BICYCLE AND PEDESTRIAN CONSIDERATIONS AT ROUNDABOUTS

Final Report

Prepared for

Florida Department of Transportation

by

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Table of Contents

List of Tables

List of Figures

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1.0 INTRODUCTION

A roundabout was defined by the Florida Department of Transportation as "any intersection of two or more streets that is designed around a central island." Roundabouts are designed as an effective traffic control measure to resolve conflicts between two competing traffic movements. The basic principle is to channelize the vehicle paths in order to disperse the conflicts that are concentrated at a conventional intersection and resolve each one in an appropriate manner. Roundabouts allow continuous flow of traffic while slowing down vehicular speed. There are three main differences that distinguish roundabouts from traffic circles: yield-at-entry, deflection, and flare. Traffic circles are ideally designed to operate within the geometric constraints of the intersection and are also designed to cause vehicles to come to a complete stop before entering the circle.

Experiences show that, when used appropriately, roundabouts have a significant positive safety effect that decreases, not only traffic speed by 85%, but also decreases accidents. A number of studies have shown that bicyclists do not attain the same level of safety benefits as motorists when they are circulating within the roundabouts. The Swiss Advisory Committee for Accident Prevention has set up a database of a total of 130 roundabouts in Switzerland, containing information on the conditions and the geometry of roundabouts, as well as reported accidents at roundabouts. The study investigated the effects of accidents when changing various intersections to the right-of-way on the roundabouts. As a result of this investigation, studies showed, on average, the number of accidents were reduced significantly, while the number of accidents involving bicycles increased by 47%. A literature study by Allot and Lomax in 1991 demonstrated that bicyclist accident rates at roundabouts in the United Kingdom (UK) were about 15 times more for cars and were two to three times greater than bicyclist accidents at traffic signal-controlled intersections. A Victorian study (Jordan 1985) involving about 800 roundabouts over a period of four years showed 65 bicyclist accidents, of which 74% of the bicyclists involved were struck by a vehicle entering the roundabout. Surveys taken from bicyclists indicated that they found roundabout treatment significantly more stressful to negotiate than other forms of treatment, particularly on roads with heavy traffic. Other researchers have found that the existence of roundabouts will affect bicyclists' choices of routes on regular journeys.

Horizontal alignment changes using traffic circles were pioneered in the U.S., in Seattle, Washington. Since 1978, Seattle has constructed more than 800 traffic circles. Recently, traffic circles and roundabouts have begun to gain acceptance and popularity in other cities throughout the U.S. In South Florida, residents from several cities have requested that roundabouts be implemented on state roads as a traffic calming measure. The safety of bicyclists in roundabouts, however, remains a serious concern. In the "Design Guide and Evaluation Plan for Modern Roundabouts in Florida," it is stated that "no special markings or lanes are generally needed in the roundabouts to accommodate the bicyclists." Evidently, there is an urgent need to investigate the safety and effectiveness of roundabouts with bicyclists as a traffic component, as well as to enhance the roundabout design guidelines to include considerations of safety for bicyclists.

1.1 OBJECTIVES

The objectives of this project are to study selected roundabouts and traffic circles in Districts IV and VI, to evaluate their effectiveness, and to identify hazardous conditions and safety features for the circulation of bicyclists within these facilities. The results will be used to develop an enhanced geometric design of roundabouts, as well as useful guidelines for signage and markings for safe circulation of bicyclists.

In order to accomplish this project, the LCTR team performed extensive literature reviews concerning the safety and performance of different roundabouts in the United States and other countries to obtain up-to-date information in this field.

1.2 REPORT ORGANIZATION

The literature review presented in Chapter 2 includes European and Australian documents, as well as information from several other roundabout guides that have been considered for the preparation of guides for the design and/or justification of roundabouts in the United States. Chapter 3 describes the data collection procedure and the equipment used. Collected traffic data at selected sites in South Florida (Districts IV and VI) are presented in Chapter 4. This data includes preliminary condition diagrams, volume counts, speed and vehicle classification studies and data analysis using the SIDRA software. Chapter 5 presents the process of developing a computer simulation model to determine the effects of pedestrians and bicycles at roundabouts in South Florida. A summary of findings from this study is presented in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

During the past three decades, the use of roundabouts has increased worldwide due to their benefits in comparison to traditional intersections. Roundabouts are often chosen because of their low accident rates, low construction and operating costs, and reasonable capacities and delays. The performance of roundabouts has been the interest of many researchers based on specific features of the roundabouts in different countries.

While it has been proven that the use of roundabouts generally enhances the overall intersection safety, little or no safety gains are provided to bicyclists and pedestrians. Even though roundabout design guides have considered improving bicycling/pedestrian safety at roundabouts, including pedestrian paths, bicycle lanes, underpass, and special crossings, roundabouts still present problems for bicyclists and pedestrians. Many studies show that the risk of a bicycle/pedestrian accident is higher at certain intersections. Accordingly, more research was produced in order to investigate the main causes for high accident rates of bicyclists and pedestrians.

Existing literature tends to advise against using roundabouts in highly populated pedestrian/bicycle locations. The introduction of roundabouts leads to a slight reduction in pedestrian fatal accidents, but also increases bicycle fatal accidents (Jordan 1985). Roundabouts are both a safe form of intersection control and an effective method in reducing various types of accidents (CRB 1981, Daley 1981 and Green 1977). Fatal accident rates are reduced by 68% after the installation of roundabouts (CRB 1981). Roundabouts also effectively reduce right angle accidents by 87%, with a 47% reduction in overall reported accidents (Daley 1981). There is a slight reduction in accidents involving pedestrians after the installation of roundabouts (Daley 1981 and Green 1977). Bicycle accident rates at roundabouts are 15 times those of the cars, and pedestrian accident rates are the same as the rates for vehicles (Maycock and Hall 1984). Bicycle, pedestrian and motorcycle accidents account for 13% - 16%, 4% - 6%, and 30% - 40% of all accidents respectively.

This chapter reviews several bicycle and pedestrian accident research papers and reports carried out in Europe, Australia and the United States, as well as other countries. Several bicycle and pedestrian treatments at roundabouts are also presented.

2.1 FOREIGN EXPERIENCE WITH ROUNDABOUTS

During the past several years there has been an increase in the interest of using roundabouts in several countries. As a result, the performance and the safety of roundabouts have become the interest of many researchers in different parts of the world.

2.1.1 Australia

Roundabouts have been in existence in Victoria, Australia for many years. The use of roundabouts declined in Victoria during the 1960's and the early 1970's, due to the preference for traffic signal controls at locations with high traffic volumes. After the initiation of a state intersection control program that highlighted the need for additional intersection control at certain classes of roads, roundabouts once again came into widespread use in 1974.

Many of the existing roundabouts are located predominantly in areas near shopping centers, schools and recreational facilities, where a high volume of bicycles and pedestrians exist. The advantages of roundabouts include low delay, clear priority and less accident frequency, when compared to other types of controlled intersections.

A study conducted by Jordan in 1985 concluded that the introduction of roundabouts led to a slight reduction in pedestrians' fatal accidents, and an increase in cyclists' fatal accidents. The study was carried out over a four-year period from 1980 to 1983, and was based on 36 study sites adjacent to areas of known high pedestrian/bicycle activity. The study showed that the conversion of intersections to roundabouts resulted in the following data:

- 95% reduction in right angle accidents per year;
- 68% reduction in total casualty per year for all sites combined;
- pedestrian volume decreased by approximately 30% (from 100 pph to 68 pph);
- slight decrease in pedestrian accidents and slight increase in bicycle accidents;
- 58% of the accidents involved pedestrians walking from the curb to the splitter island, and 16% pedestrians walking from splitter island to the curb; and
- more than one third of pedestrians involved in accidents were 60 years or older.

A comparison of accident frequency (per annum rate) for a period of three to five years before and one to three years after the installation of each roundabout is presented in **Table 2.1**. It should be noted that no special facilities were considered for pedestrians and bicycles at the studied roundabouts.

Table 2.1 - Roundabout Casualty Accidents by Accident Type (Accidents/Year)

Accident Type	Before	After	% Change
Pedestrian Accidents	1.5	1.7	-12%
Cyclist Accidents	2.5	3.2	0.28%
Right Angle Accidents	27.5	1.3	-95%
TOTAL[1]	39.1	12.7	-68%

[1] The total includes other types of casualty accidents.

Jordan also concluded that the reduction in the pedestrian fatalities was due to:

- reduced pavement widths to be crossed
- the refuge provided by the splitter island
- the pedestrian contend with only one direction of travel at a time
- lower vehicle speeds

Other studies noted that roundabouts did not give positive priority to pedestrians over through traffic, and yet both children and the elderly found traffic signals a more secure form of crossing control. Accordingly, it was suggested that consideration should be given to providing priority crossing for pedestrians where:

- pedestrian volume is high
- there is a high proportion of young, elderly or infirm citizens waiting to cross the road
- pedestrians are experiencing particular difficulties and/or excessive delay in crossing the roundabout approaches

On the exit of the roundabout, the pedestrian crossings should be located two to four car lengths (40 feet - 80 feet) from the circulating line in order to reduce the probability of vehicles that are delayed at the pedestrian crossing, ensuring a split back to the roundabout. On the other hand, if there is considerable pedestrian activity, a signalized pedestrian crossing may be required.

The following are specific design criteria that can be adopted to enhance pedestrian and cyclist safety at roundabouts:

- Reduce vehicle approach speeds by providing adequate deflection on each approach.
- Design splitter islands, as large as the site allows.
- Provide clearly defined crossings and splitter island crossings in conjunction with curb extensions, as close as possible (2-4 car length) to the roundabout entry.
- Prohibit parking on the approaches to the roundabouts to ensure clear visibility of/by pedestrians and bicyclists.
- Provide street lighting for both the approaches and the circulating roadway.
- Locate signs in a consistent manner and clear arrangement so that the motorists and other road users are confronted with an easily recognizable intersection layout.
- Ensure that planting and landscaping does not block any of the signs.
- Where bicycle volumes are high, it may be desirable to re-route a bicycle facility so as to avoid a roundabout.
- Avoid larger than necessary roundabout diameters, thus reducing travel speed throughout the roundabout.
- Avoid excessive entry width and alignment which can increase vehicle entry speeds.
- Other special provisions for cyclists that can be implemented are illustrated in **Figure 2.1**.

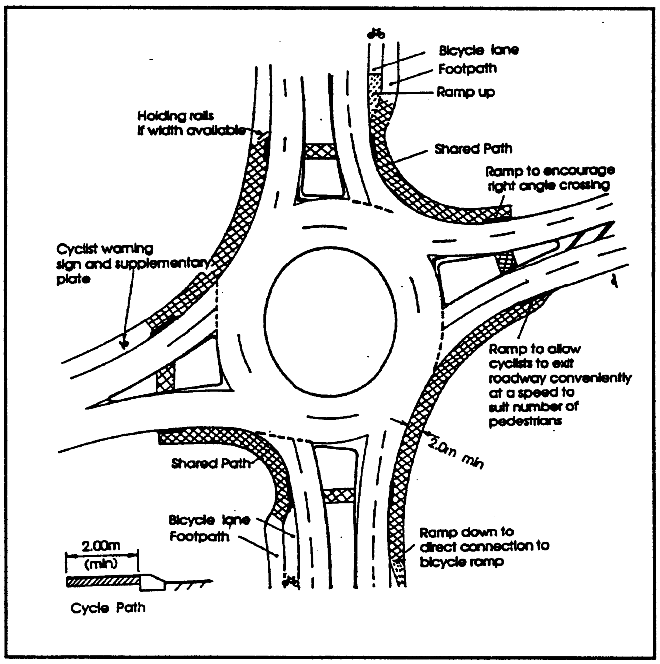

Figure 2.1 - Provision for Cyclists at Multi-Lane Roundabout

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

2.1.2 Denmark

Many roundabouts have been built for the purpose of traffic calming, traffic regulation and safety improvements. The Danish experience showed that roundabouts had a significant positive safety effect, but cyclists did not attain the same level of safety benefits as did motorists. Also, a traffic safety study by Jorgensen in 1994 concluded that the roundabouts in Denmark were considered one of the safest types of intersections in the road network.

A Danish accident study of 48 urban roundabouts showed that bicyclists accounted for approximately two-thirds of all injured users. The conflicts between circulating bicyclists and exiting and entering vehicles, as shown in **Figure 2.2**, caused high risk to bicyclists in urban roundabouts. About 20% of the roundabouts had neither a bicycle track nor bicycle lane. Bicycle traffic at these roundabouts had lower accident rates than those with bicycle facilities.

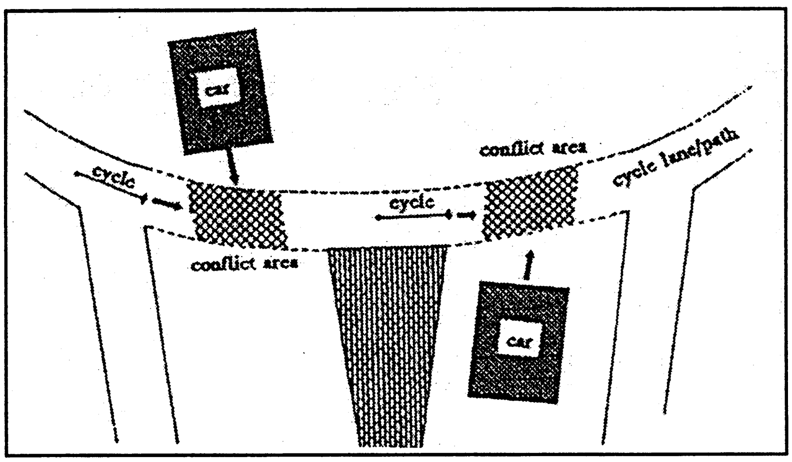

Figure 2.2 - Conflicts at Danish Roundabouts

Seven urban roundabouts with different types of bicycle treatments (shown in **Figure 2.3**) were studied. The result of the study concluded the following:

- In roundabouts with bicycle tracks, almost all bicyclists use the bicycle tracks correctly.
- In roundabouts with bicycle lanes, about 60% of the bicyclists do not use the bicycle lanes.
- In roundabouts with low car traffic volume, bicyclists often bike the wrong way around.
- The number of interactions and serious conflicts depend on the traffic volume, the

speed and the location.

Conflicts between circulating bicyclists and approaching and departing traffic contributed to 45% of the accidents. Thus, it was found to be important to design the new Danish roundabouts in such a way that the approaching vehicles have sufficient time to observe circulating bicyclists, and that the line of sight to the bicyclists is not blocked by vehicles and/or other obstacles. As a result, the following basic rules were proposed:

- The entrance speed for heavy vehicles should not exceed 9 mph (15 km/h).
- It should not be more than one lane at the entry, the exit and the circulating roadway.
- The normal width of the entrance lane for vehicles should not exceed 9.8 feet (3.0 m), and special cyclists facilities should be placed outside the circulating lane.

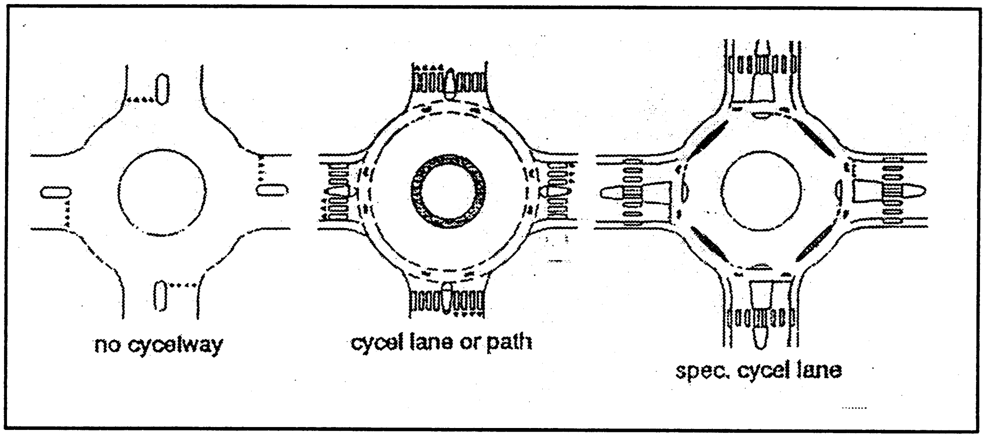

Figure 2.3 - Different Types of Bicycle Treatments at The Danish Roundabouts

2.1.3 France

The number of roundabouts in France doubled from 1982 to 1984, and again from 1984 to 1987. In 1991 there were 552 roundabouts in France, (see **Table 2.2**). Roundabouts in France were built on all types of sites, from open countryside to city centers, via commercial estates, and representing all types of roundabouts (Alphand *et al*, 1991). The radii of roundabouts in France vary from 6.5 feet to 163.5 feet (2 m to 50 m). Most of these roundabouts are small, with an average radius of less than 49 feet (15 m). Three-quarters of the roundabouts have three or four approaches and only 20% have five approaches. The average annual daily traffic (AADT) per roundabout is 12,500 vehicles, and a very small number of roundabouts have an AADT exceeding 25,000 vehicles per day.

Eighty percent of the roundabouts in France were located in urban and suburban areas. The remaining 20% were divided over open countryside, industrial or commercial developments (see **Table 2.2**).

In an attempt to determine the involvement of pedestrians and drivers of two-wheeled vehicles in personal injury accidents, a study was carried out, in 1988, by CETUR and SETRA to investigate accidents at the existing 522 roundabouts in France. The results of this study showed that no personal injuries were recorded in a total of 469 roundabouts out of the 522. Three of the roundabouts recorded four accidents. The results of this study are given in **Tables 2.3, 2.4, 2.5, 2.6,** and **2.7.**

Table 2.2 - Number and Locations of Roundabouts in France

Site	Number	Percentage
Suburban areas	192	37
Residential areas	131	25
Town Center	88	17
Industrial Developments	22	4
Commercial Developments	25	5
Open Countryside	64	12
TOTAL	**522**	100

Table 2.3 - Pedestrians Involvement in Personal Injury Accidents

Number of Roundabouts	With Accidents	Percentage	No. of Accidents
469	0	90%	0
36	1	7%	36
12	2	2.1%	24
2	3	0.4%	6
3	4	0.5%	12
Total: 522 Roundabouts		100%	78[a]

[a] The 78 accidents resulted in 5 dead, 26 seriously injured, and 47 slightly injured.

Most of the accidents occurred in suburban areas where the level of traffic and speeds of approaching vehicles are higher than in the city center. Accidents were numerous in the city center, where there are a greater number of bicycles and pedestrians. Accidents are more serious in open countryside, where the speed is higher, than in the city center. The location and severity of accidents are presented in **Table 2.4**.

Table 2.4 - Accident Locations and Severity

Location	**Open Countryside**	**Suburban Area**	**Residential Area**	**Town Center**	**Industrial & Commercial Developments**
No. Of Accidents	7	32	18	16	5
Accidents/100 Roundabouts	12.1	18.6	13.7	18.1	10.6
Fatal Accidents	2	1	0	2	0
Seriously Injured	4	14	4	4	0
Average Traffic (Veh/day)	7,500	11,500	7,000	9,000	10,000

Table 2.5 - Comparison between Signal-controlled Intersections and Roundabouts

Items	**Signal Controlled Intersections**	**Roundabouts**
Number of Intersections	1,238	179
Number of Personal Injuries	794	59
Number of Accidents Involving Two-wheel Vehicles	278	28
Accidents / Year / Intersection	0.64	0.33
2-wheel Vehicles / Year / Intersection	0.23	0.13
Accidents to 2-wheel Vehicles / 100 Accidents	35.0	40.7
Serious Accidents / Year / Intersection	0.14	0.089
Serious Accidents to 2-wheel Vehicles / Year / Intersection	0.06	0.045
Serious Accidents / 100 Vehicles	21.9	27.1
Serious Accidents to 2-wheel Vehicles / 100 Accidents to a 2-wheel Vehicle	27.0	33.3

Table 2.6 - Users Involved in Personal Injury Accidents

	Accident Rate by Type of Users	
	All Intersections	Roundabouts*
Pedestrians	6.3	5.6
Bicycles	3.7	7.3
Mopeds	11.7	16.9
Motor Cycles	7.4	4.8
Cars	65.7	61.2
Utility Vehicles	2.0	0.6
Heavy Vehicles	2.0	3.0
Bus / Coach	0.8	0.6
Miscellaneous	0.4	0

* Based on 202 accidents

Table 2.7 - Accident Typology on Roundabouts in France

Type of Accidents	No. Of Accidents Recorded	Percentage
Refusal of Priority on Entry	74	37%
Loss of Control on Entry	23	11%
Loss of Control on Roundabout	33	16%
Loss of Control on Exit	5	2%
Head-on Collision on Exit	5	2%
Rear Collision on Entry	15	7%
Rear Collision on Roundabout	1	-
Rear Collision on Exit	2	1%
Shear Movement on Exit	12	6%
Incorrect Overtaking on Entry	2	1%
Incorrect Crossover on Roundabout	5	2%
Incorrect Overtaking on Exit	2	1%
Travel in Wrong Direction on Roundabout	2	1%
Pedestrians on Pedestrian Crossing	12	6%
Pedestrians on Roundabout	7	3%
Pedestrians Not on Pedestrian Crossing	2	1%
TOTAL	202	100%

In another study conducted in 1991 by Alphand et al, the following unfavorable situations for the installation of roundabouts were cited:

- ***Steep Gradients*** - At all types of intersections, safety problems occur when located on a steep gradient. However, the most serious accidents are caused by loss of control on entry. The frequency of this type of accident will increase when the gradient of an approach is more than 4%.

