	Yes	Yes	No	Yes	Yes
Danish		Yes	Yes	Yes	No	Yes	No
Israeli		No	No	No	No	No	No
Jordanian		No	No	No	No	No	No
American		Yes	Yes	No	No	No	No

2.4 Roundabout Analysis Packages

There are several roundabout analysis packages found in the literature. Most of the studied packages were developed in a research environment, although a few are commercial products. The most popular are described below in more detailed.

2.4.1 SIDRA

The SIDRA (Signalized and Unsignalized Intersection Design and Research Aid) package has been developed by ARRB Transport Research Ltd as an aid for design and evaluation of different types of signalized and unsignalized intersections including roundabouts. SIDRA uses detailed analytical traffic models in conjunction with interactive approximation method to provide estimates of capacity and performance statistics (delay, queue length, stop, rate, as well as fuel consumption, pollutant emission and operating cost of all types of intersections). In addition, SIDRA can handle roundabouts with more than four approaches and can analyze the effect of heavy vehicles on roundabout performance. Moreover, the condition of over-saturation can be analyzed by making use of SIDRA's time-dependent delay, queue length and stop rate formula.

The operation of SIDRA system is shown in **Figure 2.9**. The first step, using the RIDES module, data is prepared and checked for errors. Then the SIDRA computational routine carries out timing, capacity and performance calculations. The SIDRA system can also provide a graphical output.

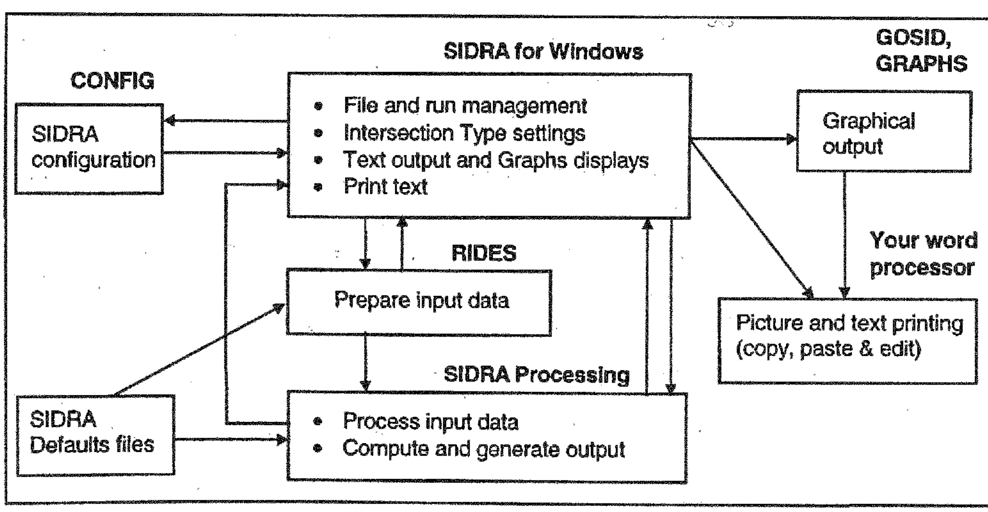


Figure 2.9 - Operation of the SIDRA System

SIDRA 5.2, the latest version, gives delays and level-of-service (LOS) results based on the new Highway Capacity Manual (HCM 97) capacity model for single-lane roundabouts, which is valid for circulating flows up to 1200 vph. All data specific for roundabouts (island diameter, circulating lanes width, number of circulating lanes and extra brunching in circulating flows) are specified in the roundabout data option. The origin-destination volumes (*from Approach - to Approach*) is essential in determining the circulating and exiting flow characteristics.

The weakness of SIDRA is that there is no data entry regarding pedestrians and roundabouts since SIDRA does not model pedestrians at roundabouts.

The HCM Model in SIDRA

SIDRA 5.2 uses the HCM capacity model for single-lane roundabout (HCM Chapter 10, Part C, Equation 10-124) as an alternative capacity model. HCM 97 does not provide a delay model for roundabouts. Therefore, in case of roundabouts, the general SIDRA delay equation for roundabouts is used. The HCM formula is extended in SIDRA by applying the heavy vehicle adjustment factor f_{HVe}.

$$Q_c = f_{HV_e} \frac{q_c e^{-q_c \alpha / 3600}}{1 - e^{-q_c \beta / 3600}} \qquad (q_c > 0)$$

$$Q_c = f_{HV_e} (3600/\beta) \qquad (q_c = 0)$$

where

Q_c = roundabout entry capacity

f_{Hvc} = heavy vehicle adjustment factor

q_c = circulating flow rate

α = critical gap

β = follow-up headway

SIDRA results are given for both the lowerbound and upperbound capacity estimates. The LOS results for the HCM model are obtained using the SIDRA delay model with the capacity from the HCM formula. Roundabout capacity predictions are also presented for other alternative capacity models.

2.4.2 RODEL

RODEL is an interactive program developed for the evaluation and design of roundabouts. This program was developed in the Highways Department of Staffordshire County Council in England (Florida Roundabout Guide). RODEL is based on an empirical model developed by Kimber at the Transport and Road Research Lab (TRRL) in the U.K. The empirical model was chosen over the gap-acceptance model because it directly relates capacity to detailed geometric parameters. RODEL is an interactive program in which the simultaneous display of both the input and output data is shown in a single screen (Florida Roundabout Guide).

There are two main modes of operation. In design mode, the user specifies a target parameter for average delay, maximum delay, maximum queue, and maximum RFC factor (v/c ratio). RODEL generates several sets of entry geometrics for each approach based on the given input. Depending on site specifics and constraints, the generated geometrics can be used for design purposes. Evaluation mode 2 focuses more on performance evaluation, using specified values of the geometric and traffic characteristics.

2.4.3 ARCADY

ARCADY (Assessment of Roundabout Capacity and Delay) is used for predicting capacities, queue lengths and delays at roundabouts (Binning, 1997). ARCADY allows the use of both queuing and geometric data and is an easy-to-use and helpful tool to aid traffic engineers in designing new roundabouts as well as allowing the users to assess the effects of modifying existing designs.

ARCADY 4 is the most recent version of the ARCADY program that has been successfully used to design and re-design thousands of roundabouts throughout the world. ARCADY calculations can be applied to single island roundabouts with up to seven approaches, allowing busy and most complex roundabouts to be modeled. The current version of ARCADY is not capable of modeling roundabouts with bicycle lanes.

By using traffic flow information and the geometry of the intersection, ARCADY can assess traffic demand and predict accident statistics. Moreover, pedestrian crossings on any or all approaches can be modeled in ARCADY.

The program uses empirical formulae for calculating the capacity of each entry as a function of the circulating flow crossing in front of the entry. The operation of the roundabout as a whole is calculated on the basis that the entries to the roundabout are linked by the common circulating lanes. Queues and delays are calculated using time-dependent queuing theory. The first feature of ARCADY is Kimber's 1980 equation that relates the entry capacity to the circulating flow. The second feature is the way in which flows from individual approaches of a roundabout are linked. The circulating flow across any entry is derived from the entry flows and turning proportions from previous approaches. The third feature is the time-dependent queuing theory, which is used to calculate queue lengths and delays. However, the more conventional queuing theories (steady-state and deterministic) yield to unsatisfactory predictions when traffic demands lie approximately in the region of 0.8 to 1.1 times the capacity.

Steady-state theory is only acceptable when traffic intensity is lower than 0.8 of the capacity, and deterministic theory is suitable when traffic intensity is higher than 1.1 of the capacity. The time-dependent queuing theory treats all traffic regions of traffic intensity by means of a technique based on probabilistic theory. For computational efficiency the program uses a mathematical transformation which gives very similar results to the direct application of probability theory (Kimber and Hollis, 1979).

2.4.4 Other Traffic Models

The Florida Roundabout Guide investigated three traffic models with respect to their ability to model roundabout operations:

TRANSYT-7F is a general signalized intersection network model that incorporates gap acceptance features similar to SIDRA. It should, in theory, be possible to construct an interconnected system of "yield" controlled intersections that would exhibit at least some of the characteristics of a roundabout from the perspective of TRANSYT-7F. During modeling "yield" controlled intersection, it was concluded that TRANSYT-7F model was not designed for this purpose and the present version does not offer a useful modeling capability (Florida roundabout Guide, 1996).

NETSIM is also a general traffic network model with the capability to model stop and yield control. An attempt to represent a roundabout as a network of interconnected yield signs met with some success by producing capacity and delay values in the same range as SIDRA and RODEL when the proportion of cross street traffic was high. However, with very low cross street proportions (below 30%) the results could not be reconciled rationally. Some development work is now underway to improve the applicability of NETSIM to roundabout analysis. The current version of NETSIM was not recommended for roundabout analysis (Florida Roundabout Guide).

SYNCHRO is a complete software package for modeling and optimizing traffic signal timing. It is possible to model a roundabout as a series of interconnected T-intersections controlled with yield signs. Although SYNCHRO allows unsignalized intersections to be added, it does not analyze them. SYNCHRO will route traffic through unsignalized intersections. Additionally, SYNCHRO requires 70 feet between nodes. For this reason, it is not able to model roundabouts, as in many cases the distance between the entry and exit conflict point is less that 70 feet.

Table 2.4 shows a comparison between different roundabout analysis packages and other currently used traffic analysis packages for their capabilities of taking into different provisions of pedestrian and bicyclist treatments at roundabouts.

Table 2.4 - Comparison Between Selected Traffic Analysis Packages

Analysis Package	Pedestrians	Pedestrian Crossing location	Bicycles	Bicycle Facility
SIDRA	No	No	No	No
RODEL	No	No	No	No
ARCADY	Yes	Yes	No	No
TRANSYT-7F	Yes	No	No	No
NETSIM	Not Recommended			
SYNCHRO	Yes	No	No	No

CHAPTER 3

DATA COLLECTION AND REDUCTION

3.1 Roundabout Description

Traffic data collected for the models described in **Chapter 4** was part of a case study for a single-lane roundabout located in a residential area in Boca Raton, Florida, at the intersection of SW 18th Street and 12th Avenue. At the time of data collection, the roundabout, shown in **Figure 3.1**, was the only single-lane modern roundabout in southeast Florida. The roundabout was constructed in 1990 and the residents are familiar with the roundabout operations. The roundabout has four approaches controlled by yield signs and all traffic is forced to move in one direction at the roundabout. The inscribed diameter of the roundabout is 130 ft. The width of the circulating lane is 18 feet and the width of the approaches is 15 feet. The east and west approaches of the roundabout are equipped with raised splitter islands, while the splitter islands on the north and south approaches are painted.

3.2 Traffic Data Collection

Traffic data was collected at the roundabout for a 24-hour period during a normal weekday. Data collected includes vehicle counts, speeds, and gaps at 12 points of the roundabout as shown in **Figure 3.2** (four entry, four exit and four circulating points). The average daily traffic (ADT) at the roundabout is 13,312 vehicles per day, and the peak hour volume is

1,075 and 1,384 vehicles during the AM and PM peaks, respectively. Also, the roundabout was video-taped to determine the interaction among different users. The video tapes were also used to determine the percentage of turning vehicles from and to each approach. **Table 3.1** presents the traffic distribution during the AM and PM peak hours. It also shows that during the AM peak period the eastbound of the west approach carries approximately 50% of the traffic volume, whereas 60% goes to the east exit and 28% to the north exit. On the other hand, during the PM peak, the westbound of the east approach carries approximately 43% of the traffic and the eastbound of the west approach carries 32%. The detailed summary of the 24-hours, 8-point traffic counts, presented in **Table 3.2** and **Figure 3.3**, shows that the west and the east approaches carry most of the approaching traffic. On the other hand, the southern section of the circulating lanes of the roundabout carries the largest volume of the traffic at the roundabout.

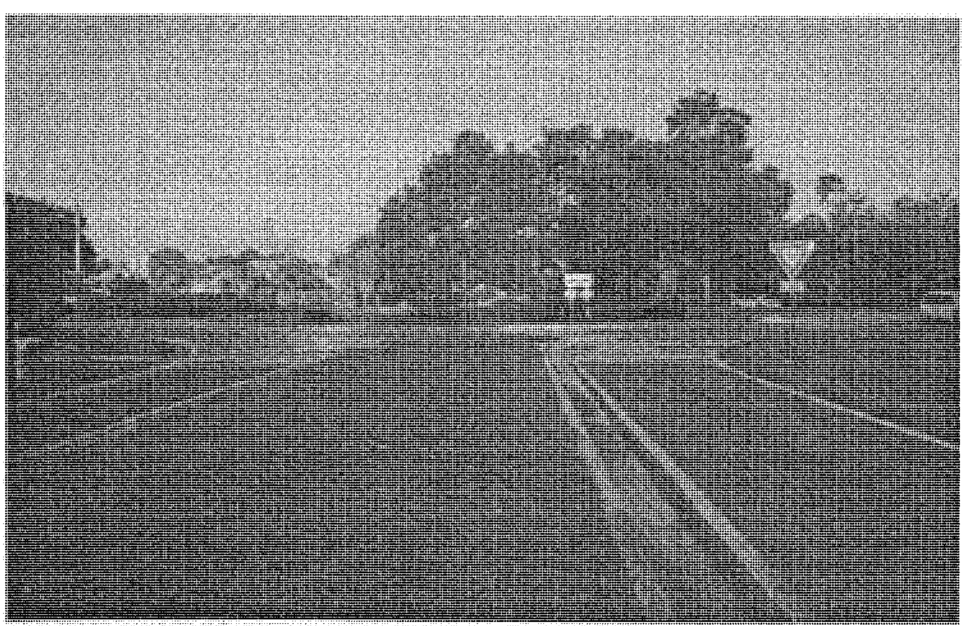


Figure 3.1 - The Studied Modern Roundabout in Boca Raton, FL

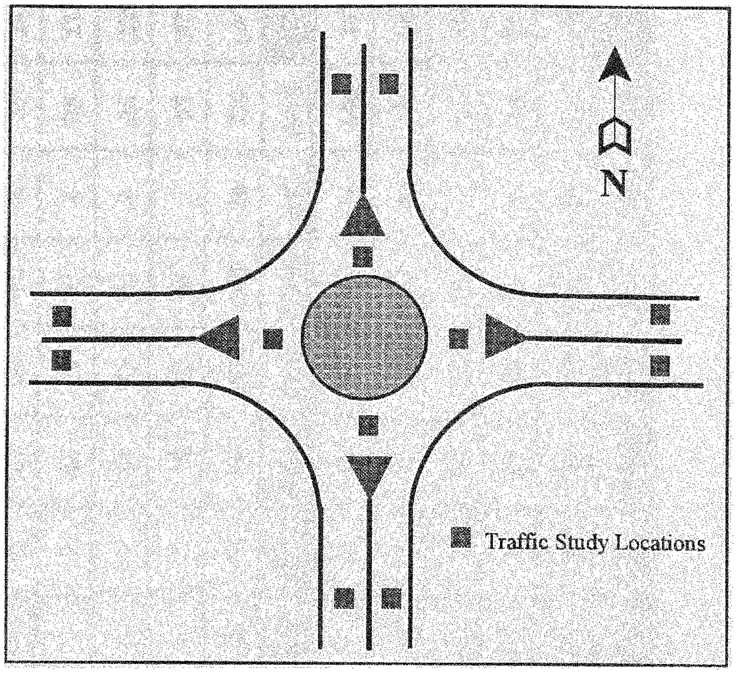


Figure 3.2 - Traffic Study Locations

From the results of the speed study, shown in **Tables 3.3, 3.4,** and **3.5**, and **Figures 3.4,** and **3.5**, it was found that the average speed of the approaching vehicles is 25 mph and that of the circulating vehicles is 15 mph. The measured speed distribution for each approach, shown in **Table 3.3**, was used in modeling the speed of the vehicles. For example, 1.55 % of the North approach vehicles will travel at a speed of 5 mph, 4.66% at 13 mph, 13.99% at 18 mph, 58.03% at 23 mph, etc.

In addition to the volume and speed studies, a gap study was performed at the selected roundabout location. The summary of the gap study is shown in **Table 3.6**, as well as **Figures 3.6** to **3.11**. It can be concluded from that the gap distribution is mostly consistent during the 24-hour period.