- ***High Pedestrian Volume on Two-Lane Entries*** - Pedestrian safety is reduced at roundabouts with entries wider than 13 ft (4 m). Thus, roundabouts as a solution can be questionable in such cases.

- ***High Volume of Heavy Vehicles and Public Transit Vehicles*** - Accidents due to the overturning of heavy vehicles are common at roundabouts. In addition, the presence of heavy vehicles and transit vehicles necessitates larger geometric characteristics which may be unfavorable to pedestrians.

- ***Unbalanced Traffic Between Approaches*** - When traffic entering from the secondary road is less than 25% of the traffic entering from the main road traffic, the flow of traffic from the secondary road is over-penalized in a roundabout.

- ***Signal Progression Roads*** - A roundabout located on a road regulated by green wave disturbs the management of the green wave.

- ***Oval-shape Roundabouts*** - On average, there are twice as many accidents on oval-shaped roundabouts than on round-shaped roundabouts.

- ***Shops and Parking on the Roundabout*** -It is essential that the roundabouts be free from all parking. Therefore, it is necessary to avoid installing roundabouts in sites where shops are likely to encourage illegal parking around the roundabouts.

Table 2.8 gives the common design guidelines classified by the size of intersection and urban context for all types of roundabouts in France.

Table 2.8 - Common Design Rules for Roundabouts in France

Designation	Conventional Urban	Semi-Controlled Island	Mini-roundabouts	Entries to Built-up Areas
Location	All Areas	Urban zones other than mid trunk roads	Experimental	Crossroads - ring roads x axial route
Geometry				
Radius of Central Island	7 - 20 m	3.5 - 5 m	0	10 - 14 m
Crossing Strip	0-2 m	1.5 - 2 m	0.75 - 2 m	0 - 2 m
Outside Radius	15 - 30 m	11 - 15 m	7 - 11 m	≥ 18 m
Width of Circulating Lane	7 - 1 m	6 - 8 m	6 - 9 m	≥ 8 m
Number of Entry Lanes	1 - 3 lanes	1 lane	1 lane	1 - 3 lanes
Width of Splitter Island	≥ 2.5 m	≥ 1.5 m	0 - 2.5 m	≥ 4 m
Level of Traffic	< 2,500 pcph (for 2-lane entries)	< 2,000 pcph	< 1,500 pcph	< 3,000 pcph (for 2-lane entries)
Pedestrian Arrangement	Pedestrian crossing with splitter island		Pedestrian crossing	Pedestrian crossing with splitter island
Two-wheel Vehicle Arrangement	Continuity of cycle lane or cycle track	None		Possibly a cycle lane or track continuity
Public Transportation	Avoid small radii on continuous routes	To be avoided	Not recommended	
Lighting	Peripheral or cental post	Peripheral		

2.1.4 Germany

In Germany, roundabouts were introduced rather hesitantly and mainly as a traffic calming measure. Recently, roundabouts have attracted attention in Germany again due to their good traffic safety experiences, as reported by other countries.

Comparative investigations at intersections and roundabouts were made by Nikolaus in 1993. Accident data for 14 roundabouts and 14 other intersections from the period of 1986 to 1988 were evaluated. Intersections were selected to have similar conditions for traffic parameters, including traffic composition, traffic behavior and traffic volume. The results of this study showed that the total number of accidents at roundabouts is higher than at intersections. However, accidents at roundabouts are less severe than those at regular intersections. The accident rates are higher at roundabouts with old-fashioned designs, such as acute-angled entrances, which have resulted in inadequate visibility for entering vehicles. Almost no accidents occurred at small roundabouts. Accidents with injuries to persons are less likely to occur at all types of roundabouts due to low speed. However, attention must be paid to pedestrians and bicyclists at roundabouts. It is important that the zebra crossings for pedestrians are not located too close to the circular roadway. It is better to move it by a length of one or two vehicles from the circular roadway. Pedestrian islands should be provided at each approach road for the protection of pedestrians.

Since cyclists have a particularly high risk of being involved in accidents at roundabouts as compared with regular intersections, the design of bicycle paths is of particular importance. The placement of bike paths within the circular roadway has proven to be the most dangerous solution.

Basic Principles of Design and Geometry

The new generation of roundabouts in Germany was developed from foreign experiences, as well as from approaches towards better integration into urban planning and roadway safety. The following elements are regarded as basic principles of a "right" design regarding traffic engineering requirements in Germany:

- Outer diameter of 80 ft - 105 ft (26 m - 35 m) in built-up areas, allowing a maximum speed of 19 mph (30 km/hr).
- Circulating lane width should be 13 ft - 20 ft (4.0-6.0 m) and a separate inner circle, which has a diameter of 8 feet to 11.5 feet (2.5 m - 3.5 m) depending on the basic geometry. A structurally separated inner circle with a flat curb of 1.2 to 2.7 inches (3 cm - 6.8 cm) and an ascending paving (5%) is important for safe driving behavior in the roundabout.

- The entries must be directed as vertically as possible towards the center of the roundabout.
- Clear diversion of vehicles driving straight-on by the central island.
- Clearly recognizable situation and obstructed sight through the roundabout by a three-dimensional design of the central island.
- Roundabout entries and exits should have a single lane and lead towards the circulating lane in both a straight and radial direction, with a width of 10.5 ft - 11.5 ft (3.25 m - 3.50 m).
- Splitter islands of 8 feet (2.5 m) wide are provided at all the approaches to the roundabout.

Guidance of Pedestrians and Cyclists

For safety reasons, pedestrians are generally kept off the circulating lane mainly by vegetation, bollards or chains. Pedestrians and cyclists may cross the approaching lanes at a distance of 6.5 ft - 16.5 ft (2 m - 5 m) from the yield line of the roundabouts, depending on the traffic volume. For capacity reasons, it is recommended to have the pedestrians and cyclists crossing at a distance of one car length from the yield line.

The design of bicycle paths at roundabouts should be given notable attention. Among the different bicycle treatments, the design of special bicycle paths within the circulating roadway seems to be the most dangerous. It is recommended to have special bicyclist paths outside the roundabouts. Sixty percent of the roundabouts in Germany have bicycle paths or combinations of bicycle paths and footpaths, 20% have bicycle lanes within a roundabout, and 20% have mixed traffic on the circulating lanes.

2.1.5 Netherlands

The Netherlands has a population of 14 million with 12 million bicycles, half of which are used regularly. Also, there are one-half million mopeds that are popular among youngsters of 16 and 17 years old. At fairly busy intersections, several hundred cycles pass by every hour. The aim of the Dutch government was to reduce the number of fatalities in traffic accidents by 15%, between 1990 and 1995, and by 50% by year 2010.

The main objective of building roundabouts in the Netherlands is to improve safety (Minnen, 1993). Roundabouts in the Netherlands are used at quieter intersections with 400 to 500 vehicles/hr during peak hours. At busier intersections with up to 2200 vehicles/hr and 300 to 700 bicyclists/hr, roundabouts are also used. Due to the presence of a large number of bicyclists and moped drivers at many intersections in the Netherlands, safety at roundabouts is carefully studied by the Institute for Road Safety Research in the Netherlands (SWOV).

Applications of New Roundabouts in the Netherlands

Roundabouts in the Netherlands are constructed in both urban and suburban areas where speed reduction is required, as well as to improve vehicular and pedestrian safety. Safety is given the highest priority by the introduction of multi-lane roundabouts. In situations where the main stream traffic is far greater than that of the intersecting traffic, a roundabout is not considered as the ideal choice.

Accident Study

Roundabouts in the Netherlands are constructed as compact as possible, forcing drivers to slow down to 12.5 mph - 19 mph (20-30 km/h), but allowing large vehicles to pass the roundabout. Roundabouts are also used as a transition from rural areas with a speed limit of up to 50 mph (80 km/h) to urban areas with a speed limit of 30 mph (50 km/h).

Among the number of roundabouts which were constructed as a solution for unsafe intersections, 46 locations were studied. Data was collected before, during and after the construction of roundabouts. The traffic volume for the studied roundabouts varies during peak hour, from 250 to 2000 vehicles. The result of this study is presented in **Table 2.9**. It was found that during a one-year period after the construction of the roundabouts, the number of injuries decreased by 80%, the number of bicyclists injuries also decreased by 70%, and no fatalities were reported at the selected locations. This study also investigated the number of bicycle accidents with regards to the existence of bicycle facilities, including no special facilities, a bicycle lane on the roundabout, or separate paths circulating the roundabout. The results in the preliminary period vary from 3.37 (no facility) to 6.84 (bicycle facility) accidents/year.

Table 2.9 - Results of Accident Study at the Netherlands Roundabouts

	All Accidents			**Injurious Accidents**			**Injured Cyclists & Moped**		
	Before	During	After	Before	During	After	Before	During	After
No. of Roundabouts	46			46			44		
Accidents/Victims	924	249	151	217	47	14	111	17	12
Accidents/Year	5.53	5.41	2.48	1.30	1.02	0.23	0.70	0.39	0.20

The main contribution to the reduction in the number of accidents is the compact design of entries and exits of roundabouts, which forces the approaching vehicles to slow down to 12.5 mph - 19 mph (20-30 km/h). At such speed the emergency braking distance is small, and accidents are less severe. Also, at such low speeds, prevailing situations at an intersection or a roundabout may be more properly assessed. Finally, by giving way to traffic on the roundabout, conflicting traffic comes from only one direction.

Design Considerations

The design of the Dutch entries to roundabouts can be characterized as a right angle. The entry width is designed in such a way that the roundabout is large enough to be accessible for heavy vehicles. A comparison between a roundabout entry layout in the Netherlands and the United Kingdom is shown in **Figure 2.4**. The British design of the entries allows the drivers to maintain a reasonable speed while entering the roundabout, assuming there is no conflicting traffic. In the Dutch design, drivers are forced to reduce speed before entering the roundabout. Speed reduction of approaching vehicles is also achieved by special geometric provisions in the approaching roads.

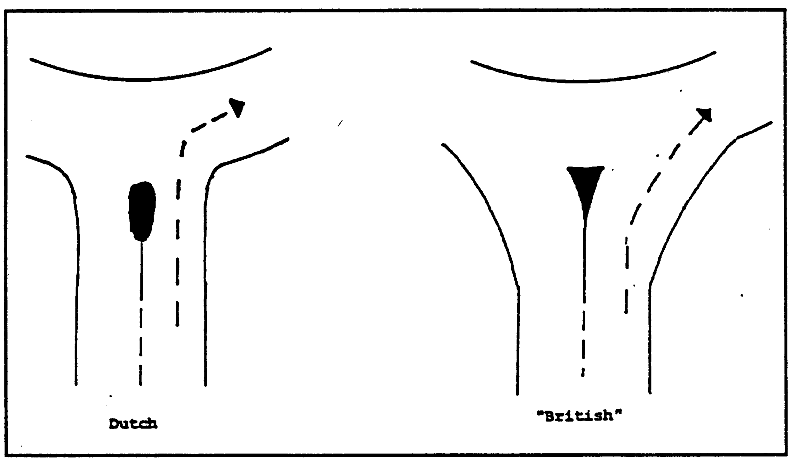

Figure 2.4 - Comparison Between the British and the Dutch Roundabout Entries

Bicyclists Considerations

Different provisions for bicyclists have been taken into consideration at roundabouts in the Netherlands (see **Figure 2.5**). They can be divided in two categories:

Priority for bicyclists - cyclists crossing an approach have the priority over all drivers entering and exiting the roundabout. In this case bicyclists may have a considerable influence on the capacity and delays at the roundabout.

No Priority for Bicyclists - in this case a separate lane is provided for bicycles, thus, bicyclists have to give way to vehicles entering and exiting the roundabout. In this category, bicyclists have no effect on capacities and they delay vehicle drivers.

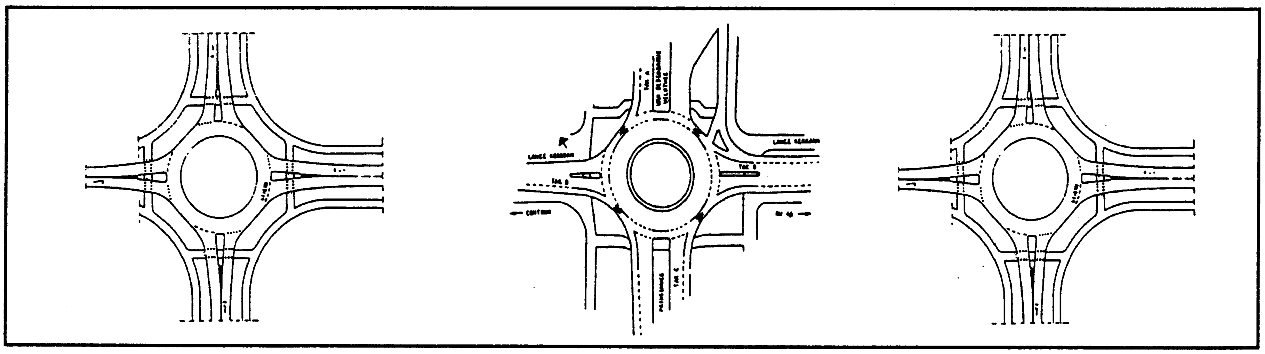

Figure 2.5 - Different Bicycle Treatments for Roundabouts in the Netherlands

A study conducted by the SWOV offered the following observations:

- The safety of bicyclists seems to improve as the difference in the speed is reduced and a better separation between bicyclists and motor traffic is realized.
- Where the connecting roads to the roundabout have separate bicycle lanes, it is recommended that the bicycle lanes be continued on the roundabout; bicyclists should then give right-of-way to vehicles at all times.
- Mopeds should be permitted to drive on the roundabout, even when a separate bicycle path is present.
- If a bicycle lane is present on the roundabout, a partial physical separation between the road and the bicycle lane is advisable.
- The capacity of a roundabout begins to suffer when bicyclists have priority over vehicles.

Deciding which option is suitable for a certain location depends on several factors including the following:

- the available space
- the geometry of the approaches, since they may have a separate bicycle lane
- the bicycle traffic, as they may seriously impede the vehicle traffic

2.1.6 Norway

Small roundabouts have become very popular in Norway during the last two decades. The number of roundabouts increased from 15 roundabouts in 1980 to about 350 in 1990 (Seim 1991). All of the existing roundabouts have a circular center island, and it is usually possible to drive over their outer part. Also, there is often a street lighting column in the center island.

A study conducted by Johannessen in 1984 concluded that the introduction of roundabouts in Norway reduced personal injury accidents by 30 - 40% compared to signalized intersections. Another study conducted by Seim in 1991 indicated that roundabouts with two-lane roads are safer for pedestrians than other types of intersections, because of the geometric design of roundabouts, which forces motorists to reduce speed. On the other hand, a substantial percentage (36%) of accidents that occurred at roundabouts involved two-wheeled vehicles. The Norwegian experience indicated that traffic volume at roundabouts varies between 2,600 to 28,400 vpd, with an average of 13,900 vpd.

Also, Seim concluded that three-approach roundabouts are safer, but the difference in the number of accidents between roundabouts with three and four approaches is not significant. It was found that the risk of accidents in medium roundabouts is greater than that of small roundabouts. Thirty-three accidents involving personal injury were recorded in 59 roundabouts. Only one of these accidents involved a pedestrian.

Design Criteria

- Small roundabouts may be suitable for local roads with a fewer number of heavy vehicles and buses. Mini roundabouts are suitable for downtown areas where the speed level is low and space is very restricted. The dimensions of four roundabout categories are shown in **Figure 2.6**.

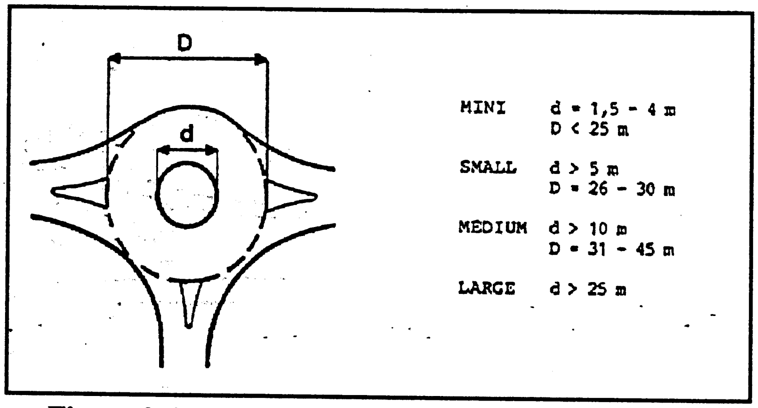

Figure 2.6 - Dimensions of Norwegian Roundabouts

- When there are two or more entry lanes on the approaching road, the routing of splitter islands should be such that the extension of the right-hand border of the splitter, in the form of a straight line, will be a tangent to the central island (see **Figure 2.7**).

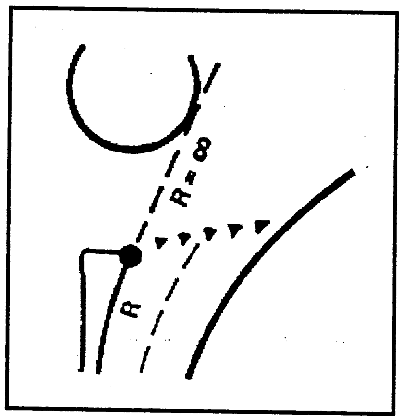

Figure 2.7 - Entry Radius at Roundabouts

- From experience, using roundabouts demonstrates that they have such a great capacity that it is often unnecessary to widen the approach to two entry lanes. A one-lane entry is more effective for speed reduction.

- Pedestrian crossings should be located at a distance of 30 ft - 36 ft (9 m - 11 m) from the roundabout, as shown in **Figure 2.8**. This will give motorists the opportunity to pay closer attention to the presence of any pedestrians, before entering and after exiting the roundabout. Pedestrians on the other part can concentrate on vehicles from one direction at a time. In such places where the speed is low, pedestrian crossings may be placed closer to the such places where the speed is low, pedestrian crossings may be placed closer to the roundabout, but not less than 16.5 feet (5 m).

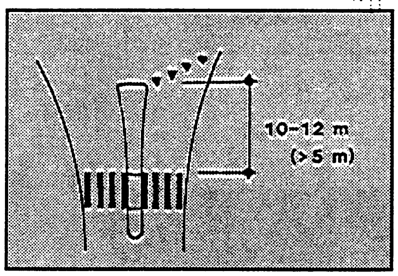

Figure 2.8 - Location of Pedestrian Crossings

Pedestrian and Bicycle Studies

Several studies performed on the Norwegian roundabouts showed that pedestrians more often use the pedestrian crossings to a larger extent than in the before situations. On the other hand, bicyclists often chose the shortest path through the roundabout, and only few travel along the periphery, as shown in **Figure 2.9**. Also, studies concluded that approximately 80 to 85% of the entering traffic yielded to circulating bicyclists as they yielded to other circulating vehicles.