Table 3.1 - Traffic Distribution (vehicles) During the AM and PM Peak Periods

Time	North Approach				West Approach				South Approach				East Approach				Total
	West	South	East	Total	South	East	North	Total	East	North	West	Total	North	West	South	Total	
8:00	19	3	27	**49**	8	75	32	**115**	6	2	4	**12**	26	43	6	**75**	**251**
8:15	21	2	32	**55**	4	75	37	**116**	11	5	7	**23**	32	42	4	**78**	**272**
8:30	12	2	27	**41**	7	96	45	**148**	12	5	5	**22**	32	32	4	**68**	**279**
8:45	13	1	35	**49**	3	114	32	**149**	11	3	4	**18**	23	32	2	**57**	**273**
Total	**65**	**8**	**121**	**194**	**22**	**360**	**146**	**528**	**40**	**15**	**20**	**75**	**113**	**149**	**16**	**278**	**1,075**
%	**34%**	**4%**	**62%**	**100%**	**4%**	**68%**	**28%**	**100%**	**53%**	**20%**	**27%**	**100%**	**41%**	**54%**	**6%**	**100%**	
17:00	44	6	27	**77**	12	53	32	**97**	5	3	9	**17**	36	96	14	**146**	**337**
17:15	43	4	23	**70**	10	63	45	**118**	2	2	4	**8**	45	116	10	**171**	**367**
17:30	51	6	29	**86**	15	71	34	**120**	4	2	7	**13**	28	104	13	**145**	**364**
17:45	33	3	22	**58**	10	61	36	**107**	5	3	8	**16**	35	91	9	**135**	**316**
Total	**171**	**19**	**101**	**291**	**47**	**248**	**147**	**442**	**16**	**10**	**28**	**54**	**144**	**407**	**46**	**597**	**1,384**
%	**59%**	**7%**	**35%**	**100%**	**11%**	**56%**	**33%**	**100%**	**30%**	**19%**	**52%**	**100%**	**24%**	**68%**	**8%**	**100%**	

Table 3.2 - 24-Hour Traffic Counts

Time	North Approach	West Approach	South Approach	East Approach	North Circulating	West Circulating	South Circulating	East Circulating
12:00 AM	21	32	3	30	25	7	37	11
1:00 AM	3	11	1	16	15	6	13	4
2:00 AM	5	16	1	10	10	2	15	3
3:00 AM	7	8	0	4	2	0	9	4
4:00 AM	4	7	1	1	1	5	7	5
5:00 AM	16	24	3	12	9	6	28	6
6:00 AM	39	94	14	63	55	18	111	34
7:00 AM	156	322	104	233	191	99	509	186
8:00 AM	193	529	72	280	230	94	835	224
9:00 AM	120	366	49	239	208	59	451	145
10:00 AM	102	296	37	216	184	62	347	99
11:00 AM	119	297	35	265	224	47	351	106
12:00 PM	152	268	41	244	225	64	337	104
1:00 PM	167	251	33	251	198	92	339	104
2:00 PM	170	317	32	295	239	96	420	132
3:00 PM	216	347	47	405	333	100	417	127
4:00 PM	197	341	47	445	380	113	408	113
5:00 PM	292	442	53	596	505	126	545	176
6:00 PM	202	354	41	388	314	100	426	121
7:00 PM	145	251	32	270	228	82	317	105
8:00 PM	107	192	21	230	177	73	231	79
9:00 PM	112	176	15	190	156	67	216	54
10:00 PM	57	88	14	132	113	30	109	35
11:00 PM	30	60	2	78	64	18	74	17
Total	2,632	5,089	698	4,893	4,086	1,366	6,552	1,994

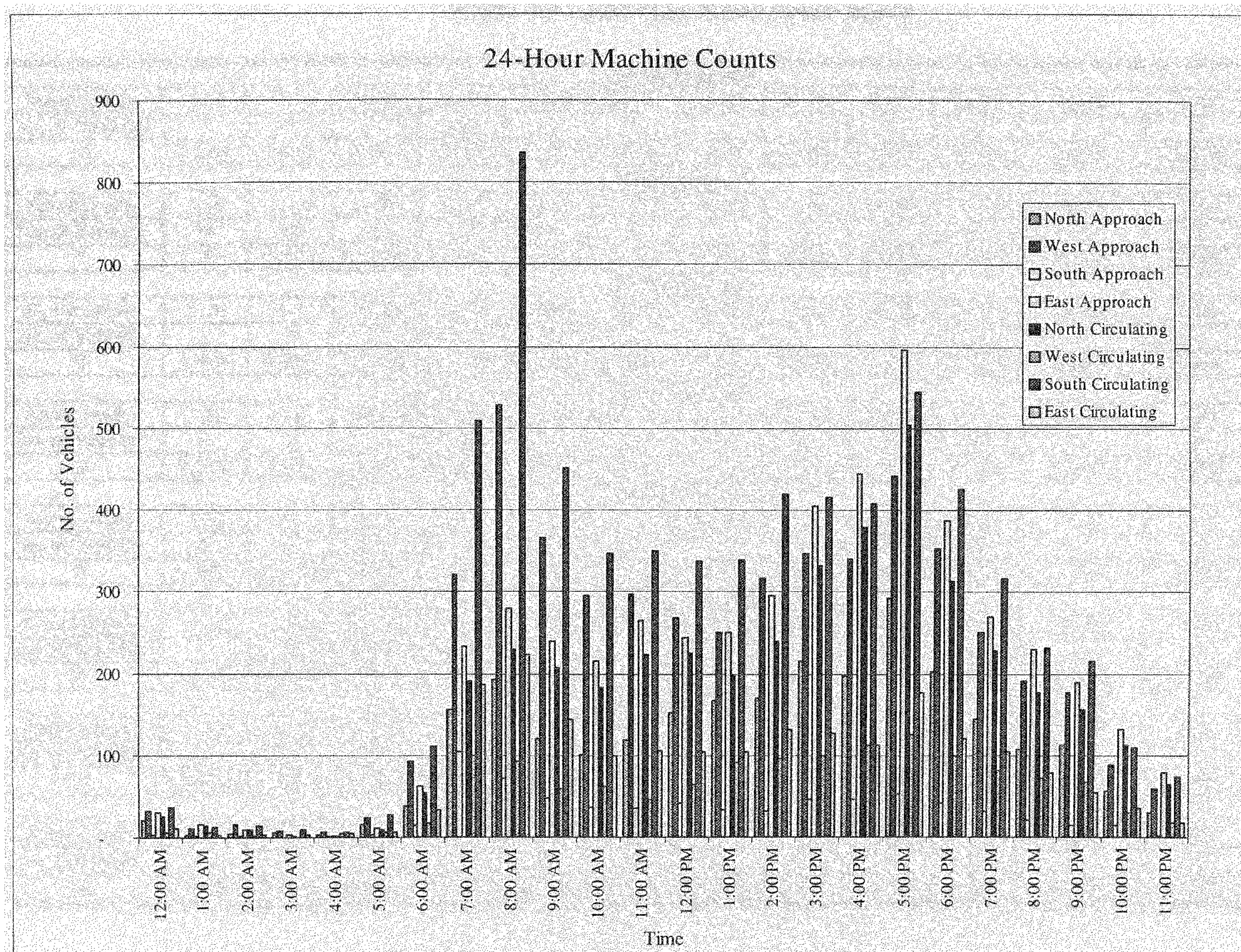


Figure 3.3 - 24-Hour Machine Counts

Table 3.3 - AM Peak Hour Speed Study

North Approach												
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	3	9	27	112	32	1	2	1	1	1	0	4	193
%	1.55%	4.66%	13.99%	58.03%	16.58%	0.52%	1.04%	0.52%	0.52%	0.52%	0.00%	2.07%	
West Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	38	105	162	156	61	6	1	0	0	0	0	0	529
%	7.18%	19.85%	30.62%	29.49%	11.53%	1.13%	0.19%	0.00%	0.00%	0.00%	0.00%	0.00%	
South Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	1	0	31	32	8	0	0	0	0	0	0	0	72
%	1.39%	0.00%	43.06%	44.44%	11.11%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
East Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	0	1	1	0	13	91	131	37	5	0	1	0	280
%	0.00%	0.36%	0.36%	0.00%	4.64%	32.50%	46.79%	13.21%	1.79%	0.00%	0.36%	0.00%	
North Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	0	49	175	6	0	0	0	0	0	0	0	0	230
%	0.00%	21.30%	76.09%	2.61%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
West Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	2	42	50	0	0	0	0	0	0	0	0	0	94
%	2.13%	44.68%	53.19%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
South Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	0	277	501	1	0	0	0	0	0	0	0	0	779
%	0.00%	35.56%	64.31%	0.13%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
East Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	Total
No. of Vehicles	1	64	156	3	0	0	0	0	0	0	0	0	224
%	0.45%	28.57%	69.64%	1.34%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	

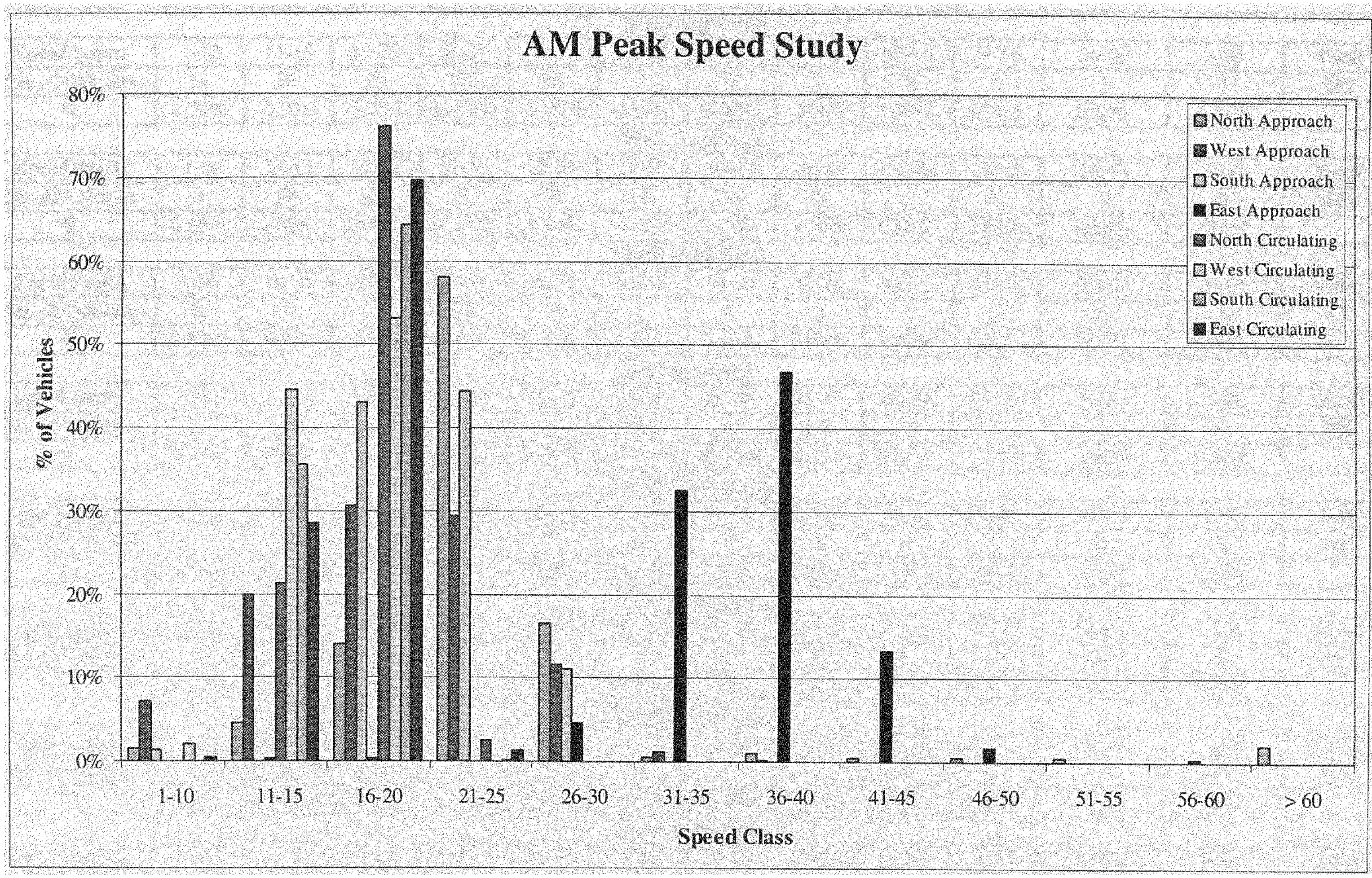


Figure 3.4 - AM Peak Speed Study

Table 3.4 - PM Peak Hour Speed Study

North Approach												
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	14	36	68	120	44	1	0	2	0	1	1	5	**292**
%	4.79%	12.33%	23.29%	41.10%	15.07%	0.34%	0.00%	0.68%	0.00%	0.34%	0.34%	1.71%	
West Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	3	29	46	47	23	43	231	20	0	0	0	0	**442**
%	0.68%	6.56%	10.41%	10.63%	5.20%	9.73%	52.26%	4.52%	0.00%	0.00%	0.00%	0.00%	
South Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	0	1	17	30	5	0	0	0	0	0	0	0	**53**
%	0.00%	1.89%	32.08%	56.60%	9.43%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
East Approach													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	0	0	3	12	23	167	255	118	17	1	0	0	**596**
%	0.00%	0.00%	0.50%	2.01%	3.86%	28.02%	42.79%	19.80%	2.85%	0.17%	0.00%	0.00%	
North Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	4	69	408	24	0	0	0	0	0	0	0	0	**505**
%	0.79%	13.66%	80.79%	4.75%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
West Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	1	34	87	4	0	0	0	0	0	0	0	0	**126**
%	0.79%	26.98%	69.05%	3.17%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
South Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	2	172	367	4	0	0	0	0	0	0	0	0	**545**
%	0.37%	31.56%	67.34%	0.73%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
East Circulating													
Speed (mph)	1-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	1	51	122	1	0	0	1	0	0	0	0	0	**176**
%	0.57%	28.98%	69.32%	0.57%	0.00%	0.00%	0.57%	0.00%	0.00%	0.00%	0.00%	0.00%	

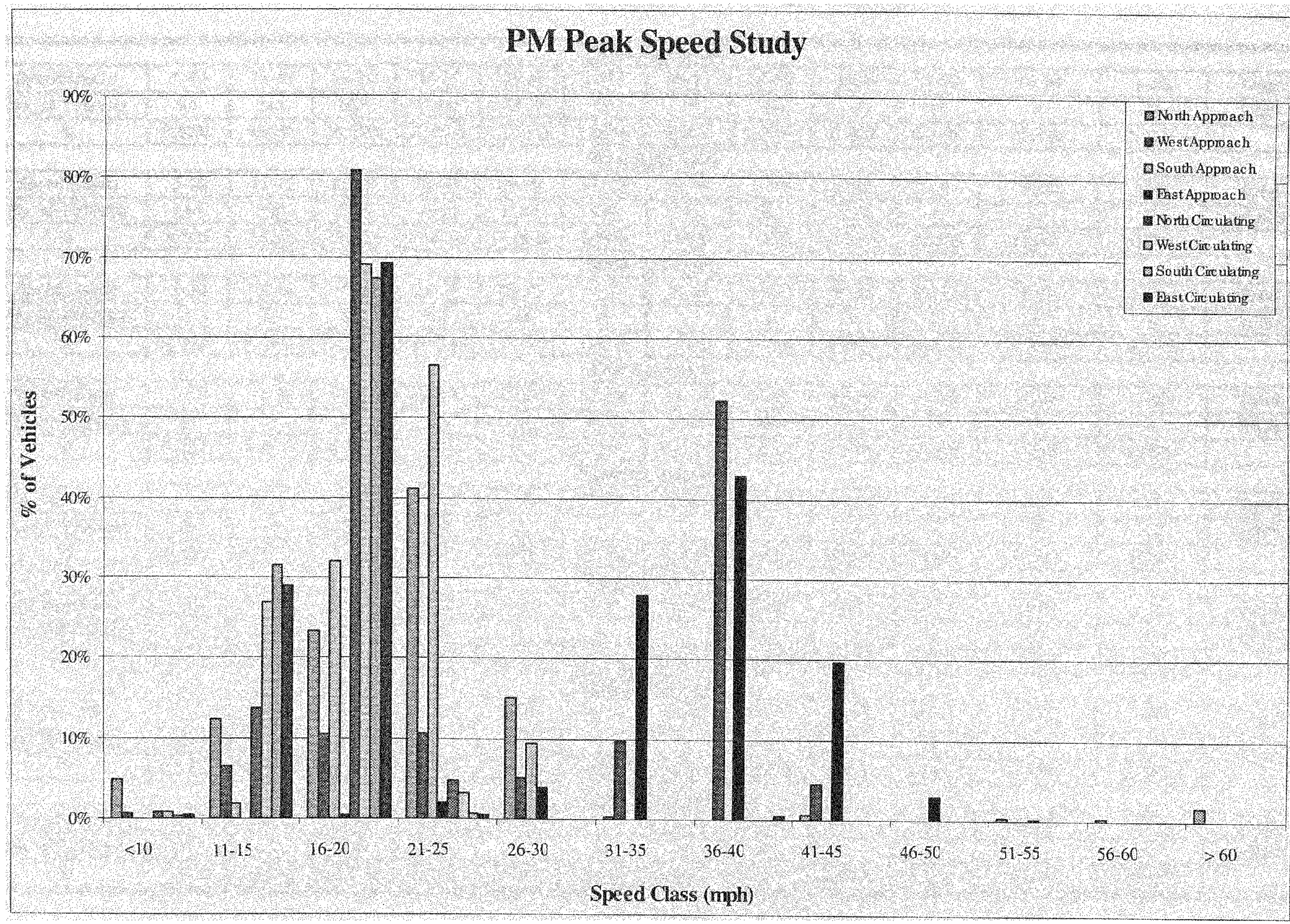


Figure 3.5 - PM Peak Speed Study

Table 3.5 - Summary of 24-Hour Speed Study

North Approach												
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	44	215	887	2750	1212	90	13	15	14	11	9	87	**5,347**
%	0.82%	4.02%	16.59%	51.43%	22.67%	1.68%	0.24%	0.28%	0.26%	0.21%	0.17%	1.63%	
West Approach													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	144	738	1104	4145	2937	480	513	261	143	1	0	2	**10,468**
%	1.38%	7.05%	10.55%	39.60%	28.06%	4.59%	4.90%	2.49%	1.37%	0.01%	0.00%	0.02%	
South Approach													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	5	39	327	741	236	14	2	1	0	1	0	4	**1,370**
%	0.36%	2.85%	23.87%	54.09%	17.23%	1.02%	0.15%	0.07%	0.00%	0.07%	0.00%	0.29%	
East Approach													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	0	17	38	124	771	3972	3868	949	117	10	4	0	**9,870**
%	0.00%	0.17%	0.39%	1.26%	7.81%	40.24%	39.19%	9.61%	1.19%	0.10%	0.04%	0.00%	
North Circulating													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	28	754	3104	197	3	0	0	0	0	0	0	0	**4,086**
%	0.69%	18.45%	75.97%	4.82%	0.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
West Circulating													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	15	472	846	32	1	0	0	0	0	0	0	0	**1,366**
%	1.10%	34.55%	61.93%	2.34%	0.07%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	
South Circulating													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	24	2216	4208	97	5	0	0	0	0	0	0	2	**6,552**
%	0.37%	33.82%	64.22%	1.48%	0.08%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.03%	
East Circulating													
Speed (mph)	5-10	11-15	16-20	21-25	26-30	31-35	36-40	41-45	46-50	51-55	56-60	> 60	**Total**
No. of Vehicles	26	645	1282	38	0	0	1	1	0	0	0	1	**1,994**
%	1.30%	32.35%	64.29%	1.91%	0.00%	0.00%	0.05%	0.05%	0.00%	0.00%	0.00%	0.05%	

Table 3.6 - Summary 24-Hour Gap Study

North Approach										
Gaps (Sec)	1	2	3	4	5	6	7	8	9	>9	**Total**
No. of Gaps	659	332	258	222	203	161	158	155	152	3038	**5338**
%	12.35%	6.22%	4.83%	4.16%	3.80%	3.02%	2.96%	2.90%	2.85%	56.91%	
West Approach											
Gaps (Sec)	1	2	3	4	5	6	7	8	9	>9	**Total**
No. of Gaps	2945	1337	742	538	462	343	293	261	214	3333	**10468**
%	28.13%	12.77%	7.09%	5.14%	4.41%	3.28%	2.80%	2.49%	2.04%	31.84%	
South Approach											
Gaps (Sec)	1	2	3	4	5	6	7	8	9	>9	**Total**
No. of Gaps	37	22	22	18	16	15	23	15	10	1192	**1370**
%	2.70%	1.61%	1.61%	1.31%	1.17%	1.09%	1.68%	1.09%	0.73%	87.01%	
East Approach											
Gaps (Sec)	1	2	3	4	5	6	7	8	9	>9	**Total**
No. of Gaps	2095	1291	778	590	461	400	338	294	211	3412	**9870**
%	21.23%	13.08%	7.88%	5.98%	4.67%	4.05%	3.42%	2.98%	2.14%	34.57%	
North Circulating											
Gaps (Sec)	≤2	3	4	5	6	7	8	9	10	>10	**Total**
No. of Gaps	1030	315	244	201	185	138	121	135	112	1605	**4086**
%	25.21%	7.71%	5.97%	4.92%	4.53%	3.38%	2.96%	3.30%	2.74%	39.28%	
West Circulating											
Gaps (Sec)	≤2	3	4	5	6	7	8	9	10	>10	**Total**
No. of Gaps	127	34	34	35	27	29	37	29	27	987	**1366**
%	9.30%	2.49%	2.49%	2.56%	1.98%	2.12%	2.71%	2.12%	1.98%	72.25%	
South Circulating											
Gaps (Sec)	≤2	3	4	5	6	7	8	9	10	>10	**Total**
No. of Gaps	3058	594	386	249	189	160	151	98	102	1538	**6525**
%	46.87%	9.10%	5.92%	3.82%	2.90%	2.45%	2.31%	1.50%	1.56%	23.57%	
East Circulating											
Gaps (Sec)	≤2	3	4	5	6	7	8	9	10	>10	**Total**
No. of Gaps	240	100	80	74	78	55	44	48	68	1207	**1994**
%	12.04%	5.02%	4.01%	3.71%	3.91%	2.76%	2.21%	2.41%	3.41%	60.53%	

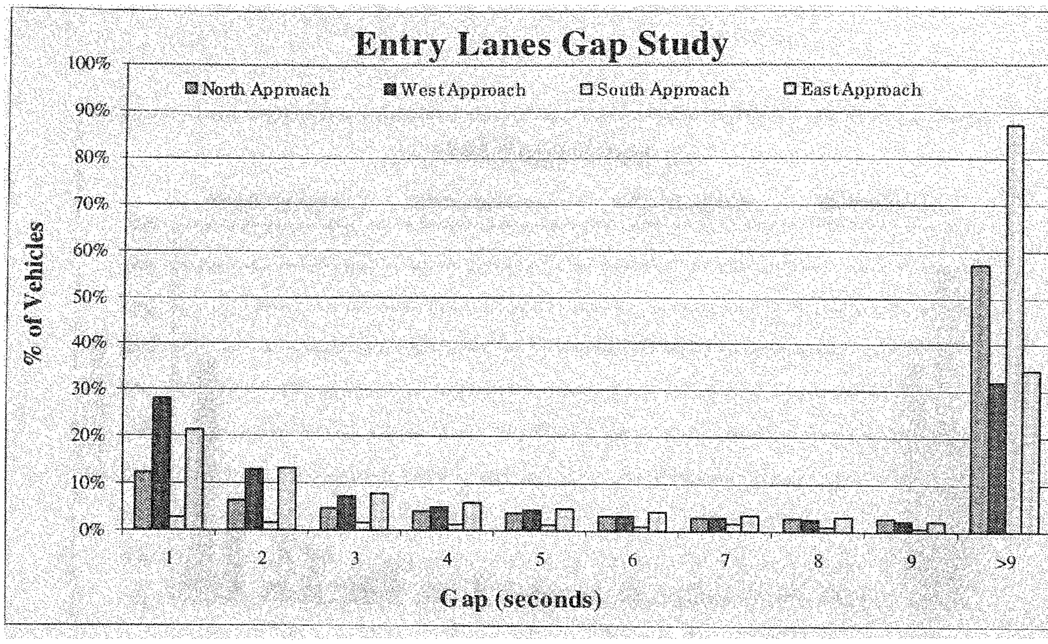


Figure 3.6 - Roundabout Entries Gap Study

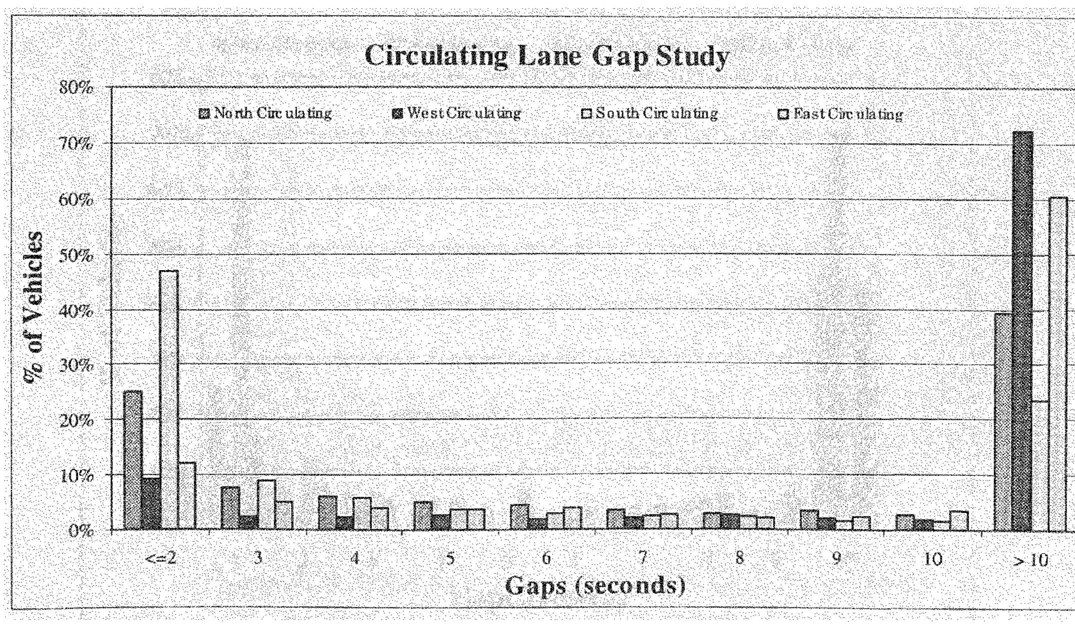


Figure 3.7 - Circulating Lane Gap Study

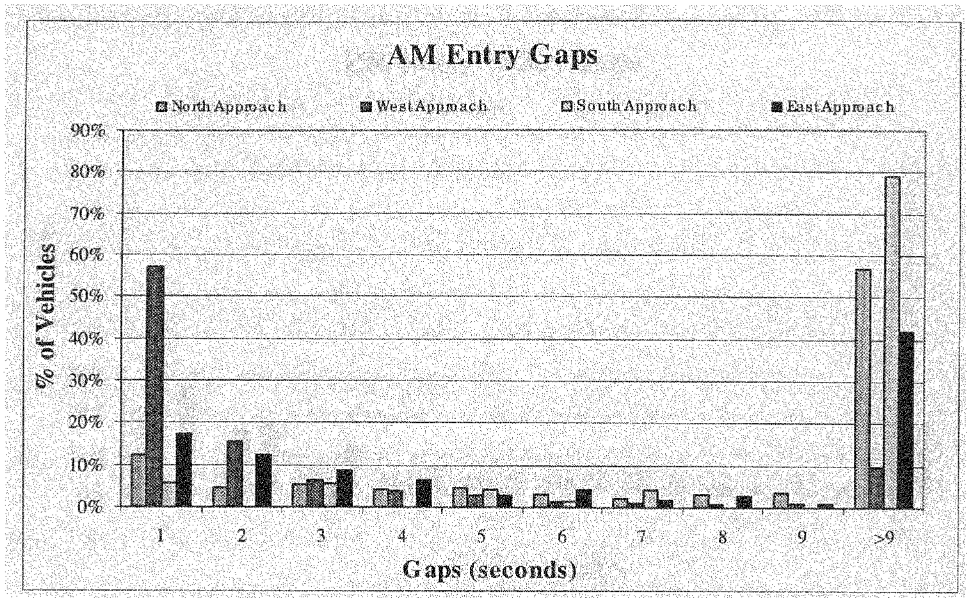


Figure 3.8 - AM Peak Entry Gap Distribution

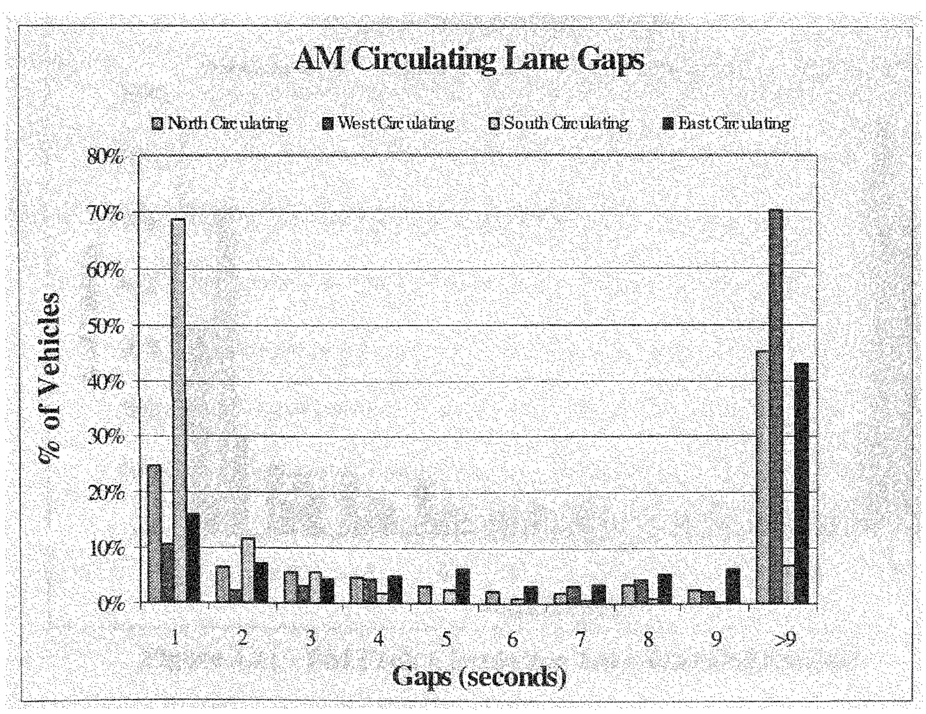


Figure 3.9 - AM Peak Circulating Lane Gap Distribution

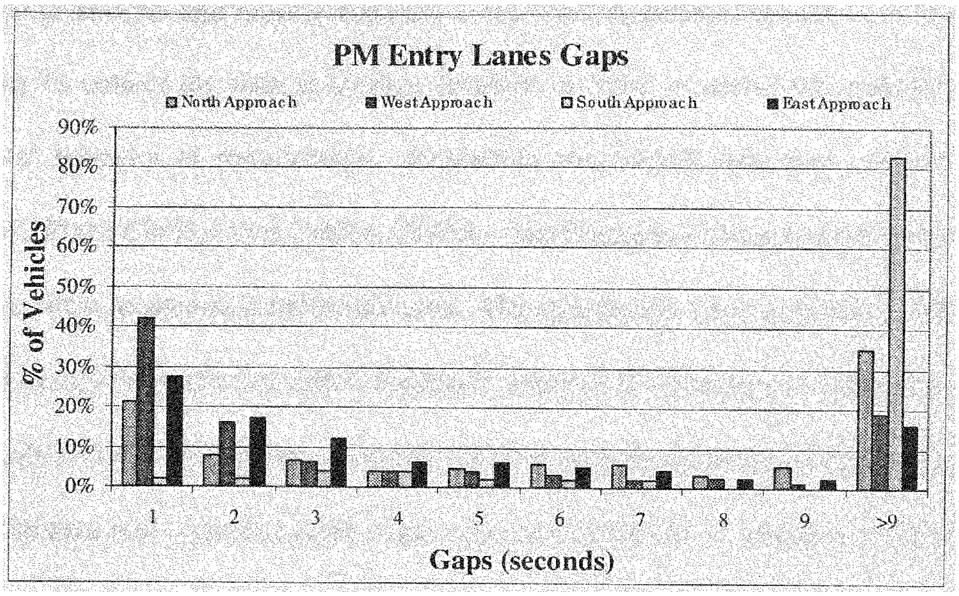


Figure 3.10 - PM Peak Entry Lane Gap Distribution

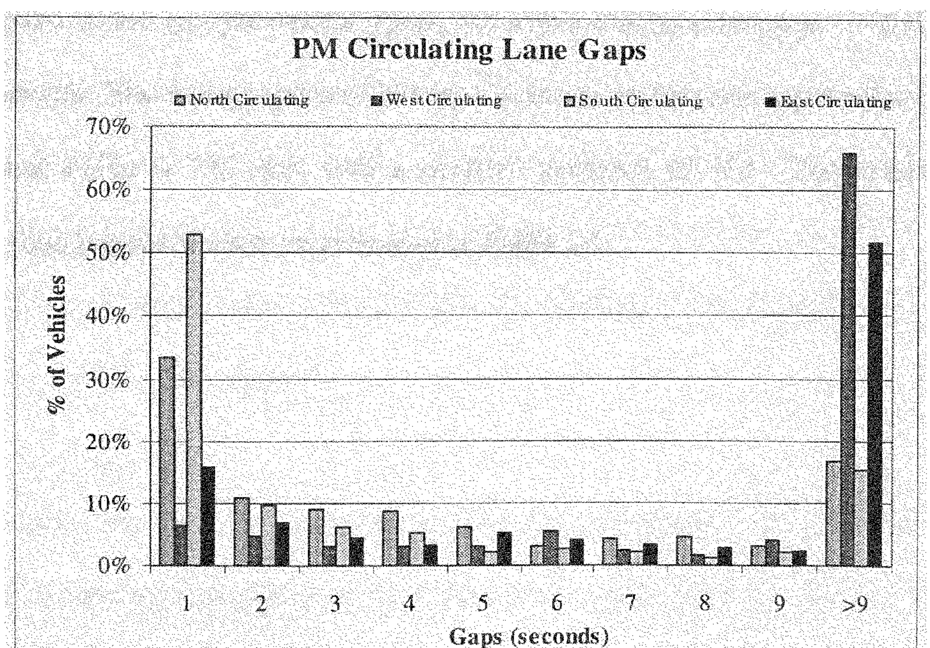


Figure 3.11 - PM Peak Circulating Lane Gap Distribution

3.3 Field Observations for Pedestrians and Bicycles

Since the pedestrian and bicycle volumes at the selected roundabout are very low, it was necessary to collect the data at another location in order to model the pedestrians' and bicyclists' behavior at roundabouts. Pedestrian and bicycle data was collected at the Cartagena Plaza Circle, Coral Gables, Florida. The Cartagena Circle is a single-lane, four-approach circle located in a residential area. The approaches are controlled by yield signs, with the exception of the Cocoplum approach, which is the entrance of a gated residential community and is controlled by a stop sign. Splitter islands are provided on all approaches. Pedestrian data was collected at the south approach of the circle, which is controlled by a yield sign. The pedestrian crossing time for the south entry was measured during a 15-minute period and it was found that pedestrians cross the roundabout approach with an average speed of 246 feet per minute (fpm), and with a standard deviation of 25.67 during the peak periods. The average speed of the bicyclists crossing the same approach or traveling with general traffic is 758 fpm, with a standard deviation of 134. The results of the pedestrian and bicycle studies are presented in **Table 3.7**.

Table 3.7 - Results of Pedestrian and Bicycle Studies

Pedestrian Crossing Time (sec)	Pedestrian Speed (fpm)	Bicycle Travel Time (sec)	Bicycle Speed (fpm)
4.56	276.32	9.46	970.22
5.29	238.19	8.80	1,043.23
5.78	217.99	13.23	694.11
5.69	221.44	11.27	814.26
5.33	236.40	13.85	662.68
4.93	255.58	10.25	895.97
4.68	269.23	14.11	650.41
5.69	221.44	10.65	862.24
4.75	265.26	12.93	709.98
4.55	276.92	13.25	692.90
4.55	276.92	13.57	676.63
5.32	236.84	13.89	661.10
4.88	258.20	14.20	646.27
6.01	209.65	14.52	632.10

3.4 Operational Observations

In order to simulate driver behaviors and the interaction between vehicles, pedestrians and bicyclists, several observations were made at the selected single-lane roundabout in Boca Raton, Florida, as well as Cartagena Plaza Circle in Miami, Florida. The following is a summary of the field observations:

- Vehicles arriving at the yield line proceed without stopping if a suitable gap exists. (At the studied roundabout in Boca Raton, the critical gap was found to be equal to the time that a circulating driver takes to traverse between the exit conflict point and the entry conflict point, which was found to be approximately 3.0 seconds.)