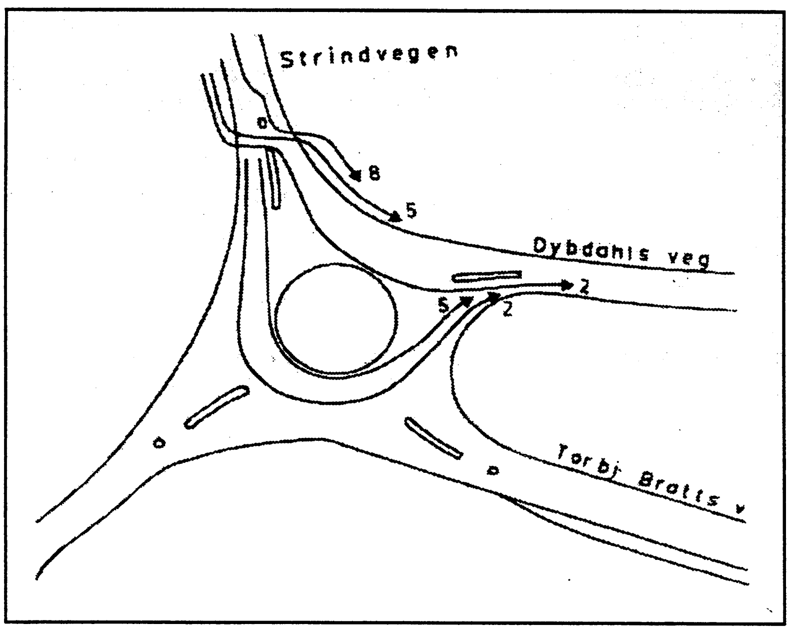

Figure 2.9 - Cyclist Route Choices Through a Roundabout in Norway

In the early 1980's there was a large impact of roundabout ideas emerging from France, where more and more roundabouts were installed and where the "give way" rule on the entries of the roundabouts was adopted (Tan 1994). Most of the roundabouts are either installed in urban or suburban areas, or a few in residential areas, and almost none in rural areas. The main objectives of introducing roundabouts at urban intersections in Switzerland are as follows:

- Improve the urban quality of the public space at intersections.
- Achieve smooth traffic conditions and high quality under changing traffic demands, at peak hours, and in between.
- Improve safety for all users by reducing the speed of motor vehicles.
- Reduce environmental impact by smoothing the traffic flows at limited speed and reducing the delays.
- Extend the flexibility of movements by allowing U-turns.

Urban traffic in Switzerland includes a considerable number of bicycles (15 to 25% of total traffic) and a high volume of pedestrians cross the approaches of roundabouts. Thus, a traffic safety study was carried out in 1987 by the Swiss Foundation for Traffic Safety in order to analyze the behavior and safety of cyclists and pedestrians in small roundabouts. The main results of the study are as follows:

- To achieve safety for cyclists, a good visibility on each of the approaches is required.
- Vertical obstacles should be avoided.
- Permanently built roundabouts are preferable than temporary ones.
- No special problems for cyclists have been observed on double-lane approaches.
- At zebra-crossings, priority is often refused to pedestrians crossing exits (see **Table 2.10**).
- All approaches of roundabouts that have traffic volume of more than 300 vehicles/hour should be equipped with traffic islands. Such islands enable pedestrians to deal with one traffic flow at a time.

Table 2.10 - Field Observations for Urban Roundabouts in Switzerland

Location of Crosswalk	Vehicle at Crosswalk		Pedestrians at Crosswalk	
	Give Way	Not Give Way	Give Way	Not Give Way
Entry Side of Crosswalk	53%	47%	33%	67%
Exit Side of Crosswalk	19%	81%	69%	31%

In 1989 another study was performed by the county police to investigate the accident before-and-after the installation of roundabouts. The results of this study are represented in **Table 2.11**.

Table 2.11 - Results of Before-and-After Accident Study for Urban Roundabouts in Switzerland

Items	Before	After
Period of Study	153	31
Number of Accidents	100	14
Accident/Month	0.65	0.45
Casualties	20	2
Fatalities Rate	0.13	0.06
Bicyclist Accidents/Month	0.08	0.06
Pedestrian Accidents/Month	0.01	0.00

The following are general conclusions from similar studies conducted in Switzerland:

- Small roundabouts have lower fatality rates than other types of intersections.
- Small roundabouts are safe solutions for bicyclists and pedestrians. However, to achieve safety, a comprehensive design and careful construction are required.
- Bicyclists should be integrated in the roundabout lanes: no bicycle lanes, no separate bicycle routes. Motorized traffic must be forced to reduce speed by layout. Therefore, diameters of not more than 100 feet (30 m) are recommended.
- To increase pedestrian safety, splitter islands should be provided at every approach.

2.1.8 United Kingdom

Although roundabouts have a good overall safety record in comparison with other types of intersections, two-wheeled vehicles have relatively high-accident involvement rates. In Great Britain, 70% of the pedal-cycle accidents occur at intersections; mainly at T-intersections, crossroads, roundabouts, and private driveways (Layfield and Maycock, 1986). Of this, 22% are at mini-roundabouts and another 22% at roundabouts. Although the above percentages are above average, roundabouts and mini-roundabouts have a relatively low portion of fatal or serious accidents (15% and 18%, respectively).

Layfield and Maycock (1986) reviewed accident information, risk of accident involvement, type of conflict, effect of roundabout geometry, and treatments. The study concluded that conventional single-lane roundabouts appear to reduce the injury accident involvement rates for passenger vehicles when compared to traffic signals. Considering the difference in the traffic flow, the risk related to two-wheeled vehicles is similar at both types of intersections. On multilane roundabouts, conventional roundabouts result in lower injury accidents to cars, but also result in higher accidents to pedal-cycles when compared to traffic signals. In the meantime, small roundabouts and traffic signals appear to have similar injury accidents of passenger vehicles, and the risk of bicycle injury accidents are substantially greater at small roundabouts.

A sample of 50 roundabouts with 30 to 40 mph speed limits and 34 roundabouts within 50 to 70 mph speed limits was selected. The accident study concluded that almost all of the accidents occurred between motor vehicles and bicycles. A small portion of accidents in this study involved bicycles, which were the only vehicles involved, and none of the accidents involved only bicyclists and pedestrians. Accidents were then classified as entering/circulating, approaching, single vehicle, and others. Sixty-eight percent of the bicycling accidents involved circulating bicyclists, where 50% were struck mainly by entering motor vehicles, and 18% were between exiting bicycles and circulating vehicles. Bicyclists approaching the roundabout accounted for 14% of the cycle accidents where cyclists were mainly struck from behind by motor vehicles. Bicyclists entering and leaving the roundabout each accounted for 7% of the bicycle accidents.

As the analysis showed, the entering/circulating accidents are particularly sensitive to the entry path curvature and entry width. The entry path curvature is the maximum entry curvature (1/minimum radius) on the straight-ahead vehicle path. This was intended to be a measure of a deflection through traffic provided by the roundabout design.

Special facilities for cyclists at roundabouts

A satisfactory solution that provided cyclists with special facilities to negotiate roundabouts cannot be concluded. The objectives are to make it easier for bicyclists to negotiate the roundabout and to make drivers more aware of bicyclists, thus reducing the number of entry/circulating bicycle accidents.

An example of an experimental roundabout is the Northgate Gyratory, Chichester (**Figure 2.10**). Bicyclists have priority when crossing entries, but at crossing exits, bicyclists must give way to traffic leaving the roundabout. This type of treatment is preferred in large roundabouts where a sufficient curb length is available to maintain such with flow lane.

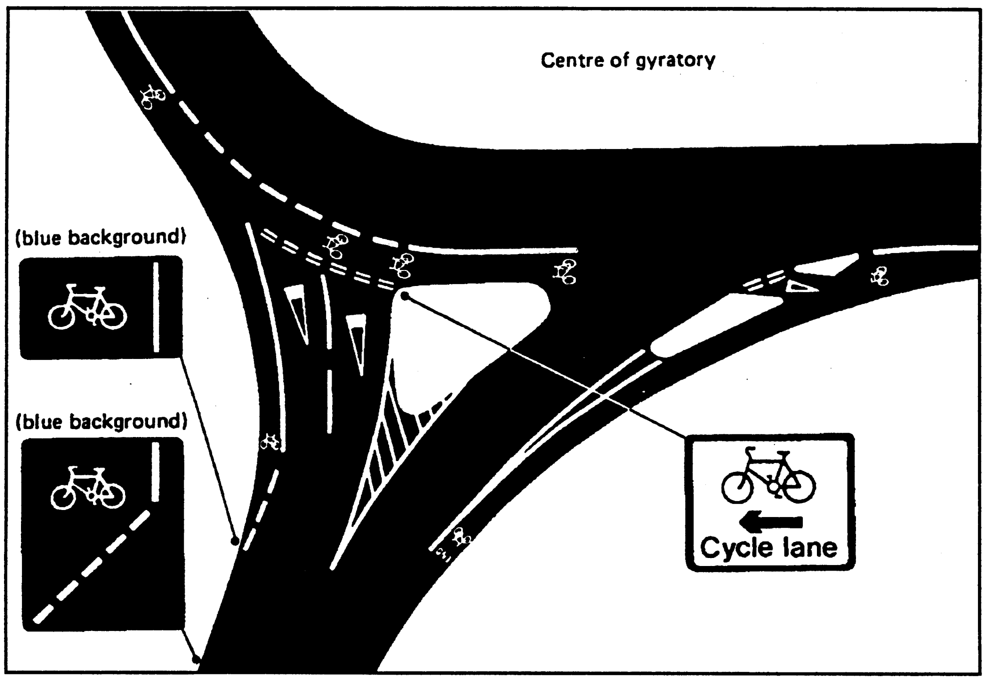

Figure 2.10 - Experimental Bicycle Lane at a British Roundabout

Accidents involving pedal-cyclists continued after the implementation of the bicycle lane and it is clear that the change was slight. Bicyclists experienced some difficulties crossing the exits that were not entirely overcome by the later addition of physical islands at these points.

Another treatment was implemented in Hull, England. A one-way bicycle track was constructed on the approaches of the roundabout to link the converted bicycle track with the roads (**Figure 2.11**). This treatment needs to give way to traffic when crossing the arms of the roundabout. Thus, it is unattractive to bicyclists, particularly where traffic flow is high.

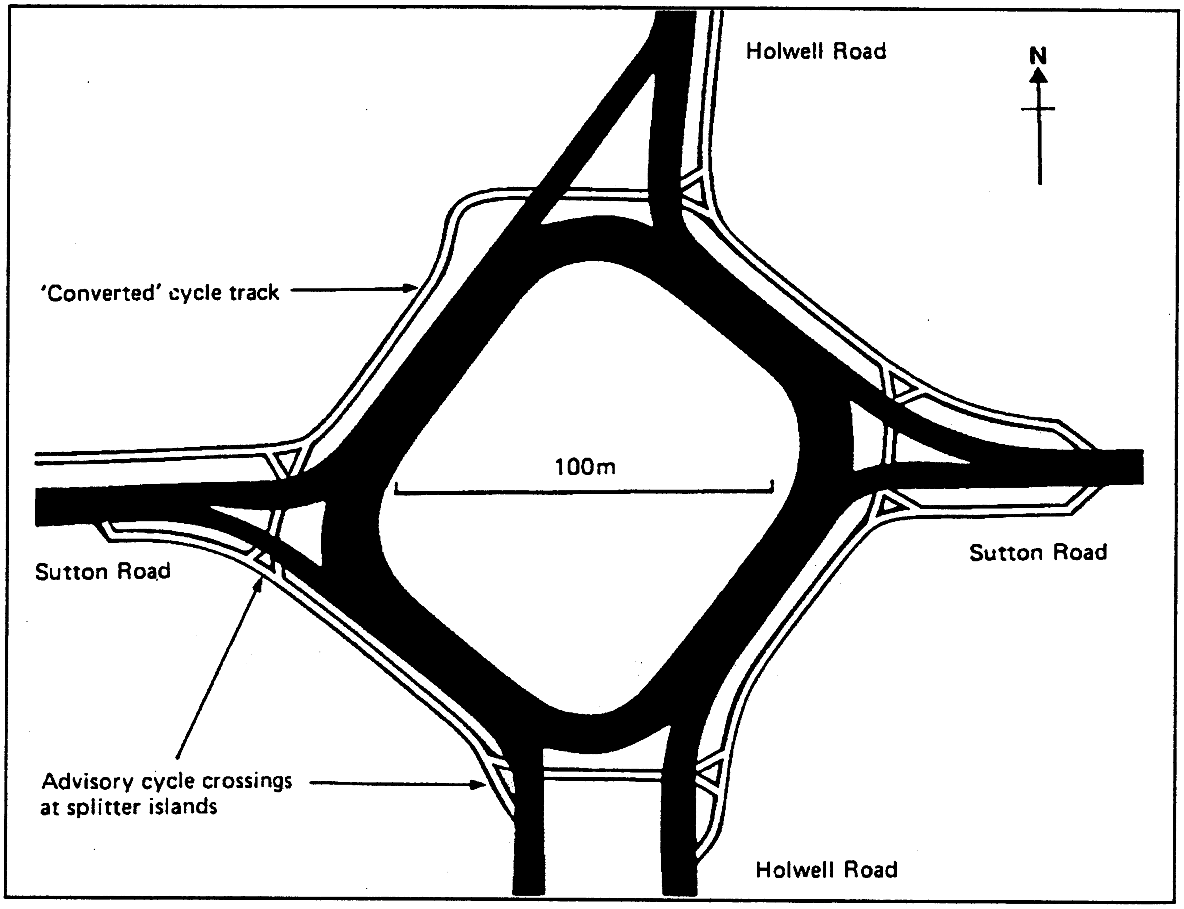

Figure 2.11 - Bicycle Track at a British Roundabout

Full grade separation allows bicyclists to avoid hazards of passing through the roundabout. One way of achieving this was converting a pedestrian subway at roundabouts to a pedestrian/bicyclist subway. This treatment was acceptable to the majority of the bicyclists and pedestrians and did not appear to cause serious conflicts between subway users (such as Odeon roundabout, Chelmsford).

The British roundabout experience concluded the following:

1- Bicyclists have a higher risk of injury accidents at some types of roundabouts compared to other road users and other types of intersection treatments.
2- Geometric design of roundabouts is an important factor in determining the expected entry/circulating bicycle accident frequency.
3- Increasing the entry deflection may be used to reduce entry/circulating bicycle accidents.
4- Special cyclist facilities have limited applications.

2.2 ROUNDABOUT EXPERIENCE IN THE UNITED STATES

In the 1930s and 1940s, traffic circles were popular in the United States, but many were converted to traditional control or were signalized in the 1950s and 1960s because of a lack of consistency in design and control. Recently, roundabouts are recognized as an alternative treatment for roadway intersections in the United States. Modern American roundabouts have produced remarkable safety records. As a result, an increase in the number of roundabouts throughout the United States is expected over the next decade. The experience of modern roundabouts in the U.S. is very similar to roundabout experiences reported in other parts of the world; thus, building modern roundabouts is a viable option for transportation agencies.

Reports of accidents have decreased considerably in areas where modern roundabouts have been built. In the U.S., various cities and transportation agencies share similar experiences. The first modern roundabouts were built in the Spring of 1990 in Summerline, Las Vegas (Ourston and Bared, 1995). With the rapid growth of the surrounding community, only four accidents were reported in a five-year period at the two existing roundabouts. No bicycle or pedestrian facilities were provided at these two roundabouts.

The first modern roundabout on the California State Highway System was installed by the City of Santa Barbara in 1992. The roundabout shown in **Figure 2.12** replaced an intersection of five two-lane streets regulated by stop signs. The old intersection averaged four accidents per year, while the roundabout averaged 2.1 accidents per year, with only five accidents in a 28-month period (Ourston and Bared, 1995).

Maryland's first modern roundabout was built in 1993 in Lisbon (see **Figure 2.13**). The roundabout replaced a lightly traveled four-leg intersection regulated by a flashing beacon. The former intersection had averaged eight accidents with eight personal injuries per year. Two accidents occurred in the first three months after construction of the roundabout, resulting in two personal injuries. For the following 21 months, there were no reported accidents. 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).

Figure 2.12 - Santa Barbra Roundabout in California, 1992

Figure 2.13 - The First Roundabout in Lisbon, Maryland

The California Department of Transportation converted the old nonconforming Long Beach traffic circle to a modern roundabout in 1993. Accidents fell 36% compared to the average rate of the previous three years. Accidents with injuries fell 20%.

General information from nearly 13 roundabouts was collected, in addition to 6 retrofitted roundabouts sited with accident data that was analyzed (Flannery and Datta, 1996). Traffic volume on roundabouts in the United States varies from 3,200 to 18,500 vehicle/day. The study showed a lack of standardization in the selection process for the use of roundabouts. It also concluded that the use of roundabouts serves mainly to avoid traffic signal installation and for various criteria, from increases in delay to improved intersection safety. This information is provided in **Figures 2.14, 2.15** and **2.16**, respectively.

Since 1973, more than 600 traffic circles have been constructed in Seattle, and the Neighborhood Traffic Control Program (NTCP) staff receive about 700 requests for traffic circles each year. Potential traffic circle locations are identified through community requests or investigations of high accident locations. Each traffic circle is individually designed to fit the intersection, without having to modify the street width or corner radii. Most of Seattle's local streets are 25 ft wide or less, and traffic circles are usually 12 to 16 ft in diameter. All intersections where circles are to be constructed are reviewed by the Fire Department, and field tests are conducted to make sure that they can accommodate fire trucks. Between 1991 and 1994, a total of 119 traffic circles were constructed. A comparison of the number of accidents before and after the construction of the traffic circles was conducted. The results of the study showed a 94% reduction in accidents. The reduction in injuries was even more dramatic, dropping from 153 injuries per year before construction to one injury after the construction.

Site No.	Location	Number of Approaches	Retro-Fitted, New or Circle with Roundabout Features	Previous Control if Converted from Traditional Control	Average Daily Traffic (ADT)	Land Use in Vicinity	Date of Construction
1	Lake South & Crystal Water Way Las Vegas, Nevada	4	Retro-Fitted	Stop (2-way)	4,069 (March 1995)	Residential	August 1994
2	Lakes of Boca Raton & Cain Boulevard Palm Beach County, Florida	4	Retro-Fitted	Stop (2-way)	7,615 (April 1995)	Residential	November 1994
3	MD-94 & MD-144 Lisbon, Maryland	4	Retro-Fitted	Stop (2-way)	8,500 (March 1995)	Residential/ Commercial	April 1993
4	SE 7th Street & SE 4th Avenue Gainesville, Florida	4	Retro-Fitted	Signal	5,500 (1993-94)	Residential	April 1992
5	Hollywood Boulevard & Doolittle Boulevard Ft. Walton Beach, Florida	3	Retro-Fitted	Stop (1-way)	12,000 (March 1993)	Industrial	May 1994
6	Killarney Way & Shamrock Drive Tallahassee, Florida	3	Retro-Fitted	Stop (1-way)	17,825 (November 1994)	Residential/ Commercial	August 1994
7	SR 789 & Bridge Street Bradenton Beach, Florida	4	Retro-Fitted	Stop (2-way)	17,000 (December 1992)	Commercial	August 1994
8	Michael & Harmony Way Las Vegas, Nevada *	3	Retro-Fitted	Stop (1-way)	3,200 (March 1995)	Residential	August 1993
9	Alamenda Padre Serra West & Montecito Street & Salinas Street & APS East & Sycamore Canyon (Five Points Intersection) Santa Barbara, California	5	Retro-Fitted	Stop (all-way)	15,600 (May 1993)		November 1992
10	Pacific Coast Highway & Highway 19 & Los Coyotes Diagonal Long Beach, California	4	Retro-Fitted Traffic Circle	Does not apply	4,700 Peak Hourly Volume April 1994		June 1993
11	Village Center Circle & Hill Center Drive & Meadow Hills Drive Summerlin, Nevada	4 (only 3 approaches open to traffic)	New Roundabout	Built as roundabout	10,000 (March 1995)	Residential	April 1990
12	Village Center Circle & Town Center Drive & Library Hil Drive Summerlin, Nevada	4 (only 3 approaches open to traffic)	New Roundabout	Built as roundabout	10,000 (March 1995)	Residential	April 1990
13	SW 12th Avenue & SW 18th Street Boca Raton, Florida	4	Retro-Fitted Traffic Circle	Square	18,500	Residential/ Commercial	1989

*Temporary barriers still in use.

Figure 2.14 - Characteristics of Located U.S. Roundabouts

Location	Number of Approaches	Center Island Diameter	Inscribed Circle Diameter
MD-94 & MD 144 Lisbon, Maryland	4	19.5 m 1.1 m truck apron	30.5 m
Town Center Drive & Library Hills Drive & Village Center Drive Summerlin, Nevada	4	34 m .5 m. truck apron	45.7 m
Meadow Hills Drive & Hill Center Drive & Village Center Circle Summerlin, Nevada	4	22.5 m .5 m truck apron	30.5 m
Lakes of Boca Raton & Cain Boulevard Palm Beach County, Florida	4	15.2m (50') .5 m (5') truck apron	30.5 m
SR 789 & Bridge Street Bradenton Beach, Florida	4	15.6 m 2 m truck apron	20.1 m
Killarney Way & Shamrock Drive Tallahassee, Florida	3	Elliptical Design 29 m major axis 18.3 m minor axis	41.5 m major axis 28 m minor axis
5 Points Roundabout Santa Barbara, California	5	16.5 m 5.2 m truck apron	26.2 m
Lake South & Crystal Water Way Las Vegas, Nevada	4	Elliptical Design 10.5 m major axis 9 m minor axis	25.1 m major axis 23.6 m minor axis
Hollywood Boulevard & Doolittle Boulevard Ft. Walton Beach, Florida	3	12.2 m 1.8 m truck apron	30.5 m

Figure 2.15 - Geometric Features of Located U.S. Roundabouts

	Site Number					
Group	1	2	3	4	5	6
Before	1 (2 yrs)	3 (2 yrs)	12 (2 yrs)	2 (2 yrs)	16 (2 yrs)	11 (2 yrs)
After	0 (1 yr)	0 (1 yr)	0 (1 yrs)	5 (1 yrs)	0 (1 yr)	1 (1 yr)

Number of Accidents (Time Period)

Figure 2.16 - Before-and-After Study Results

A recent study by Sarkar et al in 1998, studied the safety of 119 traffic circles in Seattle. It concluded that the construction of traffic circles reduced the number of collisions by 94%. Moreover, the reduction in 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 conducted by Walter in 1994, showed that the 85th percentile speed dropped from 40 mph to 22 mph. Another study conducted in Boulder, Colorado in 1996 indicated about a 20% drop in vehicular speed at roundabouts. The other contributing factor in reducing the number of accidents at roundabouts is the lesser number of conflict points at roundabouts, as shown in **Figures 2.17** and **2.18**. A comparison of collisions at signalized intersections and roundabouts was presented in *Pedestrian and Bicycle Safety Accommodation* is presented in **Table 2.12**. The results of the comparison showed that roundabouts performed better due to the fewer number of conflict points in the roundabouts (Sarkar, et al. 1998).

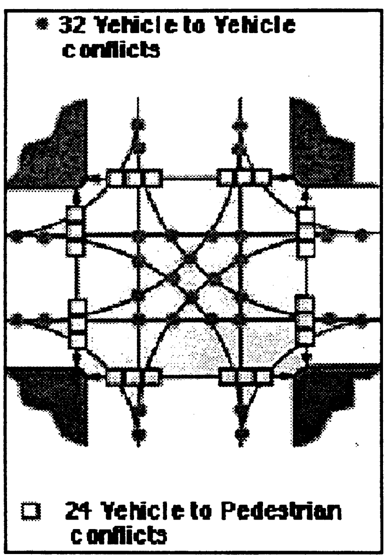

Figure 2.17 - Conflict Points at an Intersection

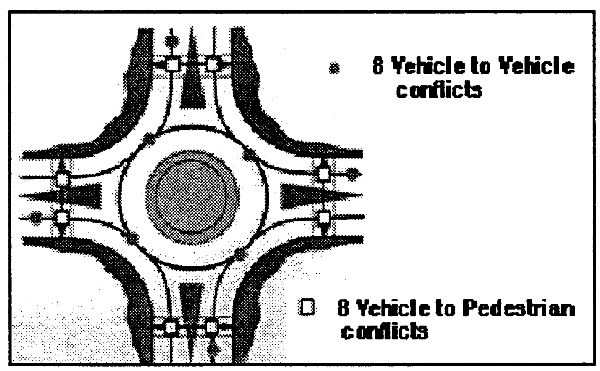

Figure 2.18 - Conflict Points at a Roundabout

Table 2.12 - Comparison of Collisions in the U.S.

Signalized Intersections	Roundabouts
2.65 collisions/intersection/year	0.83 incidents/intersection/year
34 incidents per million vehicles	20 incidents per million vehicles
20% resulted in serious and fatal injuries	19% resulted in serious or fatal injuries

In 1998, Garder investigated accidents at the first roundabout in Maine, which was inaugurated in July 1997. The total accident rate after sixteen months of operation was slightly lower than the expected one for a signalized intersection. Before reconstruction, the stop-controlled intersection had an average of six reported accidents per year. With 12,000 vehicles per day entering the intersection, the accident rate was 1.36 accidents/million vehicles entering the intersection. Four accidents were reported in the first 16 months of operation, with an accident rate of 1.42 accidents/million vehicles entering the roundabout. None of the reported accidents involved bicycles or pedestrians.

Rear-end conflicts and conflicts caused by drivers not yielding when entering the roundabout were the two basic types of conflict that were observed at the roundabout in Maine. The rate of "non-yielding " conflict was approximately one serious conflict for every 1,500 vehicles entering the roundabout (Garder 1998).

In 1995, a freeway interchange at the main entrance to the mountain town of Vail, Colorado had become badly overcrowded, especially during ski-season peak hours. The traditional solution called for $15 million worth of off-ramps, overpass widening and traffic signals (Siegman, 1997). Instead, several interchange roundabouts were selected as an alternative solution (see **Figure 2.19**). Traffic that used to back up onto the freeway so often now rarely exceeds queues of six vehicles. Also, crashes during the forth quarter of the year dropped from seven to only four, with no injuries. As a result of the roundabouts, merchants and residents of Midtown want to change the auto-oriented strip into a bicycle and pedestrian-friendly place.

In the Fall of 1992, the City Council of Montpelier in Vermont approved the request to create the Montpelier Roundabout Demonstration Committee (Committee). The Committee first selected a signalized intersection adjacent to the Capitol, in part so that a roundabout would reduce costs by eliminating a traffic signal. Later in 1993, the Committee decided to select another site to demonstrate the operation of a roundabout without a walk signal replacing an intersection, with a walk phase instead. As a result, the Committee settled on Keck Circle. The selected location was a difficult "Y" intersection composed of a north-south street intersecting with a west street, with approximately 11,000 daily vehicles and 40 tractor trailers passing though the intersection between 6 A.M. and 6 P.M. A middle school is located 500 feet on the north-south street, as well as single family and apartment housing. A considerable number of professional and service/business offices, historical buildings, hotels, and a senior housing complex also surround the intersection. On a typical day, 260 students use this intersection for the A.M. and P.M. periods. The Keck Circle, which has an average radius of 53 ft., was constructed at a total cost of $162,000 (including 900 ft of a new sidewalk).

Historical accident records showed that from 1991 to 1996, 1.4 accidents occurred per year, causing 0.7 injury per accident. Accidents from August 1996 through March 1997 showed one pedestrian accident and no reportable vehicle collisions. As a result, five additional roundabouts were approved in Vermont.

In 1998, Flannery *et al* investigated the safety performance of roundabouts in the United States. The study surveyed five single-lane modern roundabouts. Accident data was assembled from accident reports provided by local agencies. All intersections were controlled by two-way stop signs, except Fort Walton Beach, Florida and Tallahassee, Florida. They were 3-legged controlled by a one-way stop sign. The characteristics of the study sites are provided in **Table 2.13**.

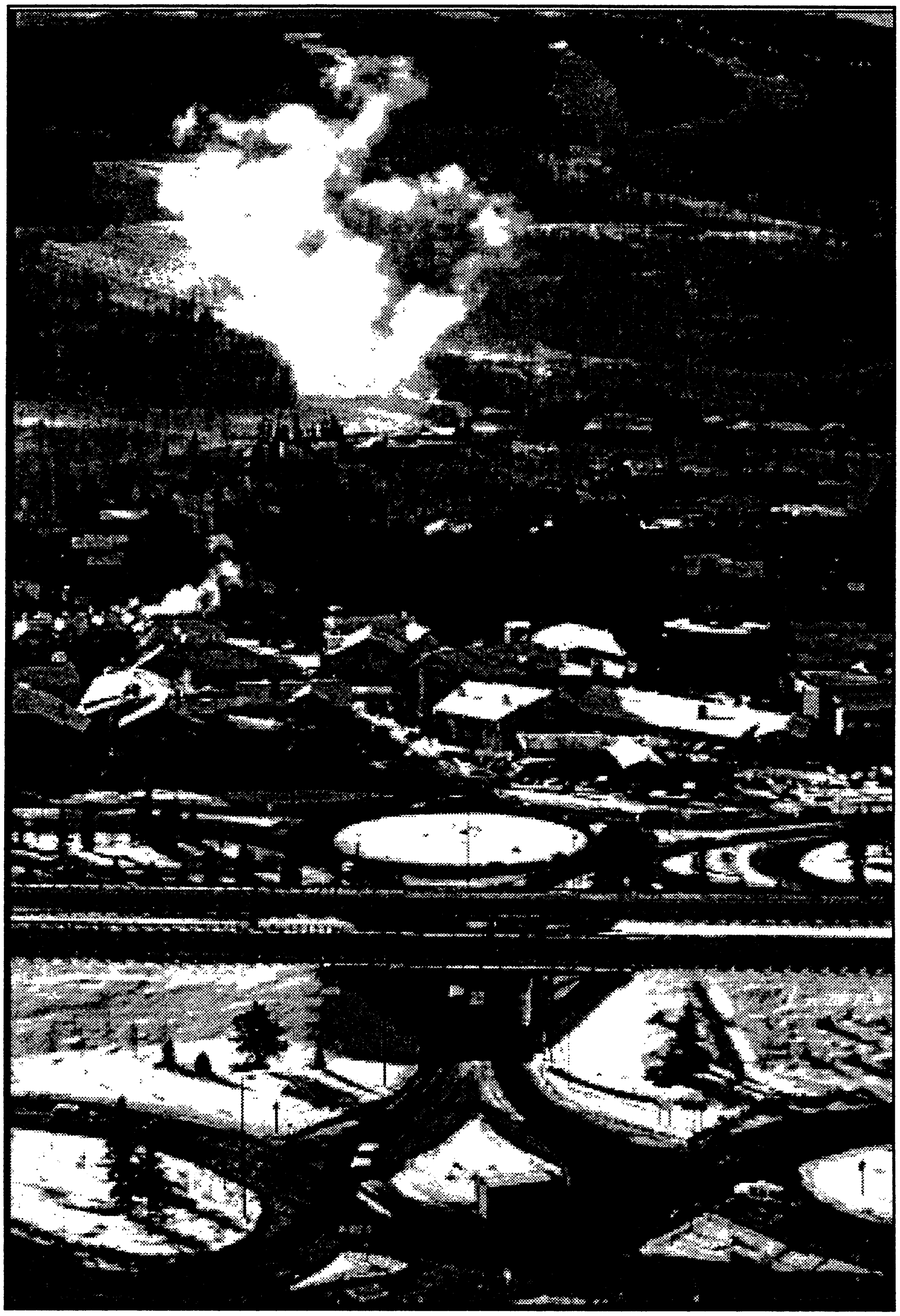

Figure 2.19 - Interchange Roundabout in Vail, Colorado

Table 2.13 - Study Site Characteristics

Location	Date of Construction	Intersection Control	ADT for All Approaches	Peak Hour for All Approaches
Palm Beach County, FL	November 1994	2-way stop	7,600 vpd	510 vph
Lisbon, Maryland	April 1993	2-way stop	8,500 vpd	856 vph
Tallahassee, FL	August 1994	1-way stop	17,825 vpd	1,085 vph
Fort Walton Beach, FL	May 1994	1-way stop	12,000 vpd	1,245 vph
Lothian, Maryland	October 1995	2-way stop	15,000 vpd	1,345 vph

Source: Flannery et al. 1998.

For all of the study sites, with the exception of Lothian, Maryland, two years of before and after accident data were available. Accident data before and after the installation of roundabouts are provided in **Table 2.14**. The results show a reduction of accident rates after the installation of roundabouts, with the exception of Palm Beach County.

Table 2.14 - Vehicular Accident Rates Before-and-After the Installation of the Five Studied Roundabouts

Location	Accident Rate/Year		Accident Rate/Million Vehicles Entering the Intersection/Year	
	Before	After	Before	After
Palm Beach County, FL	1.5	2	0.56	0.71
Lisbon, Maryland	7.5	2.5	2.59	0.81
Tallahassee, FL	4.5	1.5	0.71	0.22
Fort Walton Beach, FL	8	2	2.05	0.49
Lothian, Maryland	13	4	2.14	0.63

Source: Flannery et al, 1998.

The study sites experienced twenty injury accidents in the "before" period versus only one injury accident after the installation of the roundabouts.

3.0 DATA COLLECTION FOR SOUTH FLORIDA ROUNDABOUTS

Due to the lack of information about bicycle and pedestrian considerations at roundabouts in the United States, it was necessary to perform a comprehensive data collection for traffic circles in South Florida. The Lehman Center for Transportation Research (LCTR) team at Florida International University (FIU) surveyed several existing traffic circles and roundabouts, as well as proposed roundabout sites to obtain accident information on pedestrians and bicyclists at circular intersections.

The circles were studied to obtain data on pedestrians' and bicyclists' behavior at circular intersections. Initial visits to the nine proposed locations for the study, including six existing and three planned roundabouts (see **Table 3.1** and **Table 3.2** for locations), were performed to allow the team to become familiar with the actual conditions, as well as to identify the critical sights where data had to be collected. During these visits, preliminary condition diagrams were developed, including predominant physical characteristics and other information considered as helpful in the decision process for the data collection.

Table 3.1 - Existing Traffic Circles and Roundabouts Studied in South Florida

City	District	Circle/Roundabout	Intersection
Hollywood	IV	Young Circle	Hollywood Blvd (SR 820) and US 1 (SR 5)
Hollywood	IV	City Hall Circle	Hollywood Blvd and 26th Avenue
Hollywood	IV	President Circle	Hollywood Blvd and Rainbow Drive
Stuart	IV	Confusion Corner Circle	Colorado and East Ocean Avenues
Coral Gables	VI	Cartagena Plaza Circle	Old Cutler Drive, Sunset Drive, Le Jeune Road and Cocoplum Road
Miami Springs	VI	Royal Plaza Circle	Royal Poinciana Boulevard, Curtiss
Boca Ration	IV	Camino Real Circle	Camino Real and Royal Palm
Boca Raton	IV	SW 18 St/SW 12Ave Roundabout	SW 18^{th} St and Juana Rd. (SW 12^{th} Ave.)

Table 3.2 - Planned Roundabouts Studied in South Florida

City	District	Intersection
Lake Worth	IV	Lake Worth Road, Lake and Lucerne Avenues, and "A" Street
Jensen Beach	IV	Jensen Beach Blvd. (SR 707 A) and Palmetto Drive
Jensen Beach	IV	Indian River Drive (SR 707) and the Jensen Beach Causeway (SR 732)
Key West	IV	US 1 and Roosevelt Blvd.

Following the site visits, manual data collection at each of the locations was conducted by trained field observers, equipped with computerized traffic counting devices during peak and off-peak periods, in order to capture the data for the most congested and non-congested periods of the day. The field data collected includes the following:

Static Inventories: Inventory of physical characteristics of the roundabouts, which includes shape, location, designed speed, sight distance, deflection, number of circulating lanes, central islands, splitter islands, entries and exits, signing, lighting, landscaping, land use in vicinity, and traffic generators.

Dynamic Studies: Dynamic studies include vehicles, pedestrians, and bicycles, and were performed during peak and off-peak periods for the following data:

- volume counts
- delay studies
- gap and lag measurements
- speed studies

Administrative Studies: Assembly of records of engineering, public works, and/or planning offices: data already available in office files, such as measurements and/or observations of existing conditions involving operational measurements.

Compilation of accident data records: Number of accidents involving bicycles and pedestrians and the number of fatalities and injuries during the last five years at the nine locations. The accident data was broken down by time of day, weather conditions, vehicle, bicycle and pedestrian movements, violations, and other relevant contributing factors.

Video Data Collection

In order to determine traffic patterns, including movement conflicts and behaviors of motorists, bicyclists, and pedestrians, video cameras were installed to capture activities at each of the approaches at the study locations. Three cameras were placed simultaneously at each roundabout to observe vehicles, pedestrians, and cyclists, over a 24-hour period. Strategic placement of the video cameras and selection of focal length were geared toward collection of appropriate pedestrian bicycle and traffic data.

4.0 SOUTH FLORIDA ROUNDABOUTS

4.1 EXISTING TRAFFIC CIRCLES AND ROUNDABOUTS IN SOUTH FLORIDA

4.1.1 Cartagena Plaza Circle, Coral Cables

Cartagena Plaza Circle is located in a high-income level residential area. The Cartagena Plaza Circle is a single-lane, 4-approach traffic circle, with the exception of Cocoplum Drive, which has two lanes. The width of the circulating roadway varies from 40 ft to 63 ft (12m to 19m). Parking is provided between Le Jeune Road and Cocoplum Drive. A six-feet (1.8 m) pedestrian/bicycle path is provided outside the Circle. The foot path is discontinued between Sunset Drive and Old Cutler Road. All approaches are controlled by yield signs, except for Cocoplum Drive, which is controlled by a stop sign. The condition diagram for the circle is shown in **Figure 4.1**.

Traffic data was collected manually during a.m. and p.m. peak periods. The results of the manual traffic data collection are presented in **Table 4.1.** Automatic counts are presented in **Table 4.2**, as well as the speed and vehicle classification data collected. Observations and data collection showed that pedestrians and bicyclists usually travel from Le Jeune Road to Old Cutler Road, and that Cocoplum Drive has the highest number of pedestrians and bicycles crossing the approach. Detailed pedestrian and bicycle activities during the weekdays are presented in **Table 4.3**.

The result of the speed study showed that the majority of the vehicles enter and exit the roundabout at an average speed of 27 mph (43 km/hr). The only exception was Cocoplum Drive, where the speed dropped to 14 mph (22.4 km/hr) due to the stop sign at the entry of the Circle, as well as the Cocoplum Residential Community gate which is located 100 ft (30 m) from the exit of the Circle.

Based on the collected data, SIDRA software was used to analyze the Circle, operating as a roundabout. It was taken into consideration that SIDRA was not designed to analyze traffic circles and does not handle pedestrians and bicycles at roundabouts. This resulted in the simulation of the traffic circle operating as a roundabout without considering pedestrian and bicycle volumes. The results of the analysis are presented in **Tables 4.4** and **4.5,** which show that the overall level-of-service (LOS) for both a.m. and p.m. peak periods as "B". The effect of the traffic signal located north of Le Jeune Road was not taken into consideration.