- When the critical gap is made available to the driver, it takes the driver 2.5 seconds between leaving the yield line and merging with the circulating flow. The actual distribution was found to be a normal distribution with a mean of 2.5 seconds and a standard deviation of 1.02 seconds, N(2.5, 1.02).

- After the driver merges with the circulating flow, it takes the following driver 2.5 seconds to reach the yield line. Again, the distribution of the follow-up time was found to be a normal distribution with a mean of 2.5 seconds and a standard deviation of 0.08 seconds, N(2.5, 0.8).

- The give-way (right-of-way) rule at modern roundabouts mandates that vehicles entering the roundabout should yield to pedestrians and bicyclists on a crosswalk at the entry side. On the other hand, pedestrians and bicyclists on the crosswalk at the exit side should yield to vehicles exiting the roundabout.

- Pedestrians, bicyclists, and vehicles arrive at crosswalks independently and randomly. Pedestrians cross a road of a given width with a mean speed of 246 feet per minute (fpm), N(246, 25.67), and bicyclists with a mean speed of 758 fpm, N(758, 134).

- Pedestrians and bicyclists arriving at the crosswalk cross the approach if there are no arriving vehicles, or if there are vehicles arriving with a normal decelerating rate (a car that can decelerate and stop before reaching the crosswalk). Otherwise, pedestrians and cyclists have to wait for the car to pass.

- When a pedestrian or bicyclist arrives and finds a vehicle about to pass through the crossing, the vehicle completes its passage, but the next vehicle yields to the pedestrian.

- If another pedestrian or bicyclist arrives when there are pedestrians in the crosswalk, he/she crosses without any delay.

- When a vehicle queue at the entry extends from the yield line of the roundabout to the crosswalk, arriving pedestrians and bicyclists cross without delay.

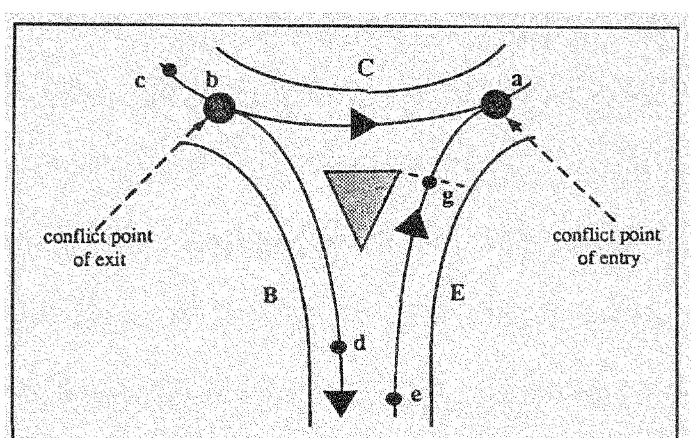


Figure 3.12 - Conflict Points at the Entrance and Exit

- Exiting traffic flow may be stopped by pedestrians and/or bicyclists at the crosswalk on the exit side, and a queue may be formed near the exit. If the queue extends to the circulating roadway, the circulating lane of the roundabout is blocked.

- When a segment of the circulating lane is blocked, vehicles at the previous entry can either enter with low speed, or not enter at all.

- If there are vehicles at the conflict point of the entry (see **Figure 3.12**), the vehicles at the entry cannot enter.

- If there are vehicles at the conflict point of the exit, or between the exit and the entry conflict points, the vehicles at the entry cannot enter (see **Figure 3.12**).

CHAPTER 4

DEVELOPMENT OF SIMULATION MODELS

4.1 Introduction

Current roundabout analysis and simulation software packages do not take into consideration the effects of pedestrians and bicycles on the capacity and level of service of roundabouts. This chapter describes a methodology for developing a simulation model for single-lane roundabouts, which handle pedestrian and bicycle traffic.

Service Model Simulation Package was used to simulate the effect of different pedestrian and bicycle treatments on the performance of a single-lane roundabout. Service Model is a powerful Windows-based, discrete event simulation tool for simulating and analyzing service systems of all types (ProModel, 1998). It provides flexibility and power for modeling nearly any situation. Service Model was used to model the new international terminal in John F. Kennedy International Airport. Delta Airlines also used Service Model to simulate gate operation in Salt Lake City International Airport. Service Model has demonstrated good capabilities in handling toll and parking plaza operations. A toll plaza model was developed to simulate various shift schedules, to find the optimal schedules that will best serve the traffic needs, and to analyze the impact of dedicated lanes for trucks, special passes, etc., versus having all lanes handle all types of traffic. The Federal Aviation Administration uses Service Model to identify emergency safety issues to implement intervention strategies and to investigate methods for improving the use of aviation safety data information.

4.2 Model Elements

Any simulation model should include elements to represent the structure and operation of the system being simulated. Model elements can be divided into elements, which define system objects, define the system operation, and specify object parameters and operation logic.

4.2.1 System Objects

The system objects include locations that represent fixed places in the roundabout where vehicles, bicycles and/or pedestrians are generated and queued to make a decision. Another important system object are entities. Entities are the items that are processed by the system, such as vehicles, pedestrians and bicycles. Entities move from one location to another by using a defined path network. The roundabout model has multiple path networks. The first path network is reserved for vehicles, while the second one is reserved for pedestrians. An additional path network is also reserved for bicycles when using the bicycle lanes. System objects for the roundabout models are shown in **Figure 4.1**.

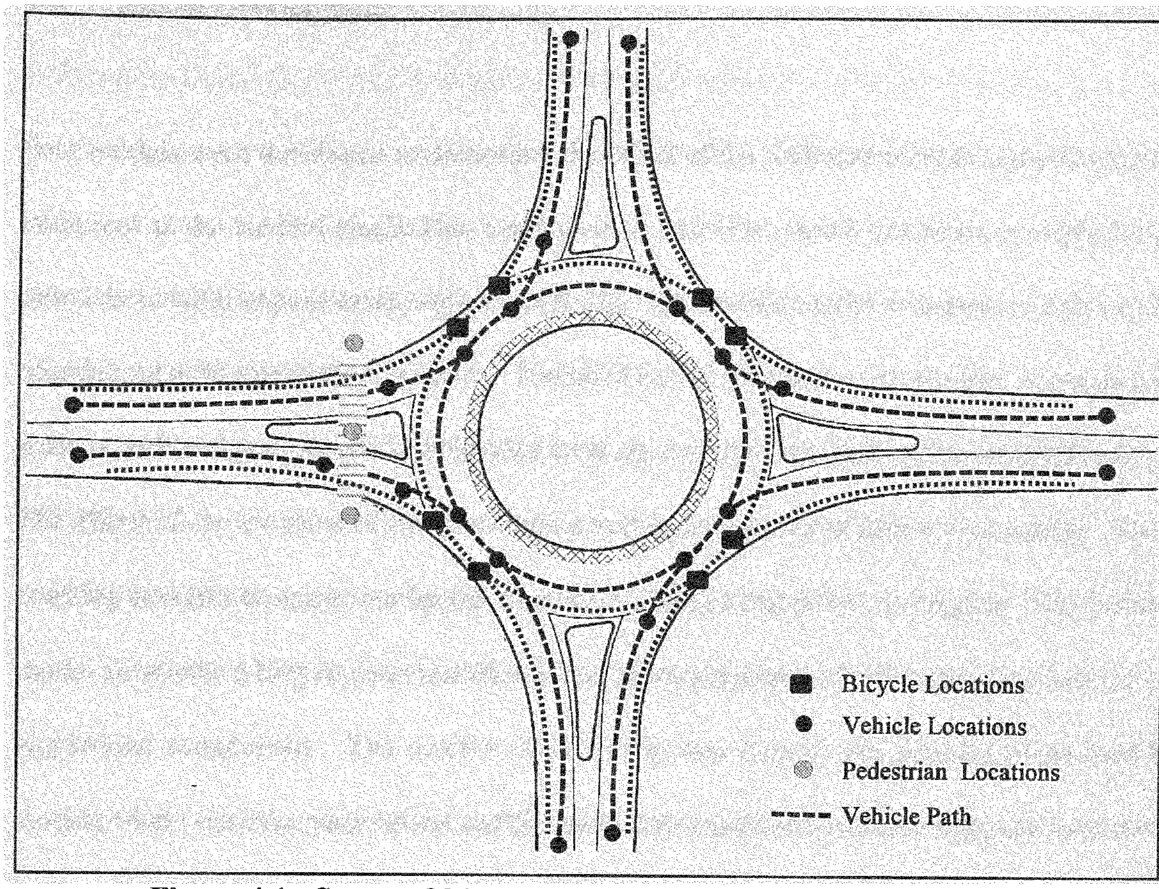


Figure 4.1 - System Object for a Single-Lane Roundabout Model

4.2.2 System Operation

The system operation consists of processes which define the routing of entities through the system, as well as the various operations that take place for each entity at each location. Entity routing is constrained by the capacity of the next location so that no entity will be able to claim and move to the next location until capacity is available at that location. Arrival defines the entry of entities into the system. Arrivals can be defined as occurring at scheduled times, at periodic intervals, at increasing or decreasing rates, or follow a predefined distribution.

4.3 Model Development

Four models were developed to determine the effect of the different bicycle and pedestrian treatment at the studied single-lane roundabout. The first model simulates a single-lane roundabout without pedestrian and bicycle traffic. The second model simulates a single-lane roundabout with mixed flow bicycles. The third model simulates a single-lane roundabout with a combined pedestrians and bicycles crossing that was installed on the west approach. The effect of the location of the combined crossing is also simulated in this model. The crossing was placed at one car length, then shifted to two and three car lengths. The fourth model simulates a bicycle lane installed at the outer perimeter of the circulating lane of a single-lane roundabout. The models described in this chapter are discrete event-based models where vehicles, pedestrians and bicyclists arrive at the roundabout independently and with random distribution. Vehicle, pedestrian and bicycle volumes were increased gradually to measure the performance of the simulated single-lane roundabout under different bicycle and pedestrian treatments.

4.3.1 Model 1 - Roundabout without Pedestrian and Bicycle Traffic

This model simulates the vehicular traffic only at a single-lane roundabout (i.e., no pedestrians and bicyclists are assumed to use the roundabout). Vehicles will approach the roundabout at a speed equal to the modeled speed. Before the vehicle arrives at point "g" (see **Figure 3.12**), if the driver found no vehicles between points "b" and "a", the driver will proceed and merge with the circulating traffic. Otherwise, the driver will stop at point "g" and wait for a suitable gap of at least 3 seconds before merging with the circulating traffic. If the approaching driver found another vehicle at the yield line, the driver must wait until the proceeding vehicles merge with the circulating traffic, then proceed to the yield line (the follow-up time is 2.5 seconds). If the approaching vehicles found a suitable gap, the driver can proceed and merge with the circulating traffic without stopping at the yield line, otherwise, the driver must wait for an acceptable gap. When the vehicle reaches the exit conflict, the driver has to make a choice either to exit the roundabout or to continue until reaching the destination exit. When the vehicle exits the roundabout, the driver can accelerate to the normal cruising speed of the approach. **Figure 4.2** shows the processing logic for simulating a single-lane roundabout with vehicular traffic only.

4.3.2 Model 2 - Roundabout with Bicycles with Mixed Flow

This model simulates bicycles with mixed-flow traffic at a single-lane roundabout (i.e., vehicles and bicycles use the roundabout in the same manner and both of them have to obey to the priority rule at the roundabout entries). Vehicles will approach the roundabout at a speed equal to the modeled speed, and bicycles at a speed of N(758, 134). At point "e", vehicles are not allowed to take over preceding bicycles. Before the vehicle or the bicycle arrives at point "g", if the driver or the bicyclist found no vehicles or bicycles between points "b" and "a", the driver or the bicyclist will proceed and merge with the circulating traffic. Otherwise, the driver or the bicyclist will stop at point "g" and wait for a suitable gap of at least three seconds before merging with the circulating traffic. If the driver or the bicyclist found another vehicle or a bicycle at the yield line, they must wait until the proceeding

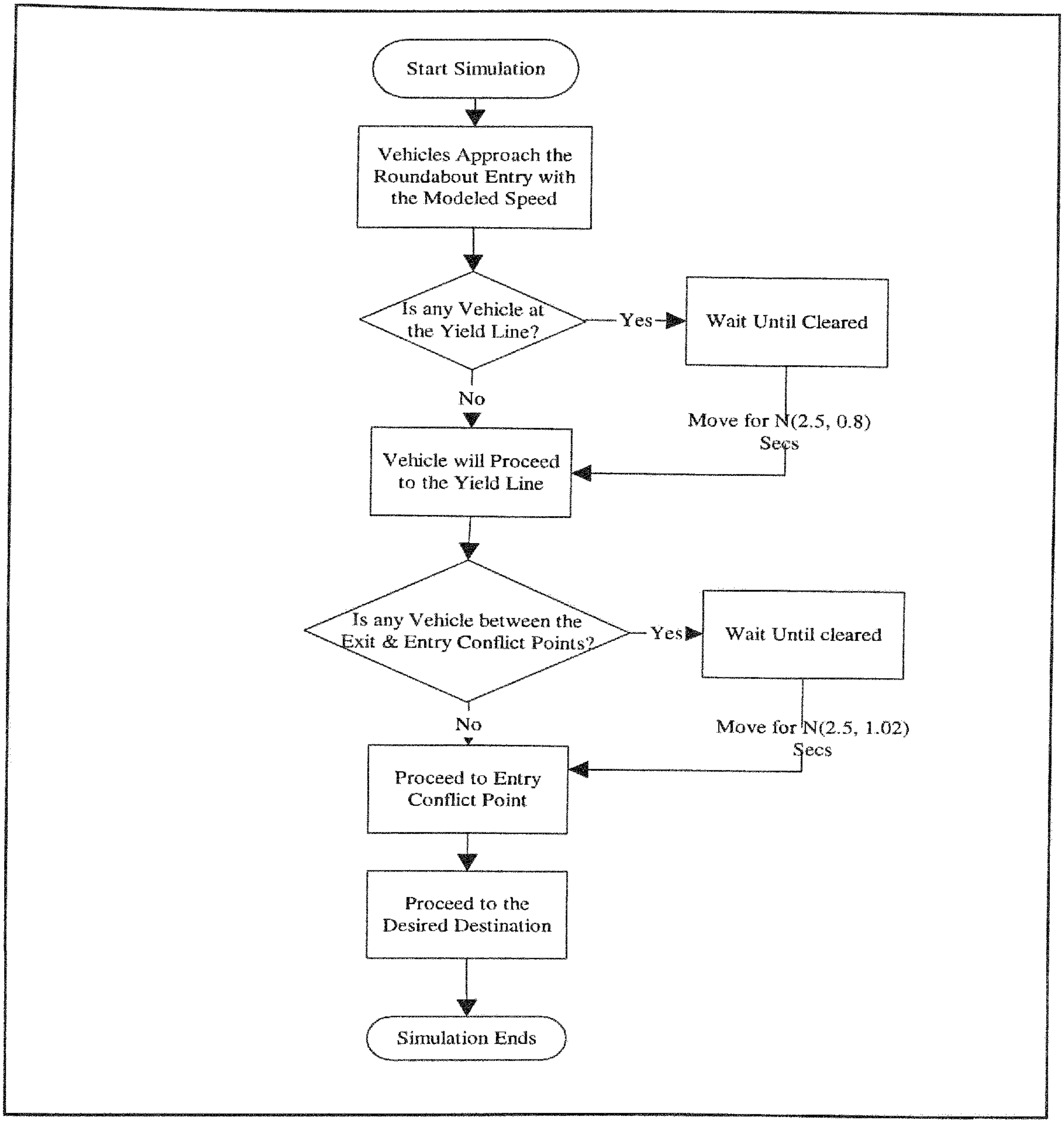


Figure 4.2- Model 1 Processing Logic

vehicle or bicycle merges with the circulating traffic; then they can proceed to the yield line. If there is a suitable gap, they may proceed and merge with the circulating traffic without stopping, otherwise they must wait for an acceptable gap. When the vehicle or the bicycle reaches the exit conflict point "b," the driver has to make a choice to exit the roundabout or to continue till they reach the destination exit. When the vehicle exits the roundabout at point "d," the driver can overtake a preceding bicycle and accelerate to the normal cruising speed of the approach. The model processing logic is presented in **Figure 4.3.**

4.3.3 Model 3 - Roundabout with Combined Pedestrians and Bicycles Crossing

This model simulates vehicular, pedestrian, and bicycle traffic in roundabouts. Pedestrians and bicyclists use a combined path outside the roundabout. The combined crossing is located on the west approach of the roundabout, at a distance of one car length from the yield line. Vehicles approach the roundabout at a speed equal to the modeled speed. If a driver observes a pedestrian or a bicyclist attempting to cross, or on the entry side crosswalk, the driver yields to the pedestrian or bicyclist. Any other pedestrian or bicyclist that arrives when there are others in the crosswalk, crosses without delay. If a pedestrian or a bicyclist arrives and finds a vehicle about to pass through the crossing, the vehicle completes its passage, but the next vehicle yields to the pedestrian or bicyclist. If there are no more pedestrians and/or bicyclists on the entry side crosswalk, vehicles can proceed to the yield line of the roundabout. If the driver finds no vehicles between points "b" and "a", the driver will proceed and merge with the circulating traffic. Otherwise, the driver will stop at point "g" and wait for a suitable gap of at least 3 seconds before merging with the circulating

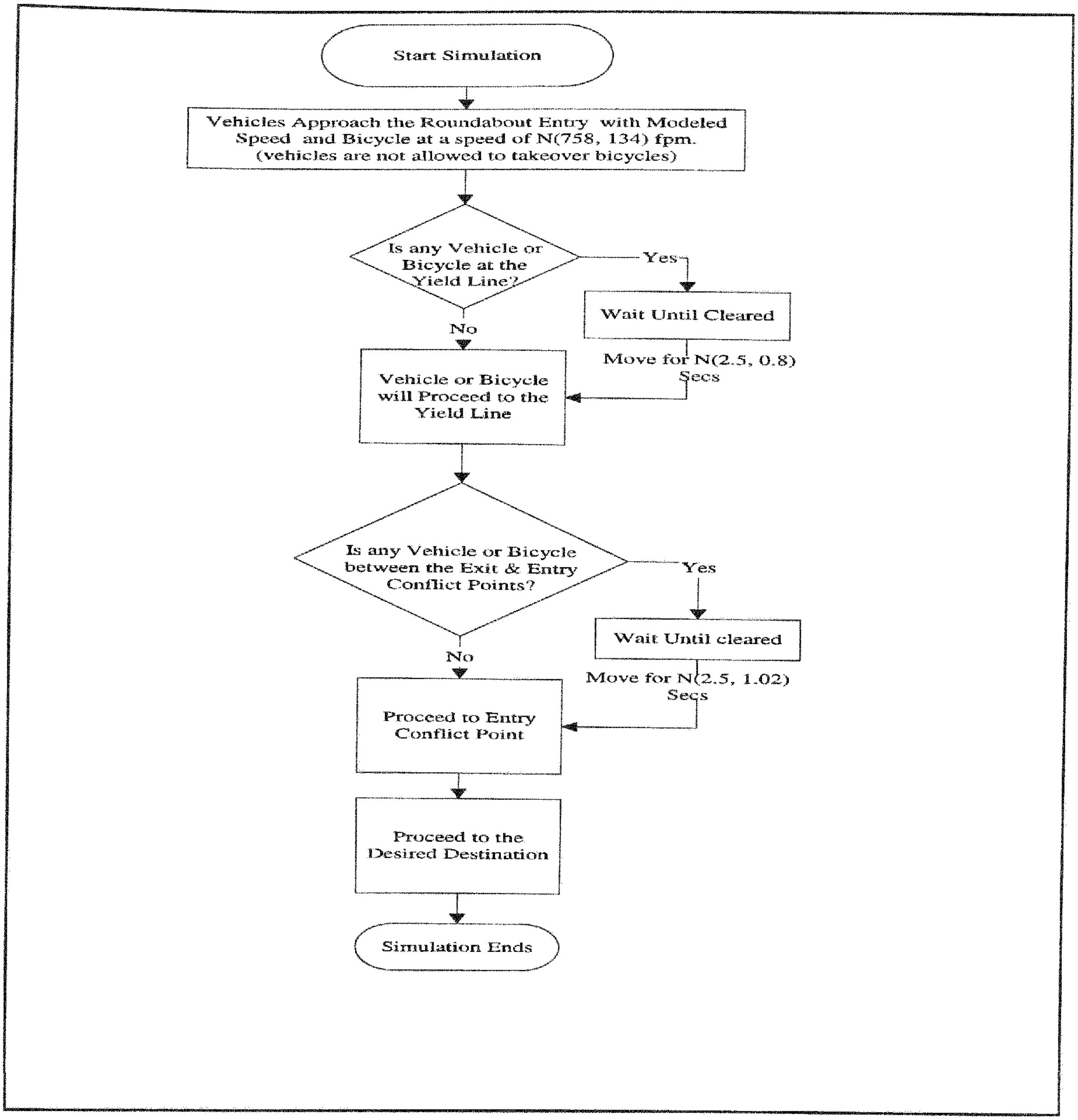


Figure 4.3 - Model 2 Processing Logic.

traffic. If the approaching driver found another vehicle at the yield line, the driver must wait before the pedestrian crossing, until the proceeding vehicles merge with the circulating traffic, then proceed to the yield line (the follow-up time is 2.5 seconds). If the driver finds a suitable gap, the driver can proceed and merge with the circulating traffic without stopping at the yield line, otherwise the driver has to wait for an acceptable gap.

When the driver arrives at the desired exit and observes a pedestrian or bicyclist on the exit side crosswalk, the driver yields. Other pedestrians and bicyclists arriving at the time when vehicles are exiting must yield to the vehicles and wait until there are no exiting vehicles. Vehicles exiting the roundabout can proceed at an average speed of 15 mph until they pass the crosswalk. After the crosswalk, the driver can accelerate until reaching the normal cruising speed of the approach. At the time when the vehicles stop before the exit side crosswalk of the roundabout for pedestrians and/or bicyclists, other exiting vehicles will queue behind the first exiting vehicle. If the queue extends to the circulation lane, other vehicles will proceed with low speed and come to a complete stop. If the queue extends to the previous entry, vehicles entering will stop at the yield line. Vehicles are not allowed to stop on the crosswalks at the entry or exit sides. The processing logic for this model is presented in **Figure 4.4**.

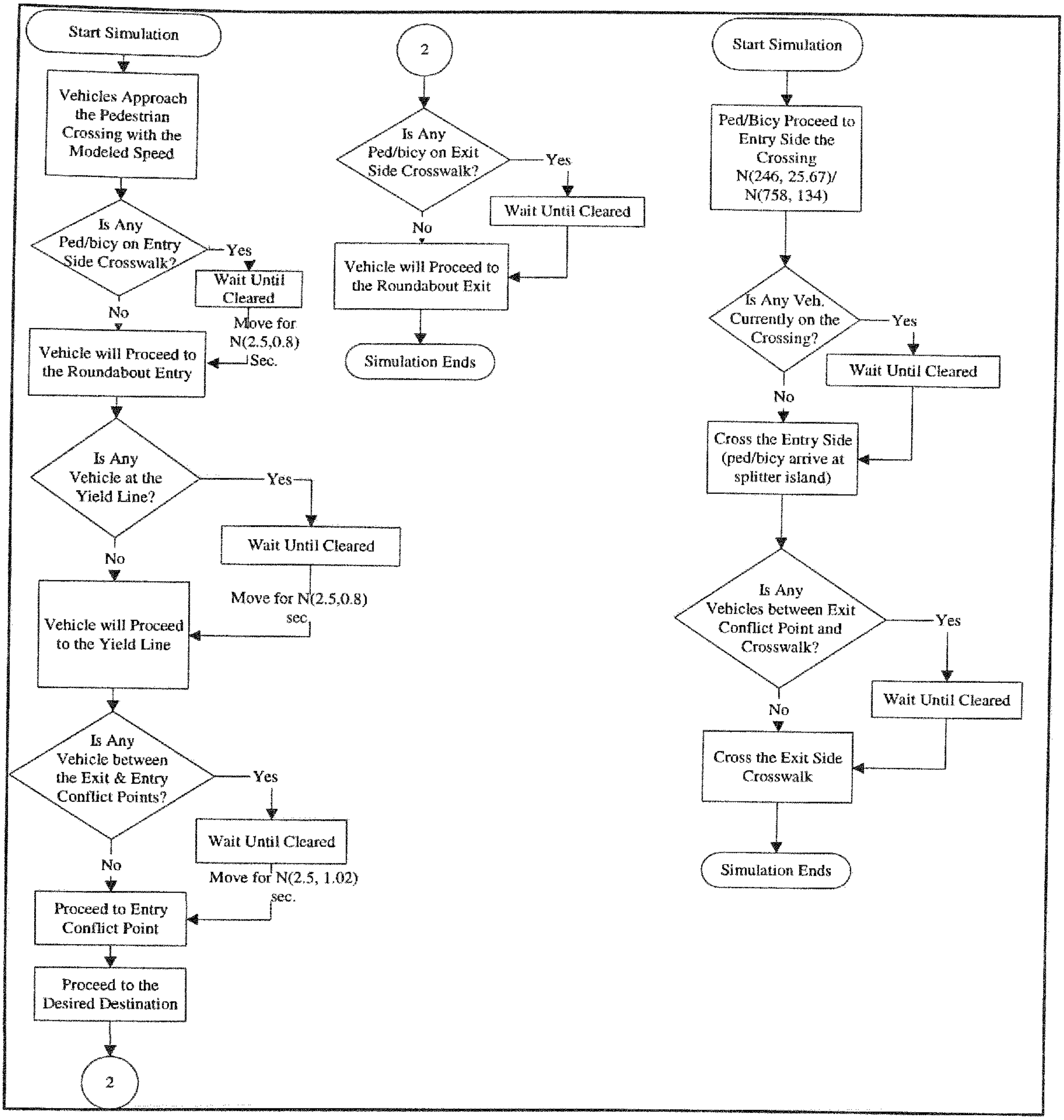


Figure 4.4 - Model 3 Processing Logic

4.3.4 Model 4 - Roundabout with a Bicycle Lane and Pedestrian Crossing

This model simulates single-lane roundabouts with a bicycle lane installed at the outer perimeter of the roundabout and a pedestrian crossing installed on the west approach at a distance of one car length from the yield line. It uses the same operational procedure described for ***Model 3***, but bicycles have the option of using the bicycle lane or the pedestrian crossing. In this model, vehicles entering and exiting the roundabout must yield to cyclists on the circulating bicycle lane.

Vehicles will approach the roundabout at a speed equal to the modeled speed and bicycles at a speed of N(758, 134). At point "e", vehicles are not allowed to take over preceding bicycles. Before the vehicle or the bicycle arrives at point "g", if the driver found no vehicles or bicycles on the bicycle lanes between points "b" and "a", the driver will proceed and merge with the circulating traffic. Otherwise, the driver will stop at point "g" and wait for a suitable gap of at least three seconds before merging with the circulating traffic. If the driver found another vehicle at the yield line, they have to wait until the proceeding vehicle merges with the circulating traffic, then they can proceed to the yield line. If there is a suitable gap, they may proceed and merge with the circulating traffic without stopping, otherwise they must wait for an acceptable gap. When the vehicle reaches the exit conflict point "b," the driver must to make a choice to exit the roundabout or to continue until reaching the destination exit. If the driver finds a bicycle crossing the desired exit, the driver has to yield to the bicycle. If there are no pedestrians on the exit side crosswalk the driver can proceed and exit the roundabout. When the vehicle exits the roundabout at point "d", the driver can overtake a preceding bicycle and accelerate to the normal cruising speed of the approach.

Bicycles approaching a crosswalk are treated as vehicles. The average speed of the bicycles is considered to be N(758, 134). As vehicles exiting the roundabout have to yield to bicycles on the circulating bicycle lane, the delays in the circulating roadway of the roundabout are expected to be high. The processing logic for this model is presented in **Figure 4.5**.

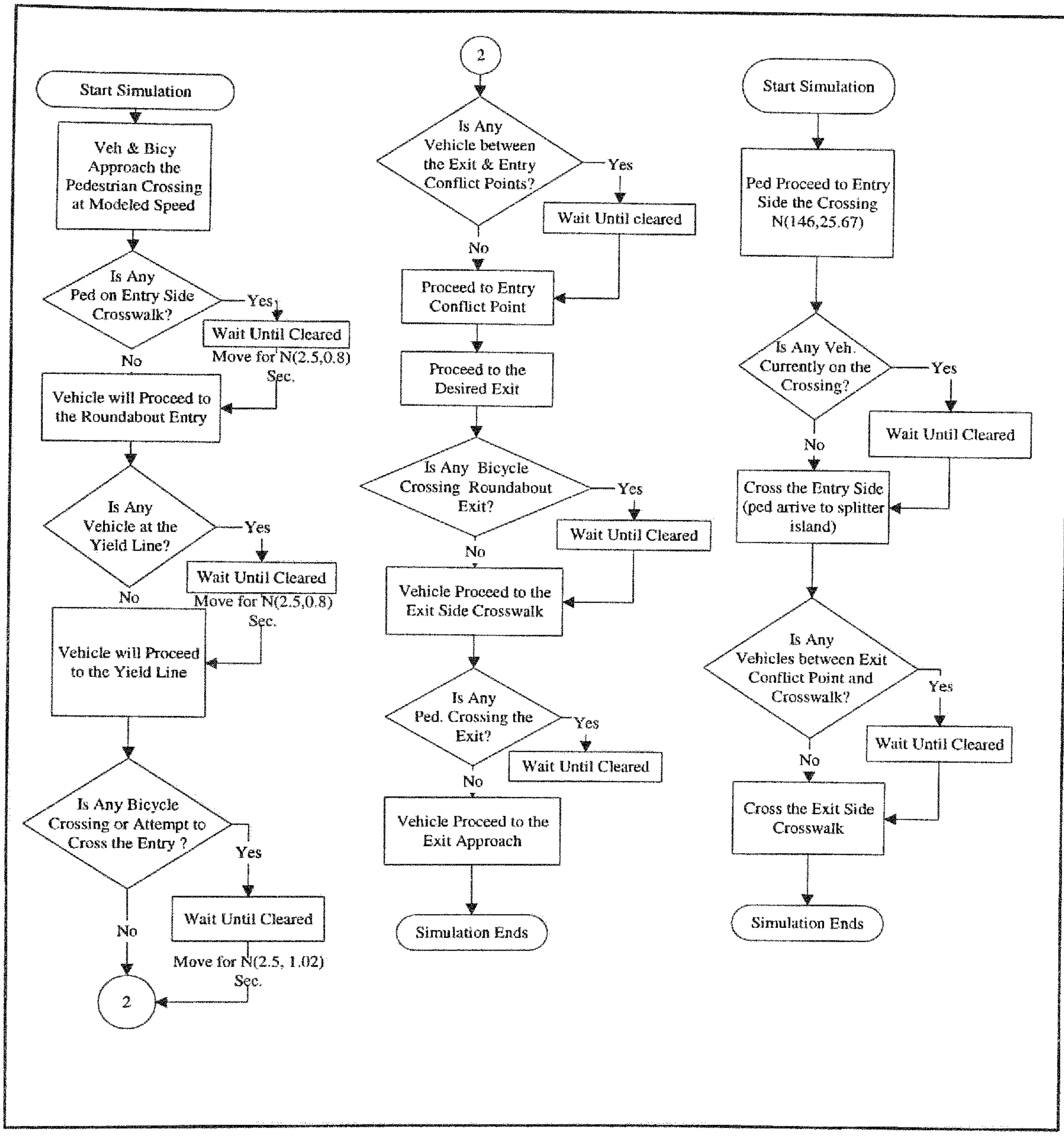


Figure 4.5 - Model 4 Processing Logic

CHAPTER 5

MODEL RESULTS

The collected traffic data at the studied roundabout location, as well as the pedestrian and bicycle data obtained from observations at different traffic circles was essential input in creating the developed models. As it was previously mentioned in **Section 4.3.1**, the Basic Model deals only with vehicular traffic which represents the current situation at the studied roundabout in Boca Raton; the runs of the Basic Model were used to model calibration and validation.

For all the models, the collected vehicle data was incrementally increased by 25 percent until it reached three times the original volume. Also, for all models, it was considered that pedestrians and/or bicycles cross the roundabout at the crossing facility installed on the west approach. In the combined crossing models, it was arbitrary assumed that 120 pedestrians and 120 bicyclists will cross the west approach of the roundabout during the peak period (50 percent from the north to the south and 50 percent from the south to the north). In the bicycle lane and mixed flow models, the pedestrian volumes are the same as the combined crossing, while the bicycle volumes are considered to be a percentage of the traffic volume. In order to study the effect of the high bicycle volume on the performance of the roundabout under different bicycle treatments, the bicycle volume was increased gradually. **Table 5.1** summarizes the vehicle, pedestrian and bicycle volume for each model.

Table 5.1 - Summary of the Modeled Traffic Data

Model	Approach	Vehicles									Bicycles									Ped.
Combined Crossing	North	194	243	291	340	388	437	485	534	582										
	West	528	660	792	924	1056	1188	1320	1452	1584	120									120
	South	75	94	113	131	150	169	188	206	225										
	East	278	348	417	487	556	626	695	765	834										
Bicycle Lanes (Fixed Bicycle)	North	194	243	291	340	388	437	485	534	582	19									
	West	528	660	792	924	1056	1188	1320	1452	1584	53									120
	South	75	94	113	131	150	169	188	206	225	8									
	East	278	348	417	487	556	626	695	765	834	28									
Bicycle Lanes (Variable Bicycle)	North	194									10	19	39	58	78	97				
	West	528									26	53	106	158	211	264				120
	South	75									4	8	15	23	30	38				
	East	278									14	28	56	83	111	139				
Mixed Flow (Fixed Bicycle)	North	194	243	291	340	388	437	485	534	582	19									
	West	528	660	792	924	1056	1188	1320	1452	1584	53									120
	South	75	94	113	131	150	169	188	206	225	8									
	East	278	348	417	487	556	626	695	765	834	28									
Mixed Flow (Variable Bicycle)	North	194									10	19	39	58	78	97				
	West	528									26	53	106	158	211	264				120
	South	75									4	8	15	23	30	38				
	East	278									14	28	56	83	111	139				

The results obtained from the four models are summarized below. The four measured indicators described below are used to compare the performance of a single lane roundabout under different conditions.

- *Maximum Content:* Indicates the maximum number of vehicles in queues under different bicycle and pedestrian considerations and/or different traffic conditions.

- *Percentage Utilization:* Shows the percentage of time that a specific location is occupied under different bicycle and pedestrian considerations and/or different traffic conditions.

- *Average Seconds in System:* Provides the time needed for an entity to negotiate the roundabout.

- *Average Delay:* Indicates the travel time of an entity on the approach until it merges with the circulating traffic in the roundabout.

5.1 Basic Model Versus Combined Crossing

In order to determine the effect of installing a pedestrian crossing on the west approach of the roundabout, a comparison between the basic model (which simulates only vehicle movements at roundabouts) and the combined pedestrian and bicycle model was performed. The results of the comparison are shown in **Table 5.2** and **Figures 5.1, 5.2, 5.3 and 5.4**. Due to the installation the pedestrian crossing on the west approach, the queues on the west approach increased by approximately 60 percent, while the downstream approaches decreased by an average of 2.6 percent and the queues on the upstream approach increase by approximately seven percent. Also, the lane utilization and the travel time of the west approach vehicles increased by 25 percent and 21 percent, respectively. On the other hand, the increase of the same indicators for the other approaches ranges from-0.28 to 0.42, from 2.43 to 3.17, respectively.