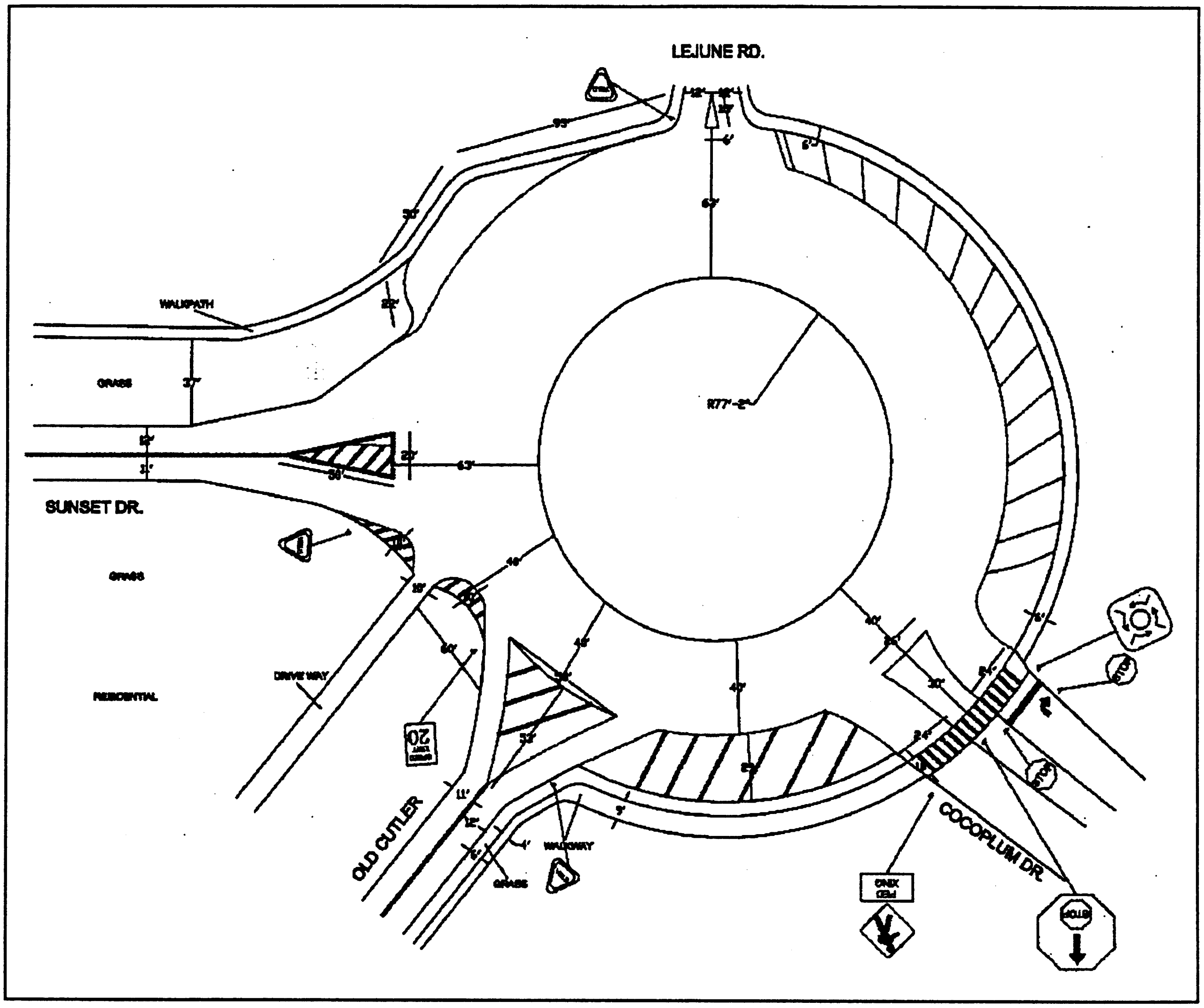

Figure 4.1 - Configuration of Cartagena Plaza Circle, Coral Gables

Table 4.1 - AM and PM Turning Movement Counts at Cartagena Plaza Circle

Time	Le Jeune Road				Sunset Drive				Old Cutler Road				Cocoplum Drive			
	Exits	Entries	Right Turns	Cir.	Exits	Entries	Right Turns	Cir.	Exits	Entries	Right Turns	Cir.	Exits	Entries	Right Turns	Cir.
7:00	407	117	16	13	31	156	0	100	79	273	6	142	44	42	30	401
7:15	420	150	23	23	46	220	5	150	120	187	4	217	38	51	29	411
7:30	423	234	37	30	53	207	4	208	172	195	3	235	50	78	45	445
7:45	407	216	52	52	77	222	9	179	170	178	2	205	48	51	37	464
8:00	414	219	53	50	80	211	3	193	170	200	0	225	49	72	45	388
8:15	435	212	41	46	87	220	4	161	160	214	3	213	51	84	43	389
8:30	401	196	42	36	67	217	3	157	140	183	4	200	48	66	39	407
8:45	410	195	37	27	54	196	27	159	155	168	1	218	57	72	41	365
3:30	278	318	54	38	99	107	4	261	248	193	5	152	55	69	15	206
3:45	246	347	42	32	94	94	5	288	264	150	4	115	54	52	13	183
4:00	202	347	48	52	105	107	12	279	268	148	1	109	61	59	13	181
4:15	233	366	52	49	97	103	15	305	287	172	0	118	46	50	23	214
4:30	227	382	40	37	82	105	10	304	306	145	2	113	40	49	18	205
4:45	238	379	48	26	85	103	9	308	287	156	1	119	53	25	12	209
5:00	207	381	42	41	95	112	8	319	302	142	0	122	57	56	19	190
5:15	234	364	46	36	80	121	13	318	323	149	1	121	48	44	9	197

Table 4.2 - Summary of Automatic Counts at Cartagena Plaza Circle, Coral Gables

Approach Name	Entry			Exit		
	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume
Sunset Drive	5,859	546	393	5,437	346	425
Old Cutler Road	8,204	711	565	10,947	621	1,148
Cocoplum Drive	2,974	268	241	2,988	213	246
Le Jeune Road	12,360	711	914	12,999	1,297	790

Table 4.3 - Pedestrians and Bicycle Activities at Cartagena Plaza Circle, Coral Gables (1998)

Approach Name	Pedestrians		Bicycles	
	AM	PM	AM	PM
Sunset Drive	22	8	2	4
Old Cutler Road	39	15	1	3
Cocoplum Drive	29	24	12	0
Le Jeune Road	0	0	0	0

Table 4.4 - AM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec/veh)	LOS
Sunset Drive	663	886	0.714	13.6	B
Old Cutler Road	666	682	0.977	38.2	D
Cocoplum Drive	257	878	0.293	13.9	B
Le Jeune Road	739	1,625	0.455	4.6	A
Intersection	2,295	4,071	0.977	17.9	B

Table 4.5 - PM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec/veh)	LOS
Sunset Drive	363	470	0.772	24.9	**C**
Old Cutler Road	552	1,012	0.545	8.2	**A**
Cocoplum Drive	286	1,489	0.192	9.4	**A**
Le Jeune Road	1,039	1,266	0.821	9.1	**A**
Intersection	2,240	4,298	0.821	11.5	**B**

Video Examination

Figures 4.2 to 4.6 were clipped from the video tapes for the Cartagena Plaza Circle. These figures show how pedestrians and bicyclists cross the approaches of the Circle, as well as the location of the main conflict points.

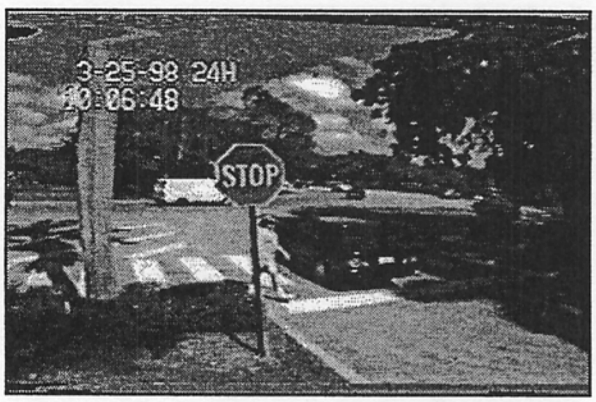

Figure 4.2 - An Entering Vehicle Not Giving the R.O.W. to Pedestrian at Crossing

Figure 4.3 - Pedestrians Getting out of Cocoplum Community Use the Roadway

Figure 4.4 - A Cyclist Going Opposite to Traffic on the Circulating Roadway

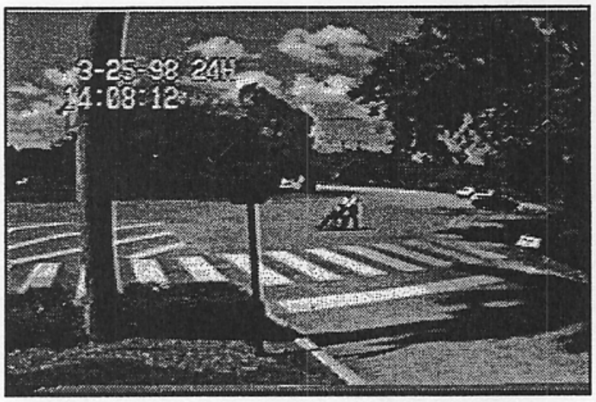

Figure 4.5 - Pedestrian on Roller Skates Pushing a Wheelchair in the Circulating Roadway Going Opposite to the Traffic Flow

Figure 4.6 - Cyclists are not Willing to Stop for Vehicles Already on the Crosswalk

4.1.2 Royal Circle, Miami Springs

The Royal Circle is a six-leg traffic circle (see **Figure 4.7**) located within an area of mixed residential and commercial activities. Most of the traffic entering the Circle is a cut-through traffic that is not generated by the surrounding activities. The approaches to the Circle are controlled by stop signs, except for the east side of Royal Poinciana Blvd., which is controlled by a yield sign, as shown in **Figure 4.8**. The north side of Curtiss Parkway is uncontrolled. The circulating roadway across the north side of Curtiss Parkway is controlled by a yield sign. Thus, circulating traffic must yield to the entering traffic from Curtiss Parkway (North).

The radius of the central island is 122 ft (37 m), while the radius of the inscribed circle is 200 ft (61 m). This leaves 78 ft (24 m) for circulating traffic lanes, which varies from one lane to three lanes with a lane width of 12 ft (3.6 m). There are several driveways on the circulating roadway providing access to different commercial activities at the traffic circle (see **Figure 4.9**). Parking is provided on the outer perimeter of the circle between Royal Poinciana Blvd./Curtiss Parkway/Royal Poinciana Blvd.

A traffic signal is located on the east side of Royal Poinciana Blvd., at a distance of 110 ft (34 m) from the Circle. As a result, queues build up in the a.m. and p.m. periods during the red phases, which causes total blockage to the circle, and in most cases, police enforcement officers are needed to regulate the traffic during the PM peak period.

Summary of traffic data collection and analysis for the Royal Circle operating as a roundabout are presented in **Tables 4.6,** to **4.10**.

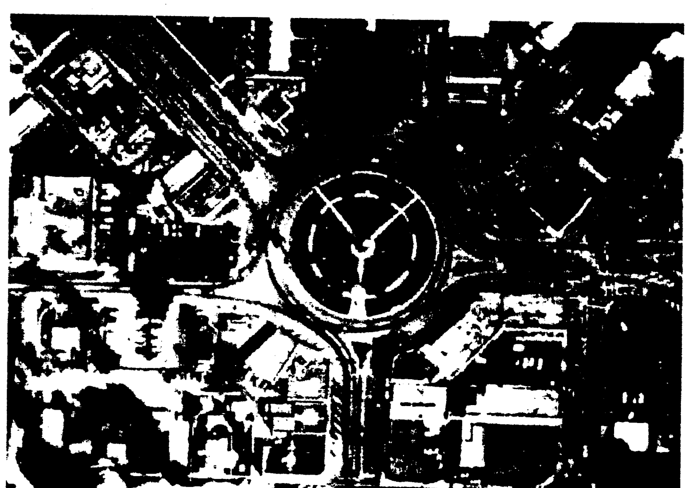

Figure 4.7 - Aerial View of the Royal Circle

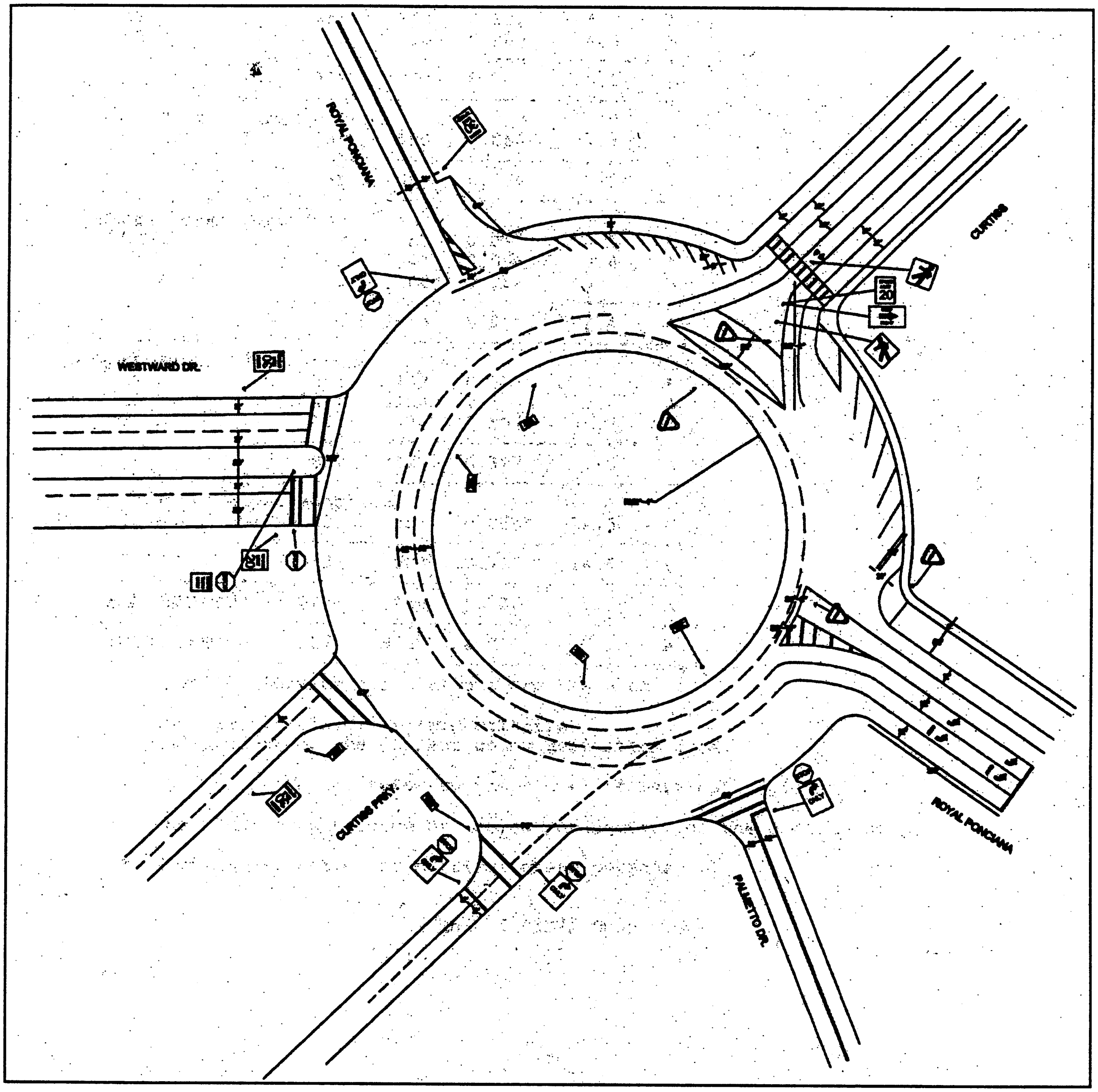

Figure 4.8 - Condition Diagram for Royal Circle, Miami Springs

Table 4.6 - AM and PM Turning Movement Counts at Royal Circle, Miami Springs

Time	Curtiss Pkwy (North)				Royal Poinciana (West)				Westward Dr.				Curtiss Pkwy (South)				Palmetto Dr.				Royal Poinciana (East)			
	Exit	Entry	Right	Cir	Exit	Entry	Right	Cir	Exit	Entry	Right	Cir	Exit	Entry	Right	Cir	Exit	Entry	Right	Cir	Exit	Entry	Right	Cir
7:00	0	165	52	74	97	175	0	114	43	52	0	236	107	85	1	148	4	6	1	267	138	55	0	12
7:15	6	214	52	81	108	193	2	151	66	79	1	244	116	80	0	180	4	5	3	324	116	58	5	8
7:30	3	241	33	37	64	103	1	337	51	99	3	294	183	69	0	231	7	3	0	463	130	39	4	7
7:45	6	218	28	65	78	91	0	312	54	89	5	409	196	79	1	256	11	3	3	390	123	39	2	9
8:00	4	182	27	55	69	67	0	267	64	102	0	421	118	76	2	279	12	5	5	245	125	46	4	11
8:15	2	165	36	53	73	95	1	158	47	95	1	371	185	89	1	164	10	0	0	296	139	41	1	10
8:30	8	155	25	45	87	70	0	213	42	97	5	378	184	76	1	118	11	5	4	337	139	35	6	10
8:45	5	127	17	47	71	60	0	295	53	89	2	354	155	76	2	252	12	9	5	316	150	33	0	17
3:30	12	168	36	93	97	97	1	299	69	84	2	312	135	120	1	252	10	4	4	368	176	46	7	33
3:45	9	172	30	119	90	108	1	174	78	68	0	271	131	114	0	217	13	13	2	342	147	65	5	32
4:00	10	184	27	85	85	94	1	173	75	70	4	323	140	132	3	230	11	8	0	359	156	45	3	36
4:15	12	165	42	97	90	90	1	270	73	63	3	290	147	118	2	186	7	9	0	296	141	52	5	31
4:30	9	176	36	93	79	81	0	189	59	54	1	277	129	118	2	189	11	5	0	279	160	46	1	26
4:45	4	182	31	98	94	105	0	237	73	79	1	289	141	148	1	209	12	8	1	360	165	52	2	27
5:00	3	206	41	124	84	111	1	282	72	79	3	332	146	139	0	231	9	10	1	399	167	53	1	32
5:15	7	207	39	132	83	116	0	273	68	52	1	247	171	165	1	225	11	10	2	401	158	55	3	26

Table 4.7 - Results of Automatic Counts at Royal Circle, Miami Springs

Approach Name	Entry			Exit		
	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume
Curtiss Pkwy (North)	10,074	855	793	496	47	49
Royal Poinciana (West)	5,669	596	487	4,955	347	369
Westward Dr.	4,373	385	378	3,801	288	295
Curtiss Pkwy (South)	6,139	348	599	7,564	753	608
Palmetto Dr.	477	42	40	633	51	58
Royal Poinciana (East)	3,020	203	260	9,522	585	650

Table 4.8 - Pedestrians and Bicycle Activities at Royal Circle, Miami Springs

Approach Name	Pedestrians		Bicycles	
	AM	PM	AM	PM
Curtiss Pkwy (North)	3	1	4	0
Royal Poinciana (West)	7	28	2	4
Westward Dr.	3	20	4	5
Curtiss Pkwy (South)	0	21	3	4
Palmetto Dr.	5	29	3	4
Royal Poinciana (East)	9	42	1	3

Table 4.9 - AM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec/veh)	LOS
Curtiss Pkwy (North)	830	2,325	0.357	5.5	A
Royal Poinciana (West)	429	583	0.736	14.6	B
Westward Dr.	234	1,277	0.183	7.2	A
Curtiss Pkwy (South)	518	1,720	0.301	5.1	A
Palmetto Dr.	39	590	0.066	7.3	A
Royal Poinciana (East)	220	2,565	0.086	3.4	A
Intersection	2,270	9,059	0.736	7.1	A

Table 4.10 - PM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec/veh)	LOS
Curtiss Pkwy (North)	788	2,376	0.332	5.2	A
Royal Poinciana (West)	407	606	0.672	12.7	A
Westward Dr.	222	1,342	0.167	6.7	A
Curtiss Pkwy (South)	492	1,770	0.278	4.8	A
Palmetto Dr.	43	616	0.070	7.3	A
Royal Poinciana (East)	209	2,596	0.081	3.3	A
Intersection	2,161	9,305	0.672	6.5	A

Video Examination

It can be observed from the video tapes that pedestrians and cyclists do not use crosswalks when crossing the approaches of the circle. Also, pedestrians are found to cross the circulating roadway instead of going around the circle. This is mainly due to the large diameter of the circle and the gazebo located in the middle of the circle, which has become a social area for the residents, attracting them to cross the circle. **Figures 3.10 to 3.15** show different cases during day and night. Pedestrians are exposed to unsafe circumstances when crossing the circulating lanes.

Figure 4.9 - View of Royal Circle, Miami Springs

Figure 4.10 - A Pedestrian Crossing the Circulating Roadway

Figure 4.11 - Pedestrians Walking on the Edge of the Circulating Roadway

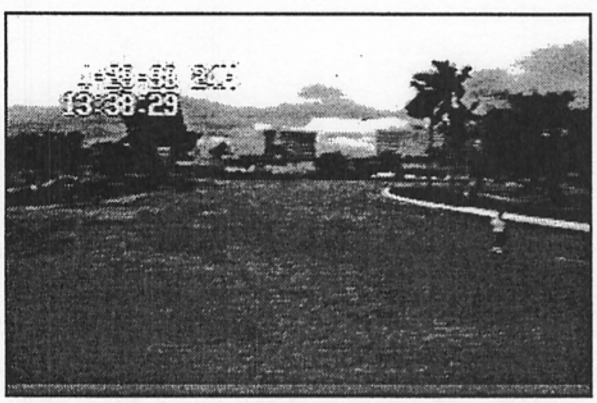

Figure 4.12 - A Pedestrian Walking in the Middle of the Circulating Roadway

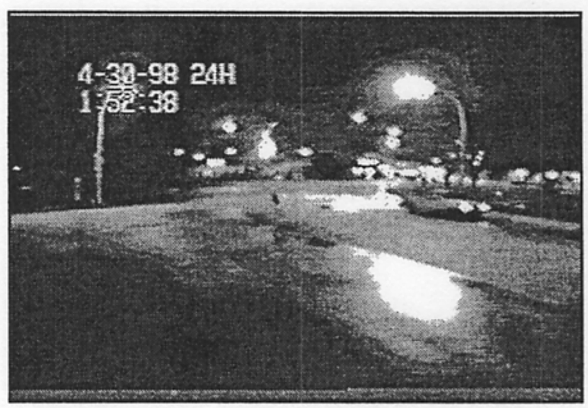

Figure 4.13 - A Vehicle Dropping off a Passenger on the Central Island

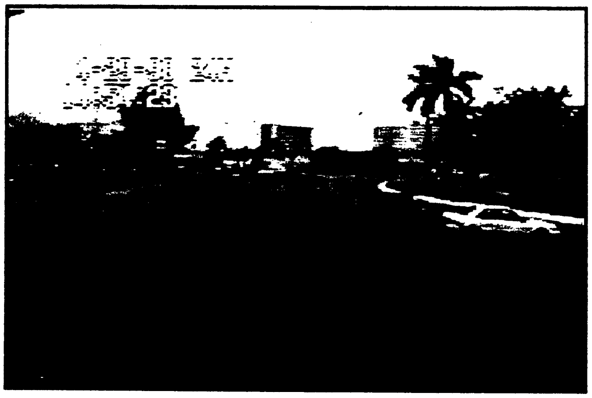

Figure 4.14 - A Vehicle Trying to Go to the Innermost Lane w/o Waiting for a Gap

Figure 4.15 - Entering Vehicles Not Giving the R.O.W. to Circulating Vehicles

4.1.3 City Hall Circle, Hollywood

The City Hall Circle (see **Figure 4.16**) is a four-approach, multilane traffic circle located in an area of mixed residential, business and commercial activities. The Hollywood City Hall building is situated in the middle of the Circle. The Circle is located at the intersection of Hollywood Blvd. and South 26th Street. The outer perimeter of the circle is occupied by commercial buildings, which create business-based activity. These businesses provide parking to their employees and visitors. Access to this parking lot can only be provided through the Circle. Also, there is a gas station located on the outer perimeter of the Circle that can be accessed from the circulating roadway. Two traffic signals are located on the circulating roadway to help facilitate vehicle access to the parking lot, as well as to the City Hall building in the central island. The east and west entries and exits of the Circle are uncontrolled, while the north and south exits are controlled by the traffic signals. The east access to the City Hall building is controlled by a stop sign, and vehicles exiting from the City Hall building are only allowed to make left turns.