It can be concluded that the installation of a pedestrian crossing on an approach will increase the maximum queue length and the average delay of the vehicles using that approach. In the mean time, the vehicles of downstream approach can utilize the gaps created by the pedestrian crossing to merge with the circulating flow, which will result in shorter queues. For example, the south approach vehicles can utilize the gaps created by pedestrians crossing the west approach to merge with the circulating flow. On the other hand, vehicles on the upstream approach might experience longer queues, as some drivers have to yield to pedestrians already crossing the exit side approach. For example, the north approach vehicles making right turns must yield to pedestrians crossing the exit side of the west approach. This resulted in increasing the north approach queue length by approximately seven percent, and one percent increase in the average delays.

In many cases, if the downstream traffic is low, the approach further down can benefit from the created gaps caused by the pedestrian crossing. In our case, as the south approach volume was very low, the east approach utilized the created gaps caused by pedestrians crossing the entry of the west approach, which resulted in shorter queues. Also, the installation of the pedestrian crossing will have impact on the average vehicle delays and the average time needed by the drivers to negotiate the roundabout.

Table 5.2 - Basic Model Versus Combined Pedestrians and Bicycles Crossing Model

Maximum Contents (vehicles)			
Location	**Basic**	**Combined Crossing**	**% Change**
North App.	2.89	3.09	*6.92%*
West App.	5.07	8.13	*60.36%*
South App.	2.07	2.01	*-2.90%*
East App.	3.56	3.48	*-2.25%*
Lane Utilization (%)			
Location	**Basic**	**Combined Crossing**	**% Change**
North App.	13.66	13.67	*0.07%*
West App.	39.88	49.99	*25.35%*
South App.	4.71	4.73	*0.42%*
East App	21.80	21.74	*-0.28%*
Average Seconds in System (seconds)			
Entity Name	**Basic**	**Combined Crossing**	**% Change**
North	16.47	16.87	*2.43%*
West	20.34	24.70	*21.44%*
South	14.60	15.01	*2.81%*
East	15.45	15.94	*3.17%*
Average Delays (seconds)			
Approach	**Basic**	**Combined Crossing**	**% Change**
North	1.41	1.42	*0.71%*
West	1.87	1.89	*1.07%*
South	2.36	2.44	*3.39%*
East	2.14	2.14	*0.00%*

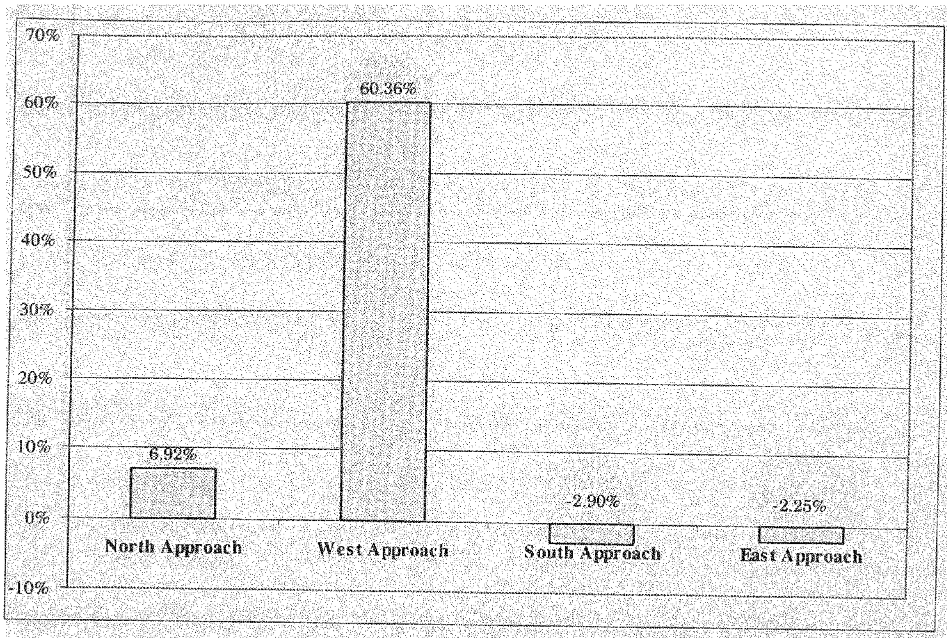


Figure 5.1 - Changes in Queue Length Due to the Installation of a Pedestrian Crossing on the West Approach of the Roundabout

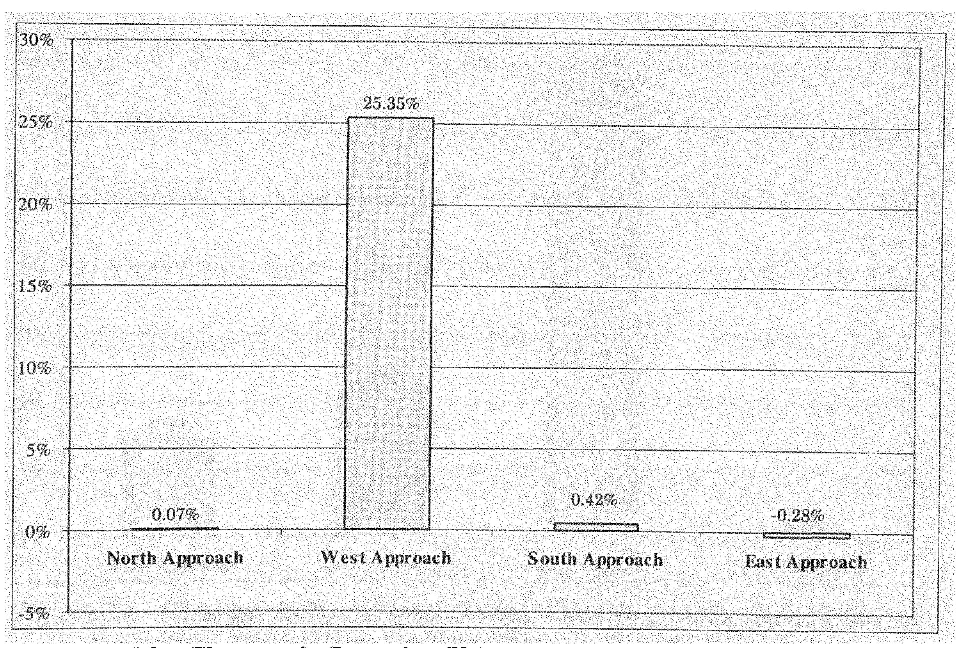


Figure 5.2 - Changes in Location Utilization Due to the Installation of a Pedestrian Crossing on the West Approach of the Roundabout

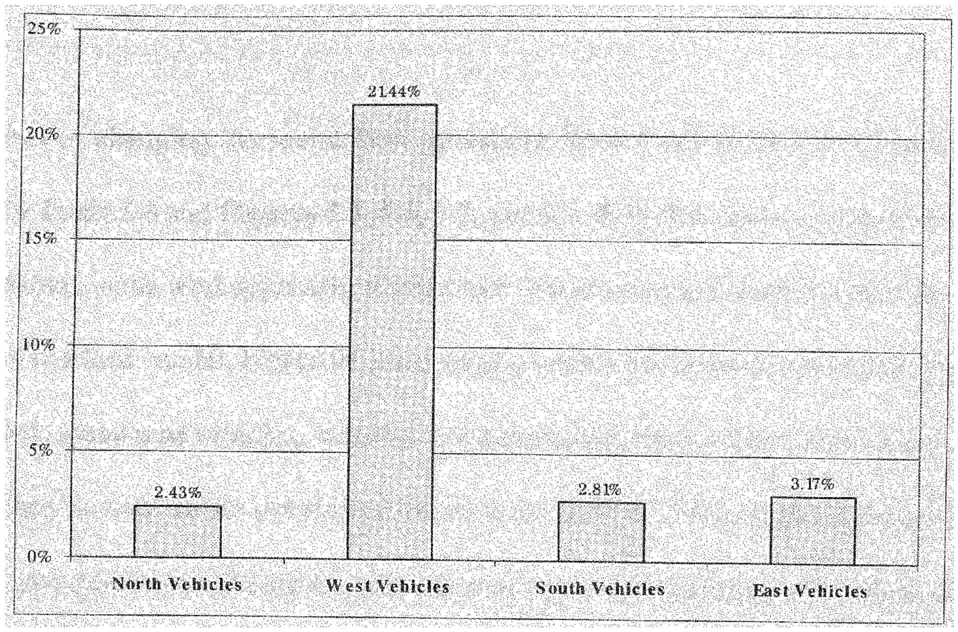


Figure 5.3 - Changes in the Average Time Needed by Approaching Vehicles to Negotiate the Roundabout Due to the Installation of a Pedestrian Crossing on the West Approach of the Roundabout

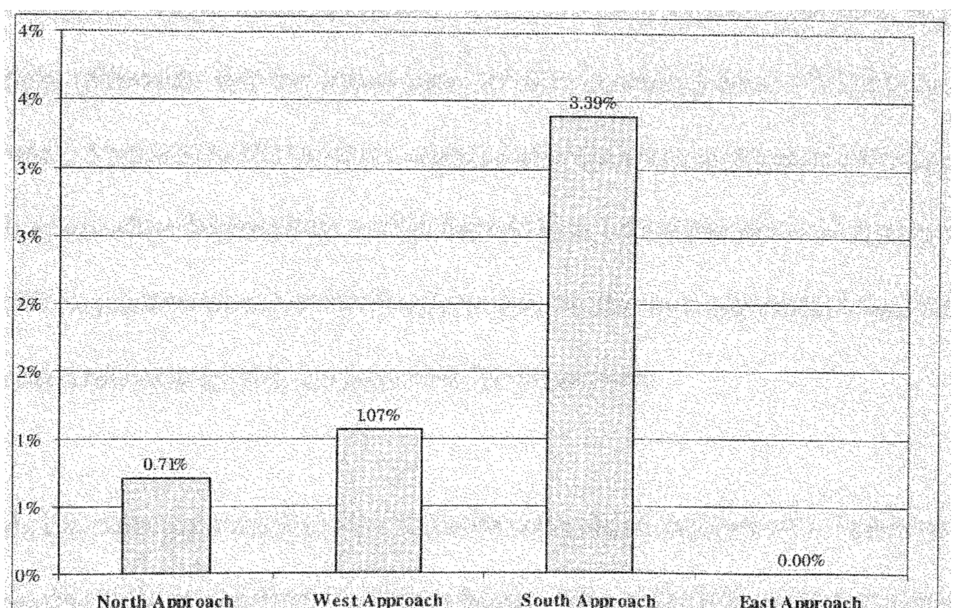


Figure 5.4 - Changes in the Average Delay Time Due to the Installation of a Pedestrian Crossing on the West Approach of the Roundabout

5.2 Mixed Flow Versus Bicycle Lane

The effect of changing the roundabout operations from a mixed flow to a bicycle lane is shown in **Table 5.3** and **Figures 5.5, 5.6, 5.7,** and **5.8**. In both models, a pedestrian crossing was installed on the west approach, at a distance of one car length from the yield line. While in the mixed flow model, bicyclists from all approaches are allowed to use the roundabout in the same manner as vehicles, in the bicycle lane model, bicycle lanes were installed on all approaches, as well as the circulating roadway for the use of bicyclists. Moreover, in the bicycle lane model, circulating bicyclists have priority over entering and exiting vehicles.

The simulation results, shown in Table 5.3, indicated that the installation of a bicycle lane reduces the queue length on all approaches from 1.15 percent to 14.0 percent. In addition, the location utilization and the travel time are also improved from 17.3 percent to 29.0 percent and 1.5 percent to 10.8 percent, respectively. On the other hand, the average vehicle delays increase, after the installation of the bicycle lane, by 6.0 percent to 17.0 percent. Also, the simulation results showed that pedestrians crossing the west approach of the roundabout experienced reduction in their crossing time by 9.4 percent.

Although, the west approach bicycles' experienced a slight increase of 1.7 percent of their travel time due to the installation of the bicycle lane, other approaching bicycles experienced a decrease in their travel time that ranges from 4.7 percent to 9.8 percent.

Table 5.3 - Mixed Flow Model Vs. Bicycle Lane Model

Maximum Contents (Vehicles)			
Location	**Mixed Flow**	**Bicycle Lane**	**% Change**
North App.	2.99	2.67	-10.70%
West App.	8.1	6.97	-13.95%
South App.	2.09	1.96	-6.22%
East App.	3.51	3.47	-1.14%
South/North Ped	2.12	2.1	-0.94%
North/South Ped	1.97	2.12	7.61%
Location Utilization (%)			
Location	**Mixed Flow**	**Bicycle Lane**	**% Change**
North App.	13.94	10.64	-23.67%
West App.	46.65	38.56	-17.34%
South App	4.96	3.52	-29.03%
East App	20.32	21.34	5.02%
South/North Ped	4.27	4.27	0.00%
North/South Ped	1.57	1.23	-21.66%
SPLITTER ISLAND	5.85	5.63	-3.76%
Average Time in System (seconds)			
Entity	**Mixed Flow**	**Bicycle Lane**	**% Change**
Vehicle N	17.59	16.08	-8.58%
Vehicle W	24.36	21.72	-10.84%
Vehicle S	15.63	14.55	-6.91%
Vehicle E	16.12	15.88	-1.49%
South/North Ped	24.04	21.76	-9.48%
North/South Ped	24.03	21.78	-9.36%
Bike N	32.76	35.97	9.80%
Bike W	37.31	36.67	-1.72%
Bike S	27.53	29.24	6.21%
Bike E	28.91	30.29	4.77%
Average Delays (seconds)			
Approach	**Mixed Flow**	**Bicycle Lane**	**% Change**
North Delay	1.35	1.58	17.04%
West Delay	1.81	1.92	6.08%
South Delay	2.35	2.58	9.79%
East Delay	1.98	2.19	10.61%

It can be concluded that the installation of a bicycle lane at the outer perimeter of the roundabout will help in reducing the queue length, location utilization and the average time needed for most of the users to negotiate the roundabout. This may be due to the fact that in the bicycle lane model, the bicycle speed is not the governing speed, but vehicles can maintain an average speed of 15 mph.

The only impact of installing a bicycle lane is on the average delays at the entries of the roundabout where entering vehicles must yield to both circulating vehicles and bicyclists. Also, pedestrians crossing the exit side of the west approach have to yield for exiting vehicles and bicyclists.

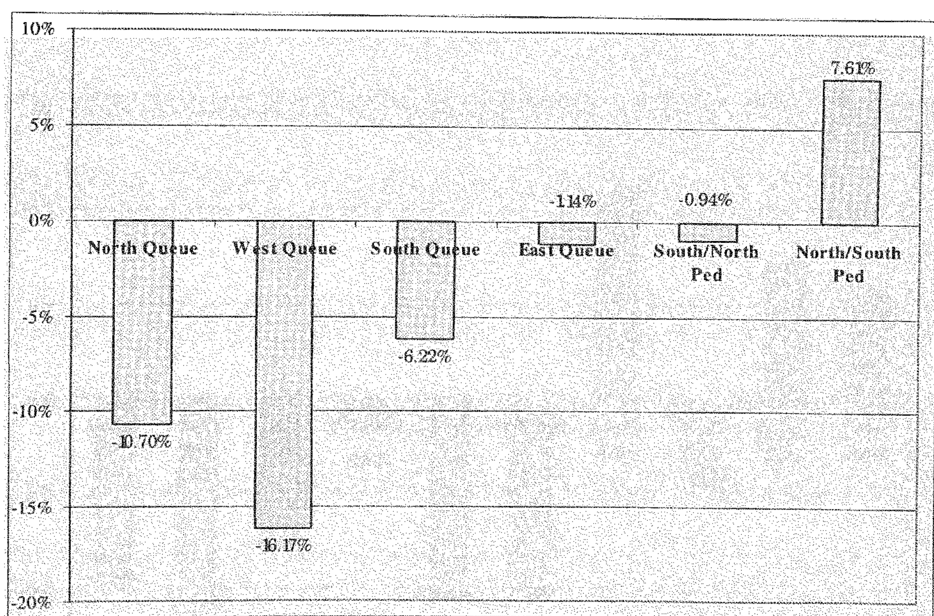


Figure 5.5 - Changes in Queue Length When Using a Bicycle Lane Instead of Mixed Flow

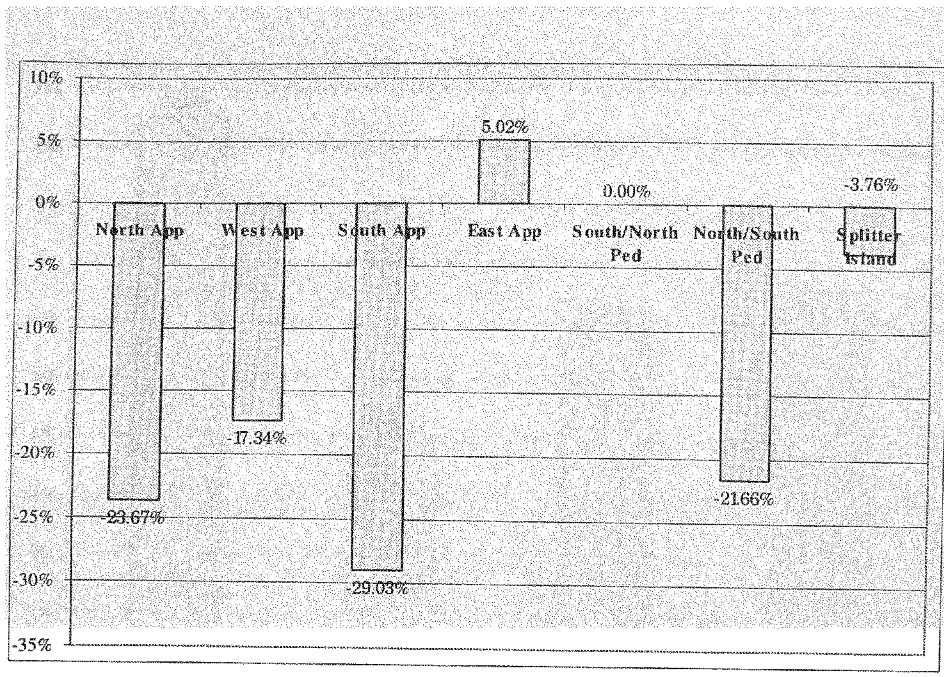


Figure 5.6 - Change in Location Utilization When Using a Bicycle Lane Instead of Mixed Flow

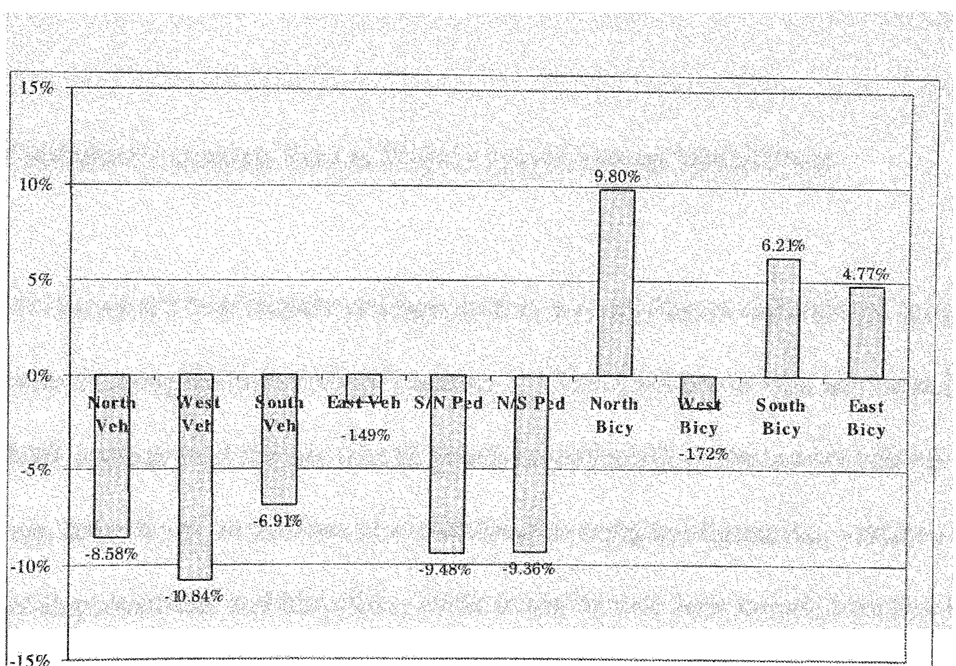


Figure 5.7 - Changes in Time Needed to Negotiate the Roundabout When Using a Bicycle Lane Instead of Mixed Flow

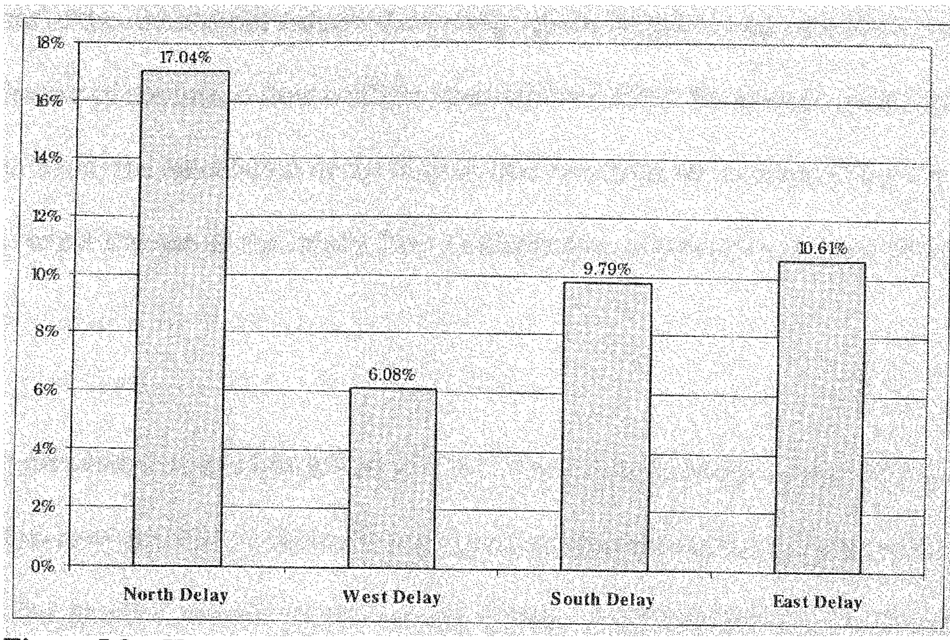


Figure 5.8 - Changes in the Average Delay Time When Using a Bicycle Lane Instead of Mixed Flow

5.3 Combined Crossing Versus Bicycle Lanes Versus Mixed Flow

In order to choose the best bicycle configuration at a single-lane roundabout, a comparison was performed among the three bicycle treatments. The simulation results, shown in **Figures 5.9** and **5.10**, indicate that the use of a bicycle lane will result in the lowest vehicle queues and average delay time. In the case of a combined crossing configuration, vehicles have to yield to both pedestrians and bicyclists, while in the bicycle lane model, vehicles have to yield to pedestrians only. Also, in the case of the mixed flow configuration, vehicles have to yield to pedestrians only.

The results of the simulation show that the installation of the bicycle lane at the outer perimeter of the roundabout reduces the average queue length by approximately 11 percent, while the use of the mixed flow configuration will not affect the average queue length. On the other hand, the installation of the bicycle lane increases the average delay time by five percent, while the use of the mixed flow configuration reduces the average delay by five percent.

It can be concluded from **Figure 5.10** that the lowest vehicle delays occur when having the mixed flow configuration, followed by combined crossing and the bicycle lane configuration, causing the greatest impact on the vehicle delays. Although the use of a bicycle lane configuration at a single-lane roundabout will not greatly benefit the average vehicle delays, it may be safer for bicyclists than the mixed flow configuration. The choice of the using any of the three bicycle configurations has to be based on a trade between safety and average delays.

Moreover, the introduction of bicycle lanes at the roundabout will greatly benefit the pedestrians that are crossing the entries of the roundabout. Since approaching vehicles have to yield for both circulating vehicles and bicycles, pedestrians will have time to cross the approach while entering vehicles are waiting for acceptable gaps. In the meantime, the mixed flow configuration will result in increasing the overall pedestrian crossing time.

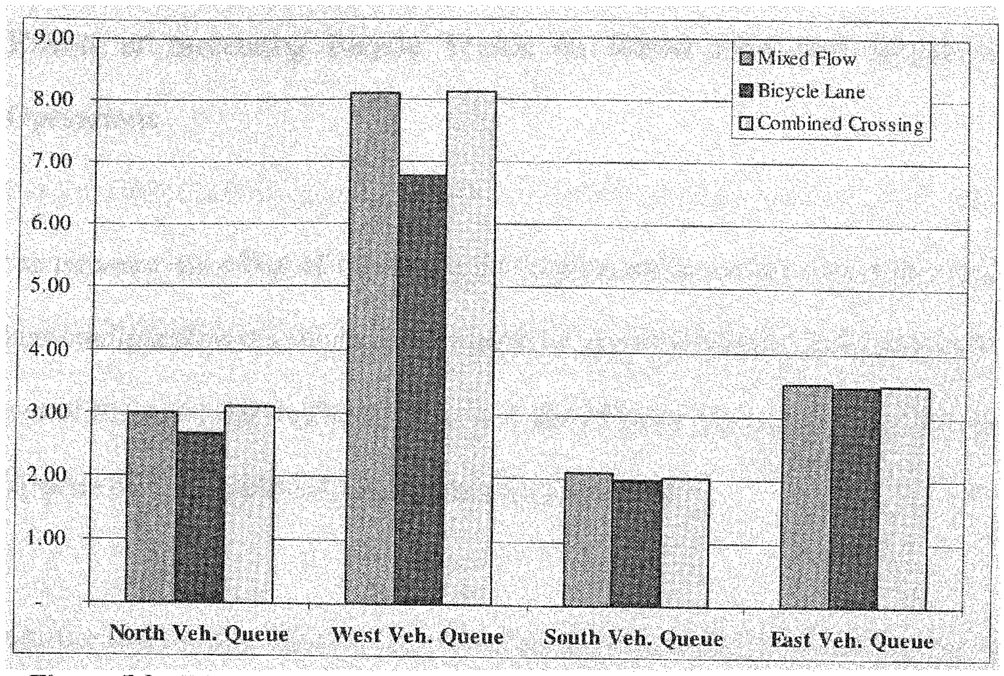


Figure 5.9 - Effect of Different Bicycle Considerations on the Vehicle Queue Length

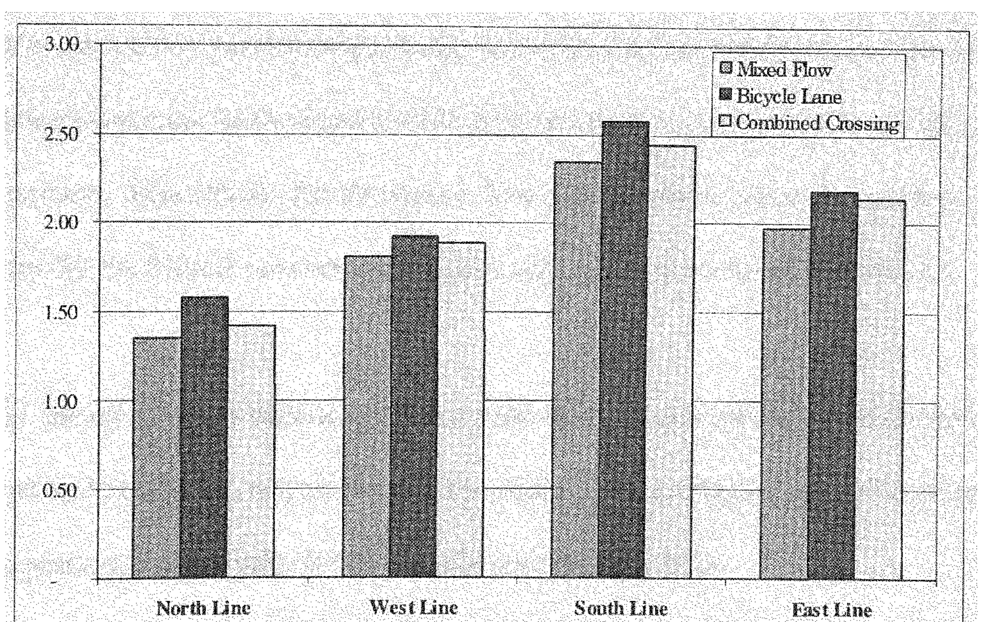


Figure 5.10 - Effect of Different Bicycle Considerations on the Average Delay Time

5.4 Effects of Increasing Bicycle Traffic on Mixed Flow and Bicycle Lane Operations

In order to measure the effect of increasing the bicycle traffic on the mixed flow and the bicycle lane configuration at a single-lane roundabout, the bicycle traffic was increased from ten percent of the vehicular traffic to 20 percent and 30 percent, respectively. The model results are presented in **Table 5.4** and **Figures 5.11** and **5.12**.

The simulation results show that by increasing the bicycle traffic from ten percent to 20 percent then to 30 percent of the vehicle traffic volume, vehicular travel time tends to increase by seven percent and 14 percent, respectively, for the mixed flow configuration, and by one percent and two percent, respectively for the bicycle lane configuration. On the other hand, the same increase in the bicycle traffic increases the bicycle travel times by 23 percent and 25 percent, respectively, for the mixed flow configuration, while the increase of the travel time for the bicycle lane configuration is only one percent for both increases.

Similarly, the effect of the bicycle traffic increase tends to increase the vehicular delays by 14 percent and 28 percent, respectively for the mixed flow configuration, and eight percent and nine percent, respectively, for the bicycle lane configuration.

It can be concluded that with the increase of the bicycle traffic, the average vehicle delays and the average time needed by all users will increase. In the meantime, the bicycle lane configuration will have less impact on the average vehicle delays and the average time needed for all entities to negotiate the roundabout than the mixed flow configuration.

Table 5.4 - Effect of Increasing the Bicycle Traffic on Mixed Flow Model and Bicycles Lane Operations

Average Seconds in System									
Entity	10%			20%			30%		
	Mixed Flow	Bicycle Lanes	% Change	Mixed Flow	Bicycle Lanes	% Change	Mixed Flow	Bicycle Lanes	% Change
North App. Veh.	18.10	16.04	*-11.38%*	19.19	16.23	*-15.42%*	20.25	16.33	*-19.36%*
West App. Veh.	25.34	21.72	*-14.29%*	27.58	21.98	*-20.30%*	30.24	22.07	*-27.02%*
South App. Veh.	16.03	14.63	*-8.73%*	16.92	14.93	*-11.76%*	17.86	15.30	*-14.33%*
East App. Veh.	16.53	15.92	*-3.69%*	17.38	16.07	*-7.54%*	18.09	16.17	*-10.61%*
North App. Bicy.	32.98	35.49	*7.61%*	24.56	35.84	*45.93%*	24.72	35.53	*43.73%*
West App. Bicy	37.64	36.73	*-2.42%*	24.46	36.95	*51.06%*	24.69	37.07	*50.14%*
South App. Bicy.	27.51	29.69	*7.92%*	33.32	30.05	*-9.81%*	33.50	30.13	*-10.06%*
East App. Bicy.	29.26	30.33	*3.66%*	38.89	30.62	*-21.27%*	40.67	30.47	*-25.08%*
Ped. SN	24.14	21.81	*-9.65%*	28.19	21.84	*-22.53%*	28.60	21.80	*-23.78%*
Ped. NS	24.77	21.81	*-11.95%*	29.68	21.78	*-26.62%*	29.85	21.80	*-26.97%*
Average Delay Value									
Approach	10%			20%			30%		
	Mixed Flow	Bicycle Lanes	% Change	Mixed Flow	Bicycle Lanes	% Change	Mixed Flow	Bicycle Lanes	% Change
North	1.45	1.58	*8.97%*	1.70	1.62	*-4.71%*	1.88	1.65	*-12.23%*
West	1.90	1.94	*2.11%*	2.09	1.99	*-4.78%*	2.25	2.03	*-9.78%*
South	2.58	2.68	*3.88%*	3.04	2.94	*-3.29%*	3.54	3.13	*-11.58%*
East	2.14	2.22	*3.74%*	2.41	2.63	*9.13%*	2.63	2.32	*-11.79%*

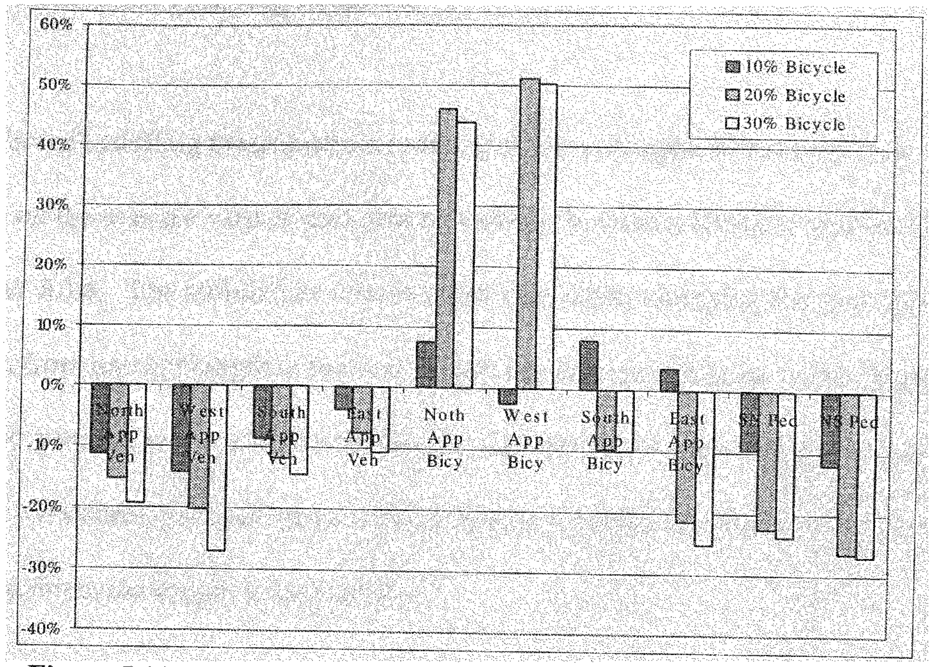


Figure 5.11 - Effect of Increasing Bicycle Traffic on the Average Time Needed to Negotiate the Roundabout When Using a Bicycle Lane Instead of Mixed Flow

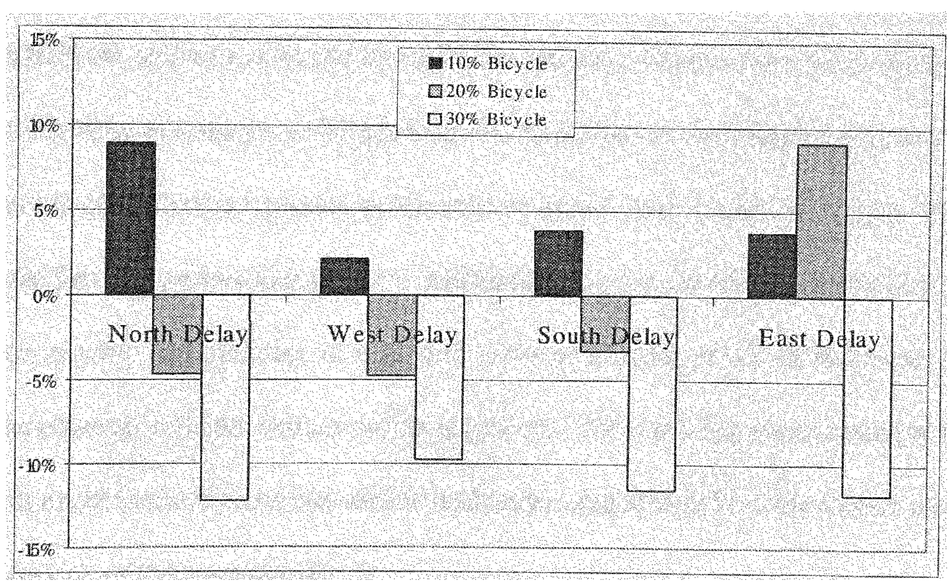


Figure 5.12 - Effect of Increasing Bicycle Traffic on The Average Vehicle Delays When Using a Bicycle Lane Instead of Mixed Flow

5.5 Pedestrian Crossing Location

The effect of installing the pedestrian crossing on the west approach at one-, two- or three-car lengths on the average vehicle and pedestrian/bicycle queues length is presented in **Figures 5.13** and **5.14**. The simulation results show that when changing the pedestrian crossing location from one-car length to two-car length, the average vehicular queue length decreases by seven percent, while at three-car length, the vehicular queue length decreases by eight percent. Similarly, the average pedestrian queues increase by 18 percent and ten percent at two- and three-car length, respectively.