The traffic distribution of vehicles using the access points to the City Hall building, presented in **Table 4.11**, shows that the south access roadway is heavily used by vehicles, followed by the north access roadway. Traffic volume entering, exiting and circulating at the main Circle is presented in **Table 4.12**.

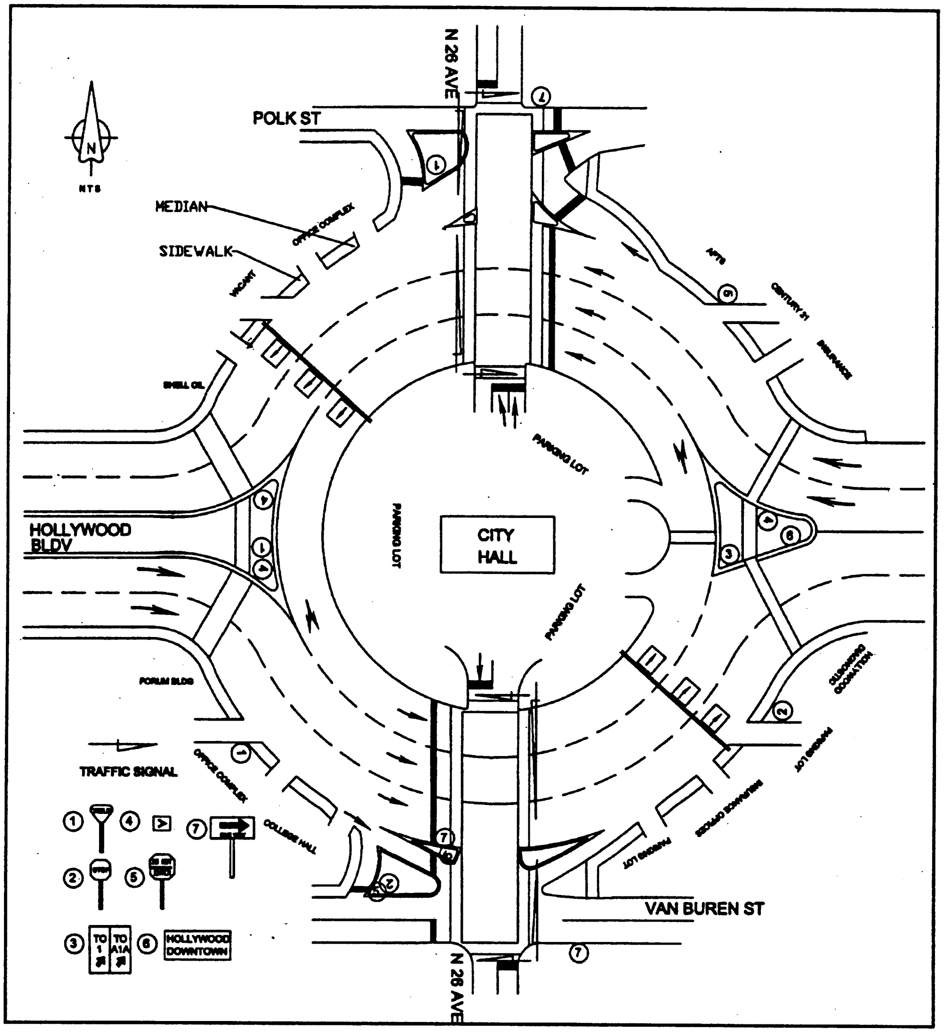

Figure 4.16 - Configurations of City Hall Circle, Hollywood

Table 4.11 - ADT Entering and Exiting the City Hall Building

Access Location	Average Daily Traffic	Entry		Exit	
		AM Peak Hour Volume	PM Peak Hour Volume	AM Peak Hour Volume	PM Peak Hour Volume
South Access	5,553	229	202	152	304
North Access	4,008	151	187	228	267
East Egress	557	60	71	62	63

Table 4.12 ADT Entering, Exiting and Circulating at the City Hall Circle

Approach Name	Entry			Exit		
	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume	Average Daily Traffic	AM Peak Hour Volume	PM Peak Hour Volume
Hollywood Blvd (west)	14,793	1,022	1,148	1,592	1,218	1,113
Hollywood Blvd (east)	12,966	941	1,023	17,394	1,238	1,306
S. 26th Street (South)	2,706	1,010	172	4,066	494	416
S. 26th Street (South)	5,255	312	478	1,138	97	143
North **Circulating** Traffic	17,083	1,156	1,358			
South **Circulating** Traffic	17,353	1,394	1,221			
East **Circulating** Traffic	11,404	782	897			
West **Circulating** Traffic	1,298	87	121			

Accident Data at City Hall Circle

Table 4.13 presents accident types, contributing causes, and actions taken to reduce the number and severity of the accidents that occurred in the City Hall Circle. It can be observed that careless driving was the main contributing cause of accidents. **Figure 4.17** shows the collision diagram for accidents in 1997.

Table 4.13 - Accident Analysis at the City Hall Circle, Hollywood

Type of Accident	Contributing Cause	Pedestrian/Bicycle Action
Collision with a fix object and a pedestrian	Unknown (hit & run)	Standing in pedestrian island
Collision with a vehicles and a pedestrian	Disregarded stop sign	Crossing not at intersection
Collision with a pedestrian and a tree	Careless driving	Crossing not at intersection
Collision with a parked vehicle and a pedestrian	Careless driving	Walking along road w/traffic

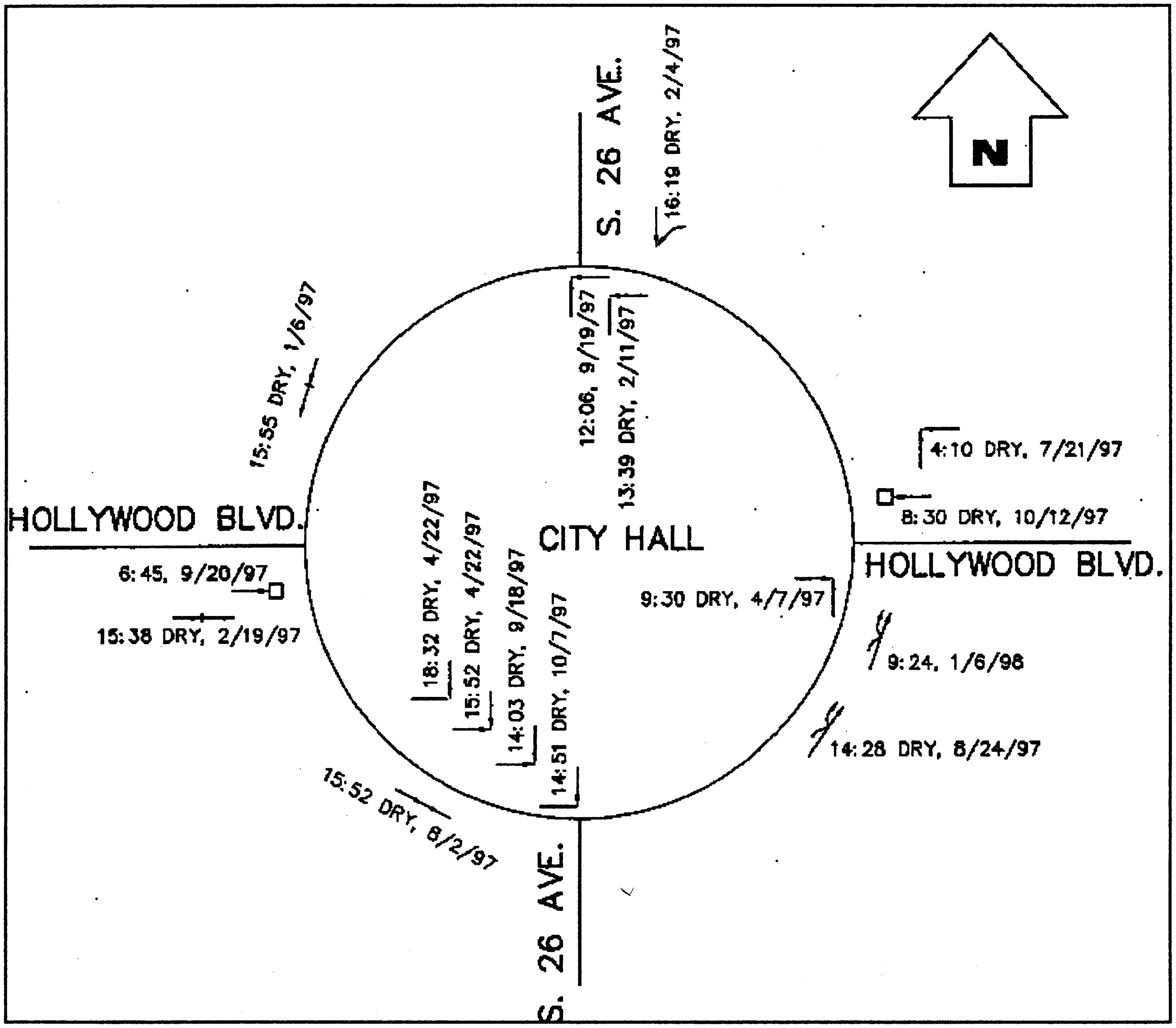

Figure 4.17 - Collision Diagram for Accidents at the City Hall Circle During 1997

4.1.4 Young Circle, Hollywood

Young Circle is located within the central business district (CBD) of the city of Hollywood, two miles west of the popular Hollywood Beach. The area is mainly commercial, with several service buildings situated on the perimeter of the Circle. The area is most commonly used by visitors from outside the Hollywood area.

The inscribed circle measures approximately 850 feet (260 m) across its diameter and has four lanes of circulating traffic. Street-side parking is provided on the inside perimeter of the Circle, as well as limited angle parking on the outer perimeter. A layout of the Circle is shown in **Figure 4.18**.

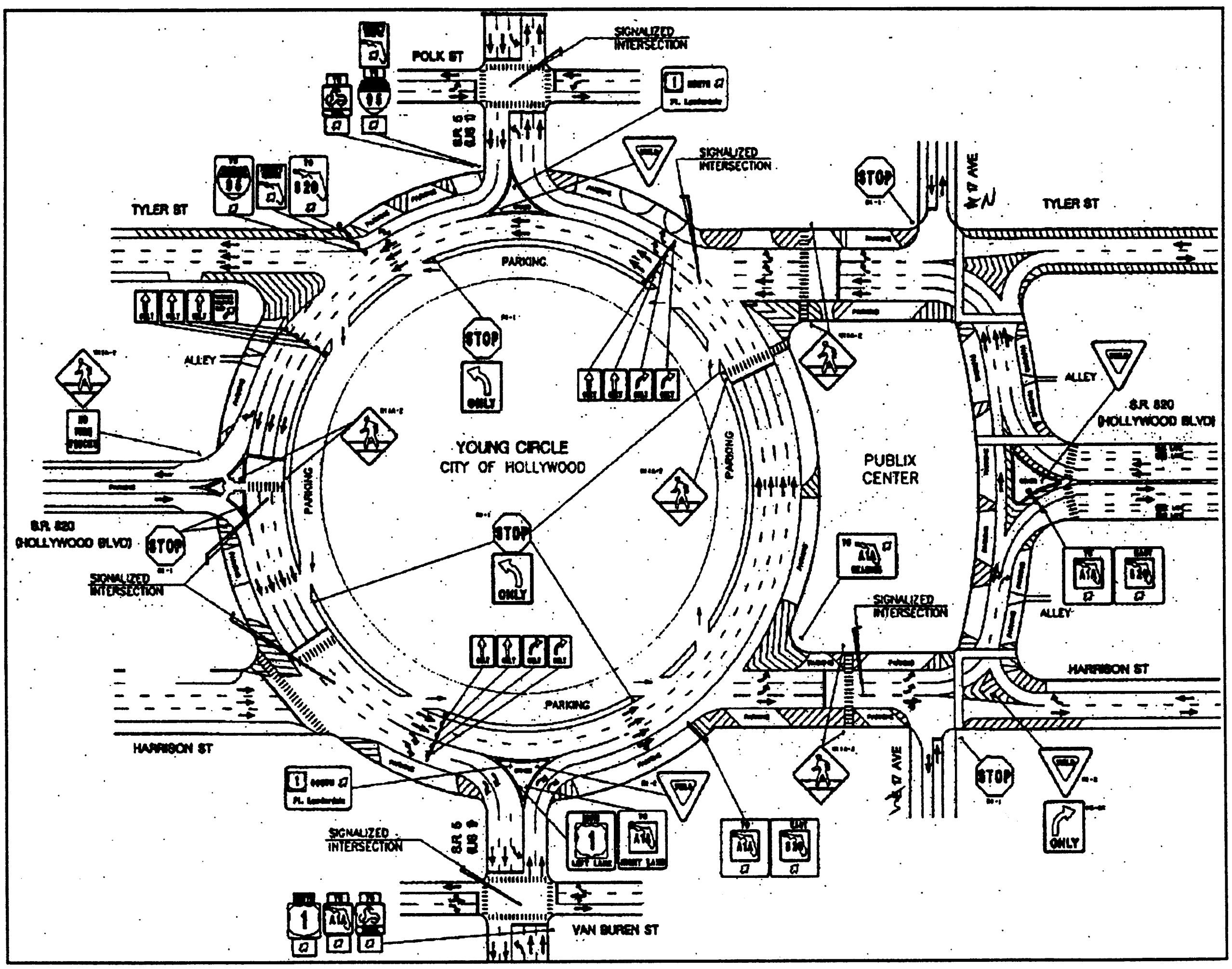

Figure 4.18 - Layout for Young Circle, Hollywood

Traffic along the Circle is controlled by a combination of traffic signals, yield signs, pavement markings, and other road signs. The Circle is extensively signed with directional lane markings and overhead signs. Several route signs have been placed to guide motorists to their desired destinations. However, it is very difficult for the average driver to read the signs and make the appropriate decision without interfering with other traffic on the Circle.

The central island of the Circle has four access points and four egress points. The locations of these access and egress points create additional conflict points. These access/egress points contribute significantly to the number of rear-end collisions on the Circle. On the other hand, the angle parking on the outer perimeter of the Circle has contributed to a number of "backing" accidents. The accident summary from 1993 to 1995 is presented in **Table 4.14**. The major type of accidents at the Circle is side-swipe, which has contributed to 43% of the total accidents within the three-year period. This may be due to the complex configuration and extensive number of lanes of the Circle.

Since the SIDRA software cannot handle such traffic circle configurations, a SIDRA analysis of Young Circle could not be performed. However, from field observations, it was concluded that parallel parking may be eliminated on Harrison Street and Tyler Street (west of the Circle) to minimize the pedestrian crossing distance that leads to the transit station located in front of the Publix Center. Also, pedestrian crossings may be installed at all intersections with "YIELD TO PEDESTRIAN ON CROSSWALK" signs in order to provide safer crossing to pedestrians. Finally, "Traffic Circle Ahead" signs should be installed at all approaches for the purpose of reducing vehicle speed.

Table 4.14 - Accident Summary at Young Circle, Hollywood (1993-1995)

Collision Type	US1-NB /Harrison	US1-NB /Tyler	US1 North	US1-SB /Tyler	US1-SB /Hollywd	US1-SB /Harrison	US1 South	Tyler EB /US1	US1 / Van Buren	US1 / Polk	Hollywd /US1 SB	Others	Total	Total (%)
Side Swipe	60	10	12	7	6	3	7	9	9	3	0	4	130	43%
Rear End	3	6	3	3	6	10	6	3	6	6	2	0	54	18%
Right Angle	2	3	2	0	1	1	4	5	19	8	0	4	49	16%
Backing	4	5	0	0	0	0	1	3	1	0	0	4	18	6%
Out of Control	2	0	8	0	1	0	1	1	0	0	0	0	13	4%
Pedestrian	0	4	1	1	1	0	1	0	0	3	0	3	14	5%
Parked	1	2	0	0	0	0	1	2	0	0	0	1	7	2%
Fixed Object	0	1	1	0	0	1	0	0	0	0	0	2	5	2%
Cyclist	0	0	0	0	0	0	0	1	0	1	0	1	3	1%
Head On	0	0	1	0	0	0	0	0	1	1	0	0	3	1%
Left Turn	0	0	0	0	0	0	0	0	3	3	0	0	6	2%
Total	72	31	28	11	15	15	21	24	39	25	2	19	302	100%
Total (%)	24%	10%	9%	4%	50%	7%	8%	13%	8%	1%	6%	100%		

4.1.5 President Circle, Hollywood

President Circle is located at the intersection of Hollywood Blvd. and Rainbow Drive. The area surrounding the Circle is mainly commercial. A business office building is located in the central island of the Circle, as shown in **Figure 4.19**. Hollywood Blvd. is a six-lane undivided roadway. The width of each lane is 12 ft (3.6 m). Several driveways providing access to businesses are located directly on the circulating roadway of the Circle. The east and west approaches of the Circle are not controlled, while the north and the south approaches are controlled by stop signs. The main traffic approaching the Circle is east/west traffic, while north/south traffic is minor. The circulating roadway of the Circle has three lanes, except for the parts adjacent to Hollywood Blvd., which is one lane controlled by a stop sign.

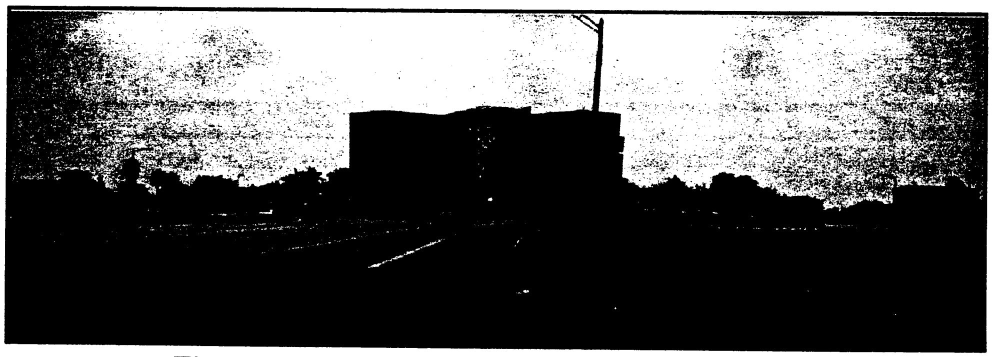

Figure 4.19 - View of President Circle, Hollywood

As shown in **Figure 4.20**, there are four access points and four egress points providing accessibility to the central island. Vehicles exiting the inner circle must get onto the acceleration lanes in order to gain speed and merge smoothly with circulating traffic. Pedestrian and bicycle activities at the President Circle are very low. This may be due to the large size of the circle and the large width of the approach lanes and circulating lanes of the Circle, which make it difficult for pedestrians and bicyclists to go around the circle.

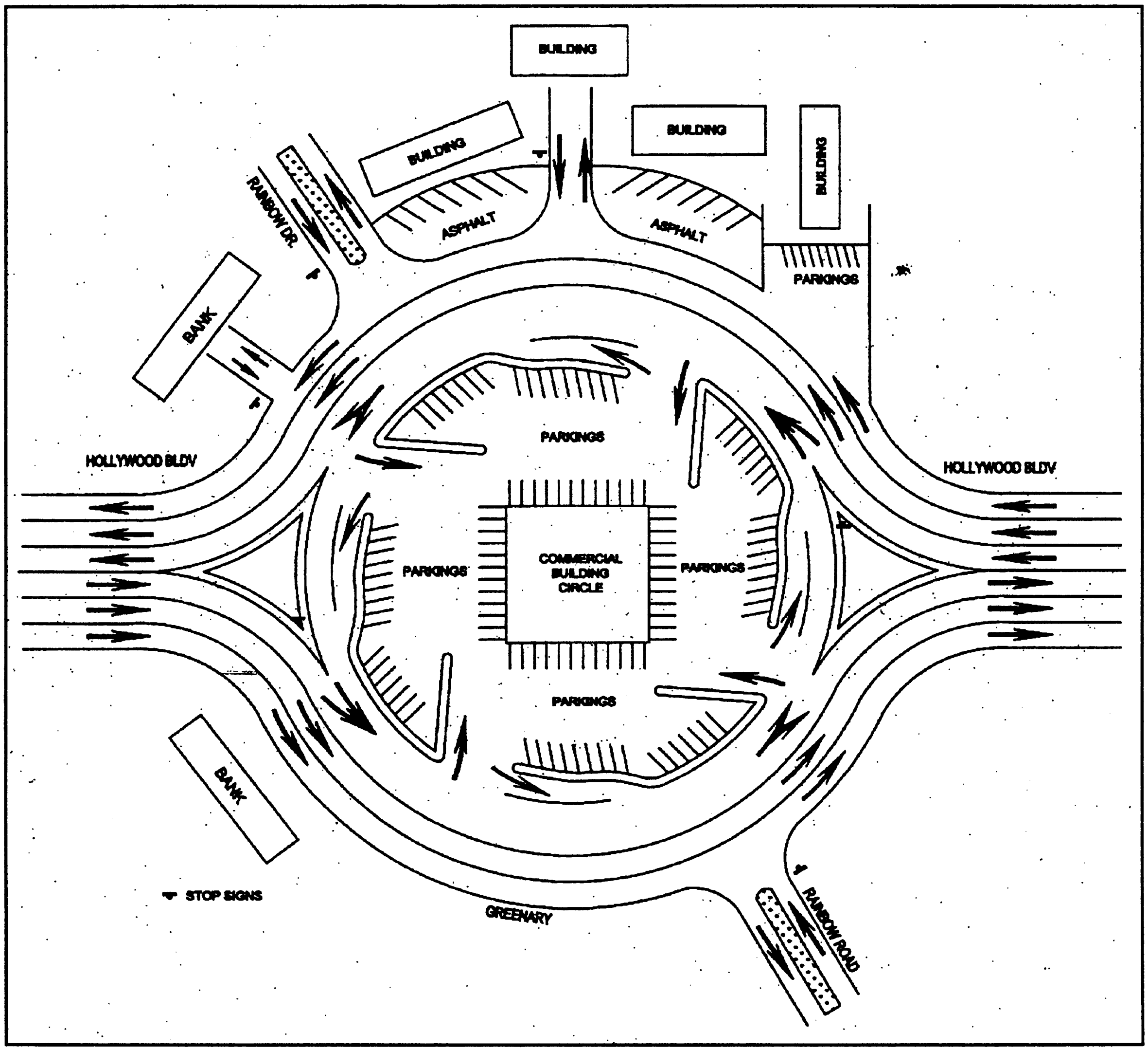

Figure 4.20 - President Circle Configuration, Hollywood

4.1.6 Confusion Circle, Stuart

Confusion Circle was constructed in 1945. It is located at the intersection of US 1/SR 76/ SR A1A. The current layout of the Circle is shown in **Figure 4.21**. The Circle has 4 multilane approaches and two lanes on most of the circulating roadway. Views of the Circle are shown in **Figures 4.22** and **4.23**, which show a railway track located just west of the Circle. When a train passes, it causes total paralysis to the traffic on the roundabout. This is the only traffic circle studied in Florida that is equipped with directional signs which help facilitate motorists to circulate and exit the circle with no significant complications. Examples of these signs can be seen in the diagrams in **Figures 4.24**, **4.25** and **4.26**.

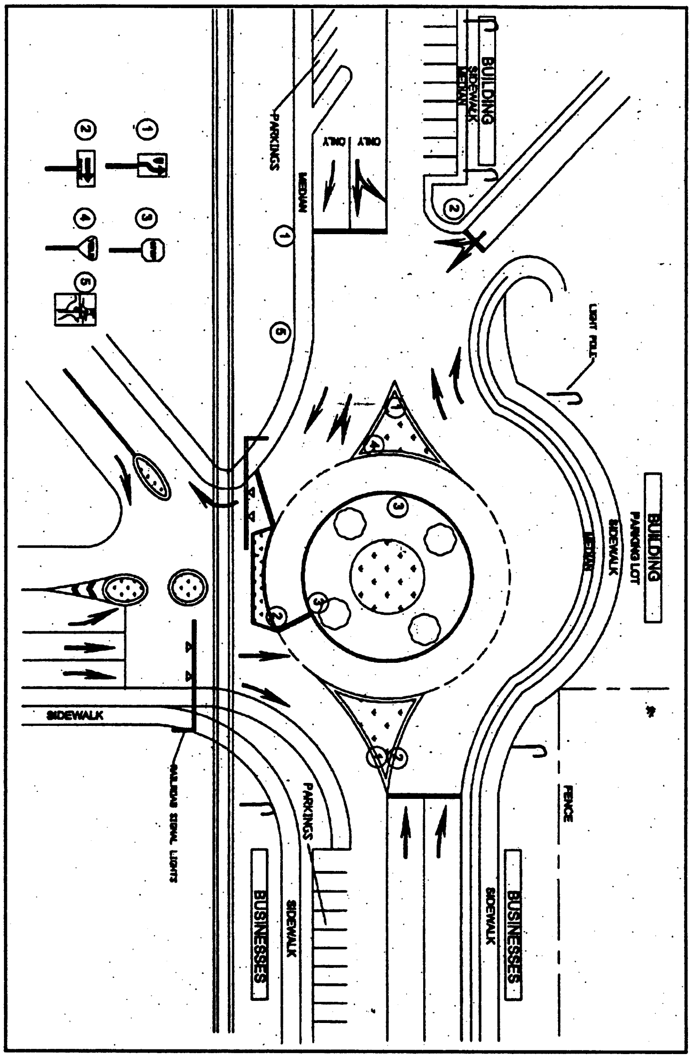

Figure 4.21 - Layout for Confusion Circle, Stuart

Figure 4.22 - View of Confusion Circle, Stuart

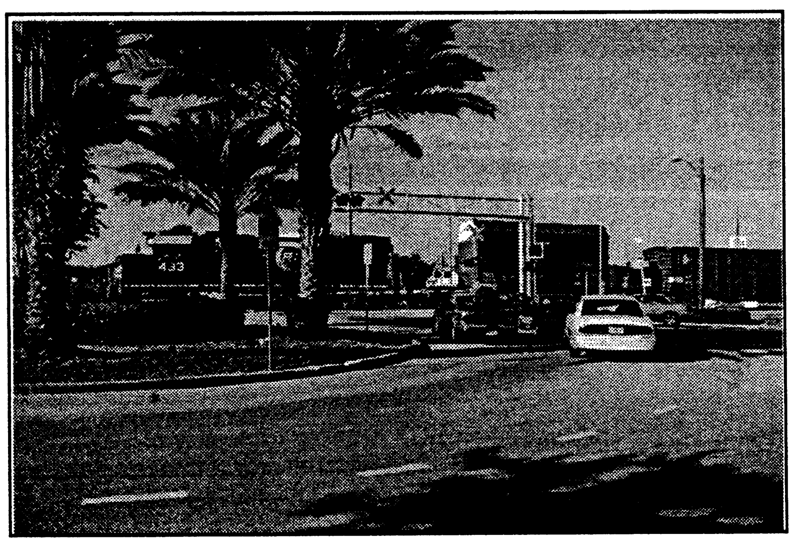

Figure 4.23 - A Train Passing next to the Circle

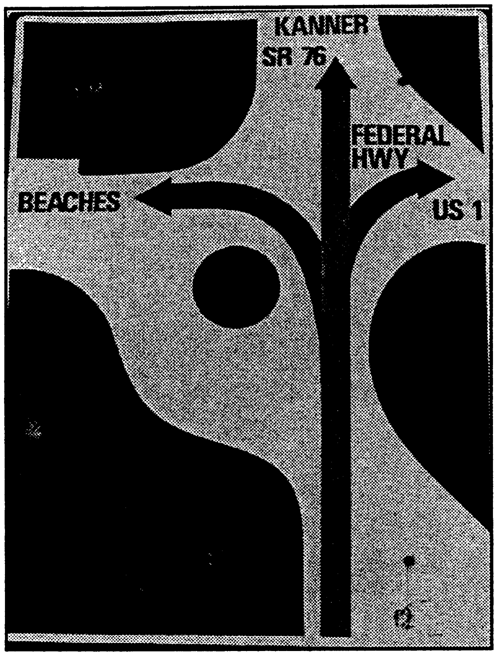

Figure 4.24 - Directional Sign at Confusion Circle

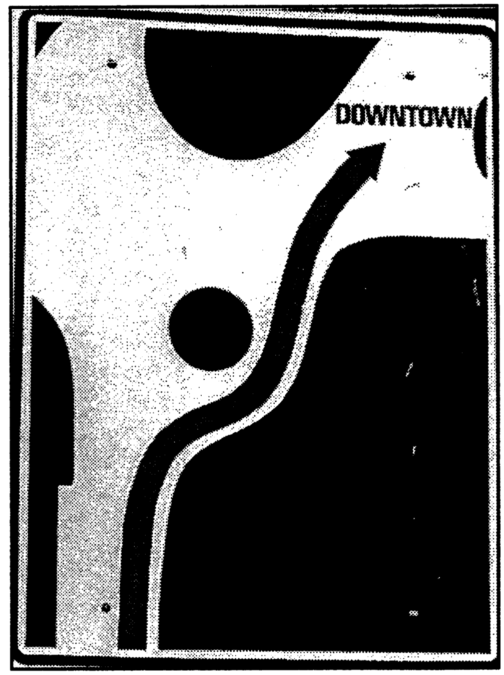

Figure 4.25 - Directions to Downtown

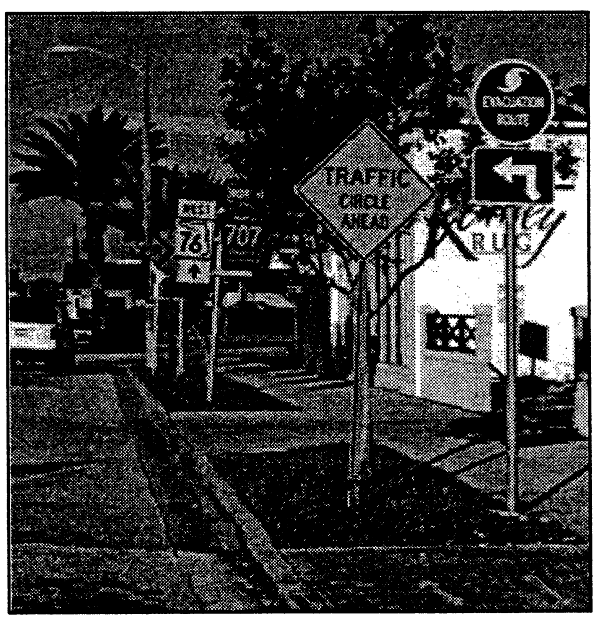

Figure 4.26 - "TRAFFIC CIRCLE AHEAD" SIGN

4.1.7 Camino Real, Boca Raton

The Camino Real circle is located at the intersection of Camino Real Blvd. and Royal Palm Drive. Camino Real Blvd. serves as a major east-west corridor connecting South Boca Raton CBD with the coastal areas. Royal Palm Drive provides access to Royal Palm Yacht Club Residential Community on the south and to a hotel on the North. The view of the roundabout is shown in **Figure 4.27**.

Figure 4.27 - View for Camino Real Circle

To the west of the circle, Camino Real Blvd. is a four-lane divided roadway. The eastbound is flared to three lanes approaching the roundabout. These consist of a combination of an exclusive right lane that provides access to the residential community, a through lane, and a shared through and U-Turn lane, while Camino Real on the east of the roundabout is a two-lane, two-way undivided. A Bascule bridge is located on Camino Real, east of the roundabout, at a distance of 100 feet (31 m). The bridge opens at the quarter hour to boats arriving between 7:00 a.m. and 6:00 p.m. At other times, the bridge opens depending on the marine traffic demand. The opening of the bridge causes severe interruption of traffic on the circle. During the bridge openings, vehicles are permitted to stop on the circulation roadway of the roundabout, which causes a total paralysis of the circle's operations. The circulating roadway varies from one to two lanes around the roundabout.

Although the intersection is considered a roundabout, it is not a fully modern roundabout, due to the existence of a "STOP" sign at the exit from the Royal Palm residential community. There is no special bicycle facility provided on the circle. Pedestrian facilities (sidewalk) are located on the northeast side of the circle, from the hotel to the coastal area.

Data was collected on a weekday, using automatic counters and video cameras. The traffic data shown in **Table 4.15** indicates that the average weekday ADT is 16,330 vehicles.

Table 4.15 - Summary of Automatic Counts at Camino Real Circle, Boca Raton

Approach Name	Entry			Exit		
	ADT	AM Peak Hour Volume	PM Peak hour Volume	ADT	AM Peak Hour Volume	PM Peak hour Volume
Royal Palm (south side)	1,952	185	164	1,522	121	137
Camino Real (east side)	1,335	124	134	6,163	512	527
Royal Palm (north side)	1,351	103	129	1,343	110	109
Camino Real (west side)	12,312	951	989	6,679	512	529

Although there are no major accidents at the roundabout, the main conflict point is a result of vehicles traveling from the north or the east, then heading south (see **Figure 4.28**). Also, there were complaints that while the bridge was open, vehicles were not able to enter the residential community. Thus, vehicles use the exit of the community rather than the entrance, which causes hazardous situations for exiting vehicles.

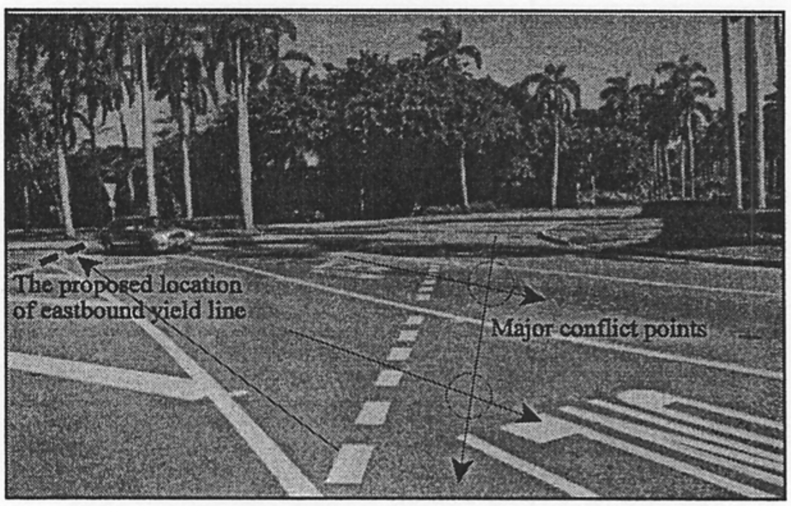

Figure 4.28 - Position of the Eastbound Yield Line

Based on field observations, the following recommendations will improve the safety as well as the performance of the roundabout:

1- Relocate the eastbound yield line to the location shown in **Figure 4.28**. This will provide shorter and safer pedestrian crossings so that they will have a clear line of sight, making them aware of vehicles approaching the roundabout.

2- Stop the vehicles entering the roundabout from Camino Real at the yield line instead of at the stop bar on the circulating lanes of the roundabout. Vehicles exiting the residential community have to travel to the edge of the roundabout in order to merge with the circulating traffic, as shown in **Figure 4.29**, where drivers have to rotate 140 degrees to be able to see the circulating vehicles.

3- Allow vehicles to merge with circulating traffic as close as possible to the exit of the residential community, as shown in **Figure 4.30**.

4- The "Traffic Circle Ahead" and speed limit signs should be installed on all of the approaches to the roundabout. It was observed that some motorists drive at high speeds, exceeding 55 mph (88 km/hr), when approaching the roundabout from both the east and west directions.

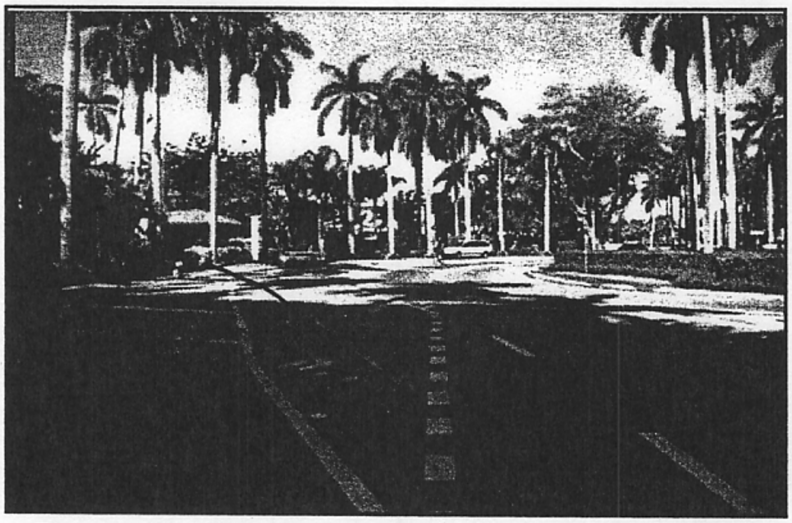

Figure 4.29 - Yield Line for Vehicles Exiting Royal Palm Residential Community

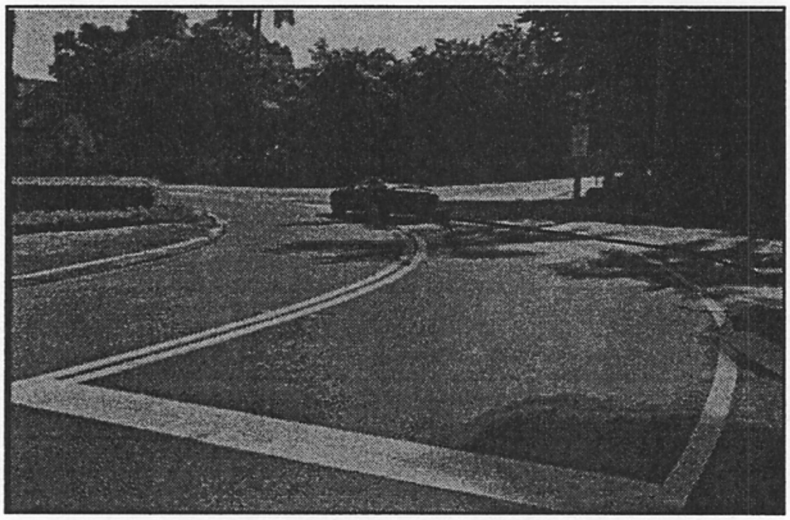

Figure 4.30 - Motorists Behavior Exiting Royal Palm Community

4.1.8 SW 18th Street / Juana Rd. (SW 12th Avenue), Boca Raton

The roundabout at the intersection of SW 18th Street and 12th Avenue is the only modern roundabout in South Florida. It is a four-approach, single-lane roundabout situated in a residential area. Its configuration is shown in **Figure 4.31**. Its inscribed diameter is 160 ft (49 m). The approaches of SW 18th Street to the roundabout are equipped with raised splitter islands, while the approaches of SW 12th Avenue are comprised of painted splitter islands. A flashing warning beacon is installed on the eastbound of SW 18th Street approach. A 'TRAFFIC CIRCLE AHEAD" sign is installed at all the approaches. Pedestrian crossings are also provided, and a combined pedestrian/bicycle path is located outside the roundabout. Pedestrian crossings are at a one-car length from the yield line of the roundabout. Pedestrian and cyclist activities at the roundabout are very low. During the a.m. and p.m. peak periods, there is only one pedestrian (see **Figure 4.32**) crossing the eastbound approach of the roundabout to go to his school, which is located on SW 12th Avenue, north of the roundabout.

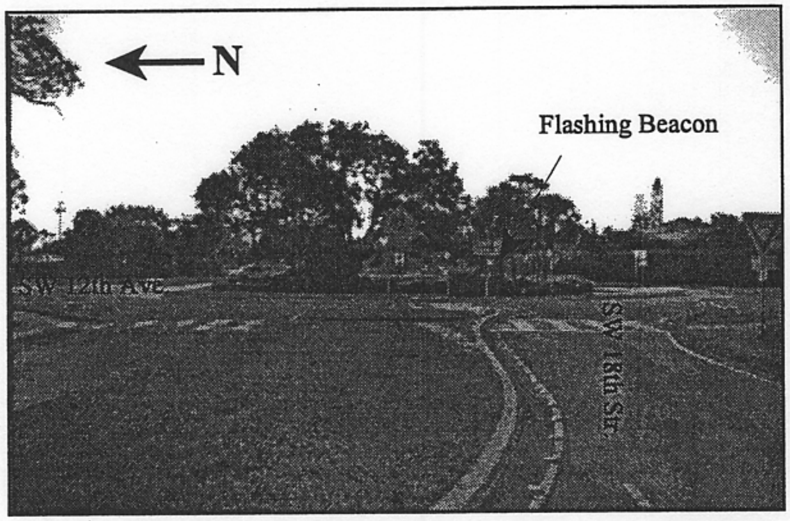

Figure 4.31 - View of the SW 18 Street/12 Avenue Modern Roundabout

Traffic data was collected at the roundabout for a period of 24 hours during a regular weekday. Data collected includes volume counts, vehicles speed and gap at twelve points at the roundabout (4 entry, 4 exit and 4 circulating points). The ADT at the roundabout is 15,800 vehicles per day and the peak hour volume is 1,272 vehicles during the a.m. peak, and 1,381 vehicles during the p.m. peak. ADT and peak hour volumes per approach are presented in **Table 4.16**, while the ADTs for circulation traffic are given in **Table 4.17**.