The analysis shows that the effect of the pedestrian crossing diminishes as the distance between the crossing and the roundabout increases. In addition, installing the pedestrian crossing at two-car length from the yield line of the roundabout resulted in longer pedestrian queues on both the splitter island and the exit side crossing. On the other hand, installing the pedestrian crossing at a three-car length from the yield line of the roundabout resulted in a slight increase of pedestrian queues on the splitter island, than at one-car length. This may be due to the fact that pedestrians observe vehicles exiting the roundabout at the exit conflict point when placing the crossing at one- and two-car lengths, while at three-car lengths, pedestrians observe vehicles already on the approach. Thus, placing the crossing at two-car lengths will result in more pedestrian delays and longer queue lengths at the splitter island and crossing the exit of the roundabout.

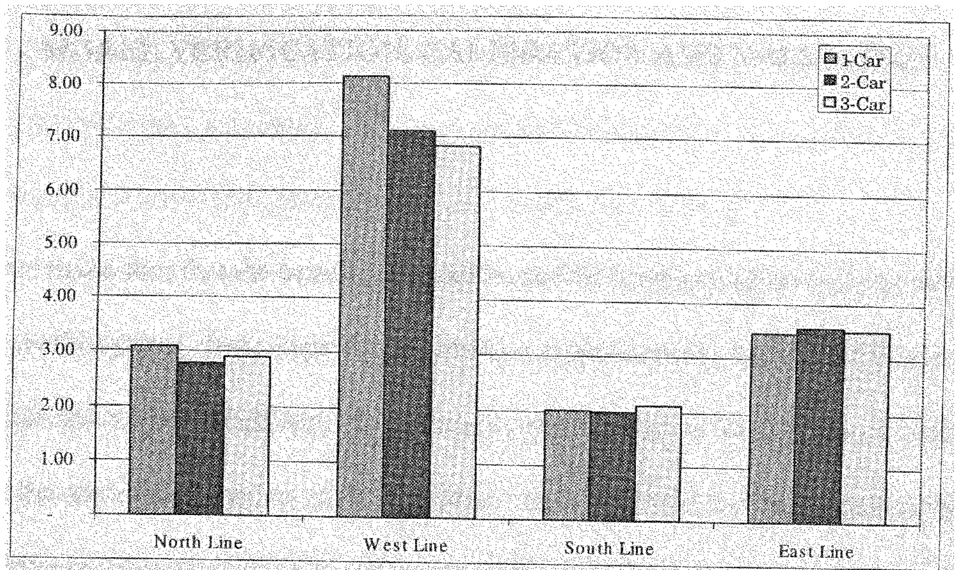


Figure 5.13 - Effect of Changing the Pedestrian Crossing Location on the Vehicles Queue Length

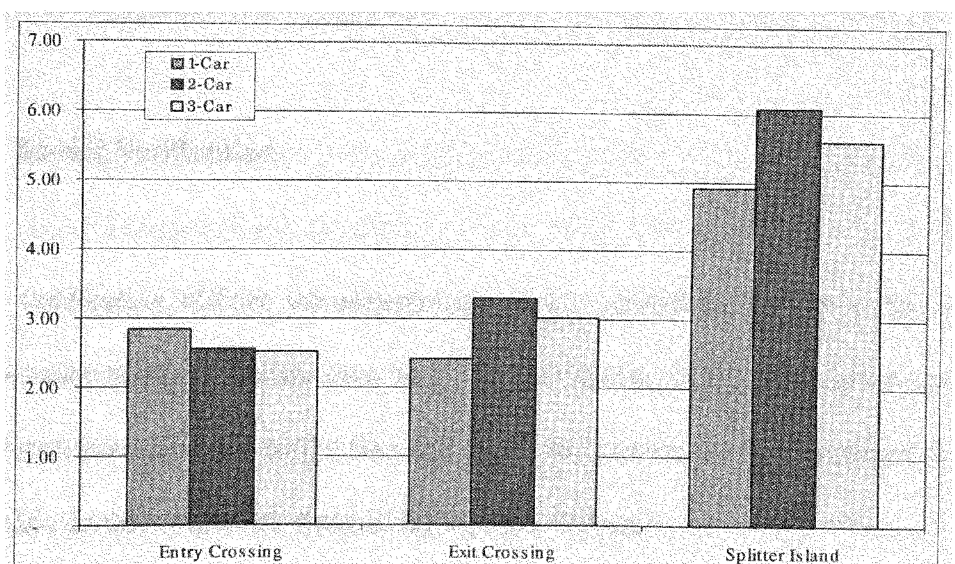


Figure 5.14 - Effect of Changing the Pedestrian Crossing Location on the Pedestrian and Bicycle Queues

CHAPTER 6

MODEL VERIFICATION, CALIBRATION AND VALIDATION

In order to make sure that the developed models are free from any errors and correctly reflect the real-world system, three steps were taken into consideration: model verification, model calibration and model validation. While model verification is the process of determining whether the simulation models correctly reflect the conceptual model, model calibration is the iterative process of comparing the model to the real world system, making adjustments to the model, comparing the revised model reality, making additional adjustment, and so on. On the other hand, model validation is the process of determining whether the conceptual models correctly reflect the real system.

6.1 Model Verification

Model verification utilizes the comparison of the conceptual model to the computer representation that implements that conception. During the verification process, unintended errors were detected in the model data and logic. In essence, it is the process of debugging the model. In this stage, two types of errors were detected:

Syntax Errors - are like grammatical errors and include the unintentional addition, omission, or replacement of notation that either prevent the model from running or cause it to run incorrectly.

Semantic Errors - are errors associated with the meaning of intention of modeling and are harder to detect. Often, these are logical errors that cause the models to behave in a different manner than was originally intended.

In order to verify the developed models, the following preventive measures were taken into consideration during the development phase of the models:

Modularity - each model was built in modules or logical divisions to simplify the model development and debugging.

Compact Modules - modules were kept as short and simple as possible.

Step Refinement - during the developmental phase, the configuration of the models became progressively complexity. It was found that it is easier to verify the models when the model is built incrementally, than when it is built all at once.

Structural Control - GOTO statements and other unstructured branching of control were avoided whenever possible, as they may lead to unexpected results. For example IF - THEN - ELSE, WHILE....DO, DO....WHILE, etc.

In addition, several verification techniques were used to ensure that the models were built correctly:

- Code reviews were conducted continuously to check for errors and inconsistencies. Also, models were tested in both top-down and bottom-up fashions.
- Model animations were observed for correct behaviors of the models. Several counters were placed to record the number of vehicles at each segment of the roundabout in order to make sure that the vehicle distribution is similar to the real system. Also, the animation component was analyzed in order to identify problems, instead of just simply discovering the cause of the problems.
- The built-in trace and debug options were used to provide textual feedback of what takes place during simulation. This offers an in-depth view, as well as help to follow and understand what takes place during the simulation process.

6.2 Model Calibration

Several visits were made to the studied roundabout site for a precise model calibration. Critical gaps and the drivers' follow-up times were measured again to ensure that the predicted queue lengths and delays on each approach were accurate.

6.3 Model Validation

While verification is concerned with building the model correctly, validation is concerned with building the correct model. In order to draw conclusions about the accuracy of the model, which was based on existing data, several techniques were used:

Watching Animation - The visual animation of the operational behavior of the model was compared to the real system by placing several counters on each approach. The counters recorded the number of entering and exiting vehicles, the queue length and the waiting time on each approach and provided visual feedback.

Comparing with Actual System - Both the basic model and the real model were compared using the same traffic conditions. Queue lengths for both systems were the same.

Performing Sensitivity Analysis - This technique consists of changing model input values to determine the effect of model behavior on the simulation output. The PM traffic data was used to run the basic model, then the simulation output was compared with the field observations. The results of running the basic model using PM traffic data are shown in **Tables 6.1**. The results show that as traffic volume increases, the queue length and the average delay time increases. In addition, by comparing field observations during the PM peak hour and the simulation output, it was found that the maximum queue length is five vehicles for the east approach of the roundabout, while the simulation results show 5.19 vehicles. It is also concluded from **Table 6.2** that the volume and queue length of the same approach are directly proportional. Moreover, the delay is proportional to the volume of the upstream approach. If the volume of the upstream approach increases, drivers will experience more delays, as there will be shorter gaps between circulating vehicles.

Table 6.1 - Sensitivity Analysis for the Basic Model Using PM Traffic Data

Approach	1st 15 min			2nd 15 min			3rd 15 min			4th 15 min		
	V	L	D	V	L	D	V	L	D	V	L	D
North	77	2.83	1.49	70	2.73	1.53	86	2.92	1.51	58	2.52	1.47
West	97	3.65	1.86	118	4.01	1.88	120	4.16	1.91	107	3.70	1.83
South	17	1.52	1.80	8	1.1	1.87	13	1.33	1.99	16	1.95	1.79
East	146	4.17	1.56	171	4.51	1.59	145	4.21	1.60	135	4.07	1.58

V = entry volume (veh), L = maximum queue length (veh) and D = average delay (sec)

Table 6.2 - Percent Change in Roundabout Performance Measures Using PM Traffic Data

Approach	1st - 2nd 15 min			2nd - 3rd 15 min			3rd - 4th 15 min		
	V	L	D	V	L	D	V	L	D
North	-9%	-4%	3%	23%	7%	-1%	-33%	-14%	-3%
West	22%	10%	1%	2%	4%	2%	-11%	-11%	-4%
South	-53%	-28%	4%	63%	21%	6%	23%	47%	-10%
East	17%	8%	2%	-15%	-7%	1%	-7%	-3%	-1%

CHAPTER 7

CONCLUSIONS AND RECOMMENDATION

7.1 Introduction

The research, embodied in this dissertation, reviews and expands the methods currently available for the analysis of roundabouts. The research effort identifies the main limitation of these methods in determining the effect of various bicycle and pedestrian treatments at roundabouts. Also, this research extends the applicability of these models by developing new models. This dissertation presents a new paradigm for modeling different bicycle and pedestrian treatment at single-lane roundabouts. The effect of each treatment was identified, and several comparisons were made to evaluate these alternatives under varying traffic conditions. Finally, the research expands the application of analytical procedures by developing an analytical approach for estimating the queue length and vehicle delays. In doing so, an extensive data collection was performed at a selected roundabout site in Boca Raton, Florida, to run the developed simulation models. Moreover, driver, pedestrian and bicyclist behaviors were also studied and modeled in order to represent a real world situation.

The analysis included in this research provide extensive and valuable information that is of particular interest to the operational performance of roundabouts. Finally, the research efforts demonstrate the need for a simulation approach in order to evaluate bicycle and pedestrian treatment at single-lane roundabouts that are beyond the scope of the current state-of-the-art existing analytical approaches.

7.2 Summary of this Research

In the following sections, brief statements are listed, which describe the highlights and contributions in this research.

- In **Chapter 2**, an extensive review of various roundabout design guides was presented. The studies design guides provide recommendations about the safest location of pedestrian crossings at roundabouts. Moreover, special provisions for bicyclists are not normally required at roundabouts. Several guidelines recommend provisions for a special bicycle facility in case of high bicycle volume at the roundabout, and, if space permits. Others recommended that bicycles using the roundabouts should have the same priority as vehicles.

- Roundabout models are numerous and new ones are being developed, while the existing models are upgraded frequently. Each model may have particular strengths and weaknesses. The majority of the models deal only with the vehicular flow at roundabouts. Although few of the existing models can determine the effect on pedestrians or bicycles on the capacity of roundabouts, they cannot model the different pedestrian and bicycle treatments.

- In addition, existing roundabout analysis packages can provide estimates of capacity and performance characteristics such as delay, queue lengths, stop rates, effects of heavy vehicles, accident frequency, and geometric delays, as well as fuel consumption, pollutant emissions and operating costs for roundabouts. These packages are not capable of determining the effect of various pedestrian crossing locations or the effect of various bicycle treatments on the performance of roundabouts.

- Thus, there is a need to develop new simulation models that are capable of determining the effect of various pedestrian and bicycle considerations at single-lane roundabouts. With the rapid growth of computer speed, the use of microscopic simulation tolls is gradually becoming the current state-of-the-practice. The developed models, presented in **Chapter 4,** have proven to be capable of determining the effects of various bicycle and pedestrian considerations at single-lane roundabouts. The performance measures presented include average delay time, queue length and overall service time.

- The simulation results, presented in **Chapter 5**, provide a new understanding of the roundabout operations under various bicycle and pedestrian configurations. In this chapter, attempts were made to determine the impact of bicycle and pedestrian provisions at a single-lane roundabout on the vehicle queues and delays.

- **Chapter 6** demonstrates different preventive measures taken during the development of the simulation models to ensure that the models represent a real system. Model validation was also performed by conducting a sensitivity analysis using the PM traffic data set, which was collected at the same studied roundabout.

7.3 Conclusions

The main conclusions in this research effort can be summarized as follows:

- The installation of a pedestrian crossing on an approach will increase the maximum queue length and the average delay of that approach. In the meantime, the vehicles of downstream approach can utilize the gaps created by the pedestrian crossing to merge with the circulating flow, which will result in shorter queues. On the other hand, vehicles on the upstream approach might experience longer queues, as some drivers will have to yield to pedestrians that are already crossing the exit side approach.

- The installation of a bicycle lane at the outer perimeter of the roundabout will help in the reduction of the queue length, location utilization and the average time needed for most of the users in order to negotiate the roundabout when compared to a mixed flow configuration.

- The only impact of installing a bicycle lane is on the average delays at the entries of the roundabout, where entering vehicles must to yield to both circulating vehicles and bicyclists.

- The lowest vehicle delays occur starting with the mixed flow configuration, followed by combined crossing and the bicycle lane configuration, which have the greatest impact on the vehicle delays.

- The choice of using any of the three bicycle configurations has to be based on a trade between safety and average delays.

- The introduction of bicycle lanes at the roundabout will greatly benefit the pedestrians that are crossing the entries of the roundabout. Since approaching vehicles have to yield for both circulating vehicles and bicycles, pedestrians will have time to cross the approach while entering vehicles are waiting for acceptable gaps. In the meantime, mixed flow configuration will result in increasing the overall pedestrian crossing time.

- The increase of the bicycle traffic, the average vehicle delays and the average time needed by all users will increase. In the meantime, the bicycle lane configuration will have less impact on the average vehicle delays and the average time needed for all entities to negotiate the roundabout, than the mixed flow configuration.

- The effect of the pedestrian crossing diminishes as the distance between the crossing and the roundabout increases.

- Placing the crossing at two-car lengths will result in more pedestrian delays and longer queue lengths at the splitter island, as well as crossing the exit of the roundabout.

7.4 Future Work

There is a dearth of modern roundabouts in South Florida; as a result, several observations were made at traffic circles. The shortcomings of this research are:

1- A single-point data source.

2- Traffic circles data for bicycles and pedestrians were in roundabout modeling.

3- Modeling only single-lane roundabouts.

4- The developed models considered only constant gaps.

Thus, to better understanding the effect of different bicycle and pedestrian treatment at roundabouts, it is necessary to collect data at roundabouts with real bicycle and pedestrian traffic. Since single-lane roundabouts represent a minute portion of the total roundabout around the world, it is necessary to model multi-lane roundabouts. For closer scrutiny for real traffic behavior variable gaps should also be considered in future roundabout modeling. Finally, future models should be able to predict accidents at single-lane, as well as multi-lane roundabouts.

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VITA

HESHAM ROSHDY ELBADRAWI

1986	B. Sc.,Civil Engineering Cairo University Cairo, Egypt
1986-1992	SETEC International, Egypt
1991-1992	Elbadrawi for Civil Works and Constructions, Egypt
1993-1994	Graduate Assistant, Florida International University Miami, FL
1994	M. Sc., Construction Management Florida International University Miami, FL
1995-1996	Graduate Assistant Florida International University Miami, FL
1996	M. Sc., Civil Engineering Florida International University Miami, FL
1996-1998	Research Associate/Transportation Engineer Lehman Center for Transportation Research Florida International University Miami, FL
1998-1999	Graduate Assistant Florida International University Miami, FL
1999-2000	Planning Manager Marlin Engineering Inc. Miami, FL

HONORS

- Strathmore's Who's Who, 2000-2001
- National Dean's List, 1999-2000

- Strathmore's Who's Who, 1999-2000
- International Who's Who for Professionals, 1998
- Who's Who Among Students in American Universities & Colleges, 1996 - 1997
- Chi Epsilon, 1998
- National Dean's List, 1994 - 1995
- Civil Engineering Honor Society, 1996

MEMBERSHIPS

- President, FIU-ITE Student Chapter, 1999-2000
- Student Member, Institute of Transportation Engineers (ITE)
- Associate Member, American Society of Civil Engineers (ASCE)
- Member, Egyptian Engineering Syndicate

PUBLICATIONS AND PRESENTATIONS

Hesham Elbadrawi, Diana Ospina and L. David Shen. *Pedestrian Crossing Location at Single-Lane Roundabouts.* In TRB 2000 Annual Meeting, Washington, D.C., 2000.

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