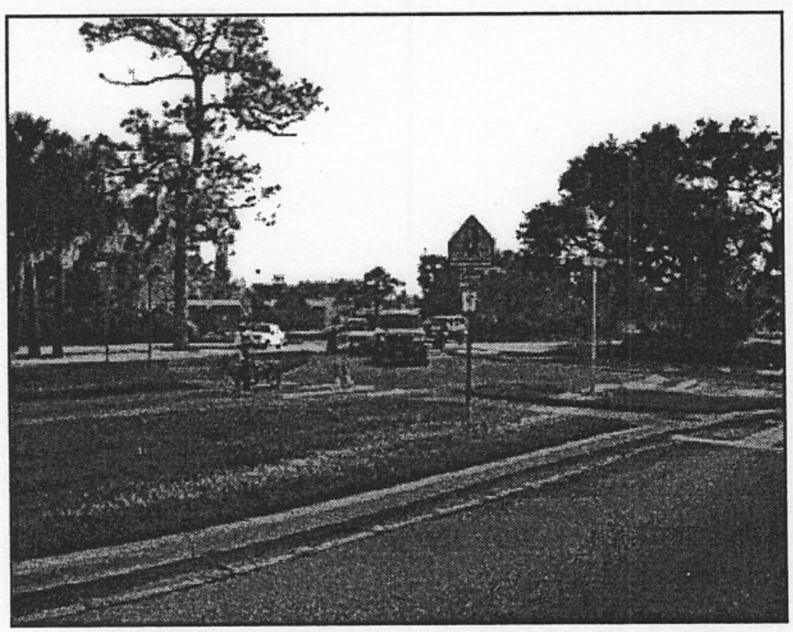

Figure 4.32 - A Student Crossing the West Exit of the Roundabout

Table 4.16 - Summary of Automatic Counts at SW 18 Street/12 Avenue, Boca Raton

Approach Name	Entry			Exit		
	ADT	AM Peak Hour Volume	PM Peak Hour Volume	ADT	AM Peak Hour Volume	PM Peak Hour Volume
East SW 18 Street	4,893	298	596	4,977	638	395
West SW 18 Street	5,089	529	442	5,379	356	670
North SW 12 Avenue	2,632	203	292	2,706	275	237
South SW 12 Avenue	698	104	53	672	43	77

Table 4.17 - Summary of Circulating traffic at SW 18 Street/12 Avenue, Boca Raton

Circulating Section	ADT	AM Peak Hour Volume	PM Peak hour Volume
East SW 18 Street	1,994	238	176
West SW 18 Street	1,366	119	133
North SW 12 Avenue	4,086	250	509
South SW 12 Avenue	6,552	835	545

The gap distribution analysis for the approaches to the roundabout shows that the 34% of the gaps of the east approach are less than or equal to two seconds and 41% for the west approach. On the other hand, the same gap duration on the circulating roadway of the roundabout is 25% for traffic on the north side of the roundabout and 47% for traffic on the south. The overall gap distribution is presented in **Table 4.18**. The results of the speed study presented in **Table 4.19** show that the average approaching speed is 25.63 mph (41 km/hr) and 16.56 mph 26.5 km/hr) for the circulating traffic.

Table 4.18 - Gap Distribution at SW 18 Street/12 Avenue, Boca Raton

Approach Name	≤2	3	4	5	6	7	8	9	≥10	Total
East SW 18 Street	3,386	778	590	461	400	338	294	211	3,412	9,870
West SW 18 Street	4,282	742	538	462	343	293	261	214	3,333	10,468
North SW 12 Avenue	991	258	222	203	161	158	155	152	3,038	5,338
South SW 12 Avenue	59	22	18	16	15	23	15	10	1,192	1,370
East SW 18 Street (circulating)	240	100	80	74	78	55	44	48	1,275	1,994
West SW 18 Street (circulating)	127	34	34	35	27	29	37	29	1,014	1,366
North SW 12 Avenue (circulating)	1,030	315	244	201	185	138	121	135	1,717	4,086
South SW 12 Avenue (circulating)	3,085	594	386	249	189	160	151	98	1,640	6,552

Table 4.19 - Summary of Speed Study at SW 18 Street/12 Avenue, Boca Raton

Approach Name	Average Speed (mph)
East SW 18 Street	30.52
West SW 18 Street	24.89
North SW 12 Avenue	24.39
South SW 12 Avenue	22.72
East SW 18 Street (circulating)	16.38
West SW 18 Street (circulating)	16.26
North SW 12 Avenue (circulating)	17.24
South SW 12 Avenue (circulating)	16.37

SIDRA was used to analyze the traffic at the roundabout for both the AM and PM peak periods. The results presented in **Tables 4.20** and **4.21** show that all the approaches to the roundabout have a LOS "A" all time, except for south SW 12 Ave, which has a LOS "B" during the AM peak period. The overall LOS for the roundabout is "A" at all times.

Table 4.20 - AM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec/veh)	LOS
East SW 18 Street	333	1,243	0.268	7.1	A
West SW 18 Street	568	1,610	0.353	7.1	A
North SW 12 Avenue	270	1,131	0.239	8.2	A
South SW 12 Avenue	128	783	0.163	11.0	B
Intersection	1,299	4,767	0.353	7.7	A

Table 4.21 - PM Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
East SW 18 Street	658	1,636	0.402	606	A
West SW 18 Street	435	1,407	0.309	7.3	A
North SW 12 Avenue	368	921	0.400	9.7	A
South SW 12 Avenue	62	895	0.069	9.2	A
Intersection	1,523	4,859	0.402	7.7	A

4.2 PROPOSED ROUNDABOUT SITES

4.2.1 Lake Worth Avenue/A Street, Lake Worth

The Lake Worth Avenue / "A" Street is currently a four-leg intersection controlled by traffic signals. The area around the intersection is mainly residential, with few businesses located directly at the intersection. A high school is also located at the southwest corner of the intersection. A middle and elementary school are located a quarter of mile south of the intersection. **Figure 4.33** shows an aerial view of the actual conditions of the intersection.

Lake Worth Avenue is a 4-lane divided roadway. The eastbound of Lake Worth Avenue is composed of two through lanes, of which the right lane is shared with through and right-turning vehicles, as well as one exclusive left-turning lane. Lake Ramp Avenue is a two-lane, one-way street heading to the east. On the other hand, Lucern Avenue is a two-lane, one-way street heading west. North and South "A" Streets are two-lane, undivided roadways with exclusive left-turning lanes at the intersection.

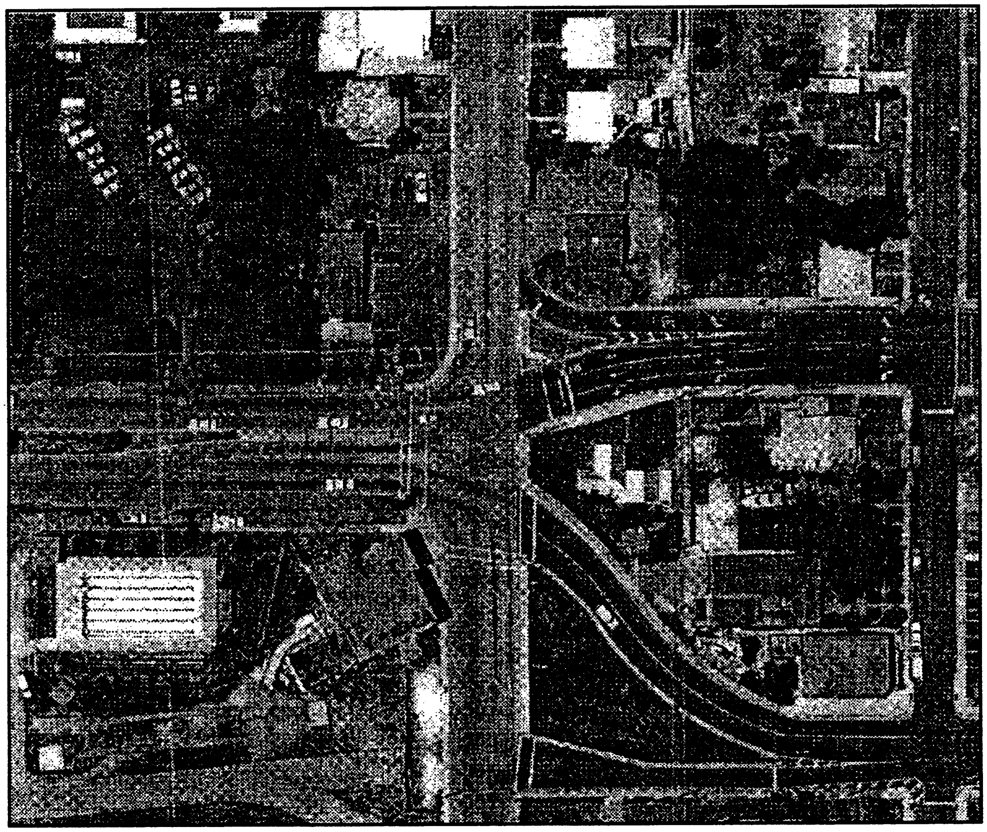

Figure 4.33 - Aerial View of Lake Worth Intersection

The traffic data collection before construction was performed by means of both manual and automatic machine counts. Also, speed and classification studies were performed for each approach. The results of the before construction data collection are presented in **Tables 4.22** and **4.23**, which shows that the main travel is in the east/west direction. The average speed at the intersection is 27.5 mph, and the average percentage of trucks is 4.14%.

Pedestrian and bicycle studies were also performed at the intersection. **Table 4.24** shows that the Lake Worth Avenue has the highest number of pedestrians, with 273 pedestrians crossing the approach during the three peak periods. Pedestrians are mainly students from the high school, and the pedestrian peaks occur just before and after school hours.

Table 4.22 - Peak Volumes/Movement at Lake Worth/A Street Intersection, Lake Worth (1998)

Street Name	ADT (vpd)	Average Approach Speed (mph)	Percentage of Trucks
Lake Worth Avenue	17,825	31.0	2.5 %
Lake Ramp	5,309	25.0	3.2%
Lucern Avenue	7,689	24.0	4.0%
North "A" Street	6,289	24.0	4.0%
South "A" Street	5,963	34.0	2.0%

Table 4.23 - Peak Hour Volumes/Approach at Lake Worth/A Street Intersection, Lake Worth (1998)

Street Name	ADT (vpd)	Direction of Traffic	AM Peak		PM Peak	
			Vol	Hr	Vol	Hr
Lake Worth Avenue	17,825	EB	603	7:00	642	2:45
		WB	590	7:00	705	3:30
Lake Ramp	5,309	EB	357	7:15	361	5:00
Lucern Avenue	7,689	WB	519	11:15	612	5:00
North "A" Street	6,289	SB	245	7:00	191	5:45
		NB	251	7:15	357	3:00
South "A" Street	5,963	NB	87	11:30	165	3:00
		SB	513	7:00	413	2:45

Table 4.24 - Pedestrian and Bicycle Volumes at Lake Worth/A Street Intersection, Lake Worth (1998)

Street Name	Pedestrian Volumes during peak periods			
	AM	MD	PM	Total*
Lake Worth Avenue	10	46	6	273
Lake Ramp &Lucern Avenue	9	2	3	41
North "A" Street	11	3	3	63
South "A" Street	8	4	7	50

* *Total pedestrian volume was counted during a 10-hour period.*

This intersection was converted into a modern roundabout in July, 2000. The configuration of the new roundabout is shown in **Figure 4.34**. The inscribed diameter of the roundabout varies from 80 ft to 101 ft (31 m), and the diameter of the inscribed circle varies from 144 ft (44 m)to 198 ft (60.5 m). Splitter islands are provided on South and North "A" Street, as well as Lake Worth Avenue. Pedestrian crossings are also provided only on North "A" Street and Lake Worth Avenue. The circulating lanes on the roundabout vary from one lane to two lanes, as shown in **Figure 4.34**. The width of the entry lanes and exit lanes is 12 ft (3.6 m), while the width of the circulating lanes is 16 ft (5 m). North and South "A" Streets consist of a single-lane entry and a single-lane exit for the roundabout. Directional signs are installed on the new roundabout to guide both motorists and pedestrians, as well as bicyclists.

After-construction traffic data collection was performed during the p.m. peak period (4:00 to 6:00 p.m.). It should be noted that South "A" Street was closed for utility construction during the data collection. Thus, South "A" Street was not taken into consideration during the after-construction analysis. Due to the project's time constraint, the after-construction traffic study was performed in the summer, when the high school was closed, and its effect was not taken into consideration. The analysis, which was derived from the after-construction data, is presented in **Table 4.25**, and was performed using the SIDRA 5.2 software. The analysis shows that the overall level-of-service for the roundabout is "A". The level of service calculations are based on the average control delay, including geometric delay, which presents Highway Capacity Manual (HCM) criteria for two-way stop sign intersections.

Thus, the before-construction traffic data was used to analyze the roundabout, taking into consideration vehicular traffic generated by the school. The SIDRA software can only simulate vehicle volumes for roundabouts; the SIDRA results are presented in **Table 4.26**.

Table 4.25 - SIDRA Analysis Using After-Construction Traffic Data for Lake Worth Roundabout, Lake Worth (2000)

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
Lake Worth Ave	795	3,405	0.23	0.2	**A**
Lake Ramp	EXIT ONLY				
Lucern Avenue	965	3,149	.31	0.7	**A**
North "A" Street	114	675	.17	3.9	**A**
South "A" Street	CLOSED				
Intersection	1,874	7,229	0.31	0.6	**A**

Table 4.26 - SIDRA Analysis Using Before Construction Traffic Data for Lake Worth/A Street Intersection, Lake Worth

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
Lake Worth Ave	870	1,526	0.570	12.4	**B**
Lake Ramp	EXIT ONLY				
Lucern Avenue	653	1,507	0.575	11.0	**A**
North A Street	267	645	0.414	13.0	**A**
South A Street	338	745	0.454	11.4	**A**
Intersection	2,128	4,423	0.575	11.9	**A**

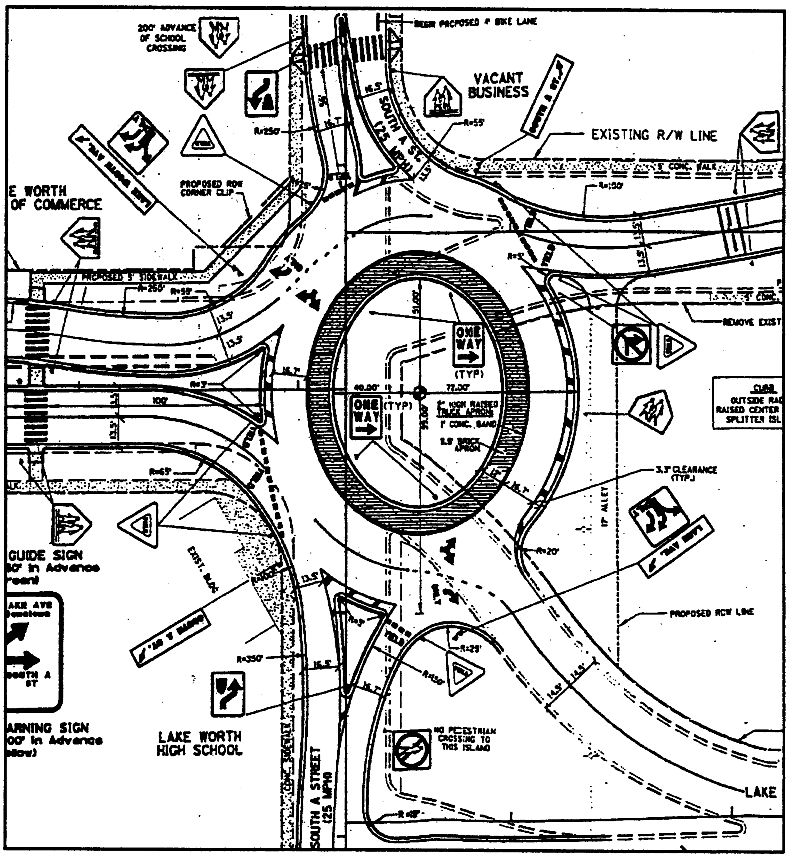

Figure 4.34 - Roundabout Configuration at Lake Worth Intersection

During the after-implementation visit to the Lake Worth roundabout location, several observations were recorded to document the behavior of the roundabout users. One major safety hazard of the Lake Worth roundabout is that drivers do not yield to circulating vehicles when entering the roundabout from Lucerne Avenue. This is due to several reasons. First, Lucerne Avenue has two entering lanes, while the circulating roadway between Lake Avenue and Lucerne Avenue is only one lane. Thus, entering vehicles think that they have priority over the circulating ones. Second, due to the change of grade of Lucerne Avenue, drivers are not aware of the existence of the roundabout. Third, the yield line of Lucerne Avenue is very close to the circulating roadway of the roundabout (see **Figure 4.35**). Comparing the location of the yield line in **Figures 4.34** and **4.35**, it is noticeable that the yield line was shifted approximately 5 feet (1.5 m) towards the circulating roadway, which causes the circulating drivers to stop for entering vehicles.

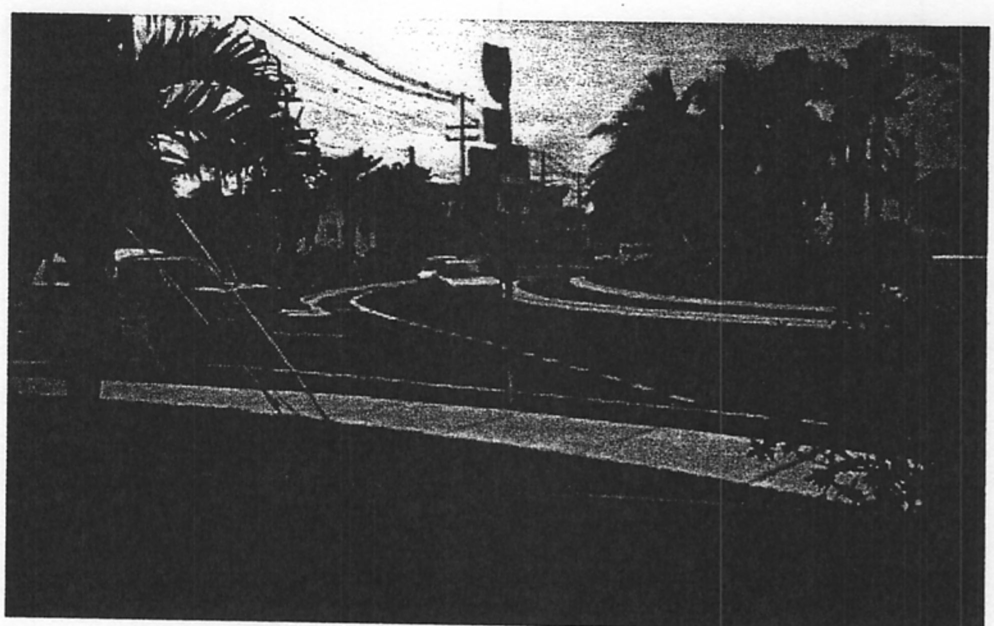

Figure 4.35 - Yield Line Location at Lucerne Avenue

Although directional signs were provided to guide drivers, several of these signs are blocked by landscaping, as presented in **Figure 4.36**. Moreover, the amount of provided directional and warning signs are causing confusion to the drivers approaching the roundabout, especially from the east approach. For example, there are more than 15 directional and warning signs on Lucerne Avenue, beginning about 200 feet (61 m) east of the roundabout.

Finally, pedestrians are not using the provided crossings on the approaches of the roundabout as shown in **Figure 4.37**. This is due to the fact that the provided crossings are located 100 feet (30.5

m) from the roundabout. Also at times, pedestrians are confused with the pedestrian crossings and the "SCHOOL" pavement markings at the exits of the roundabout, as shown in **Figure 4.38**.

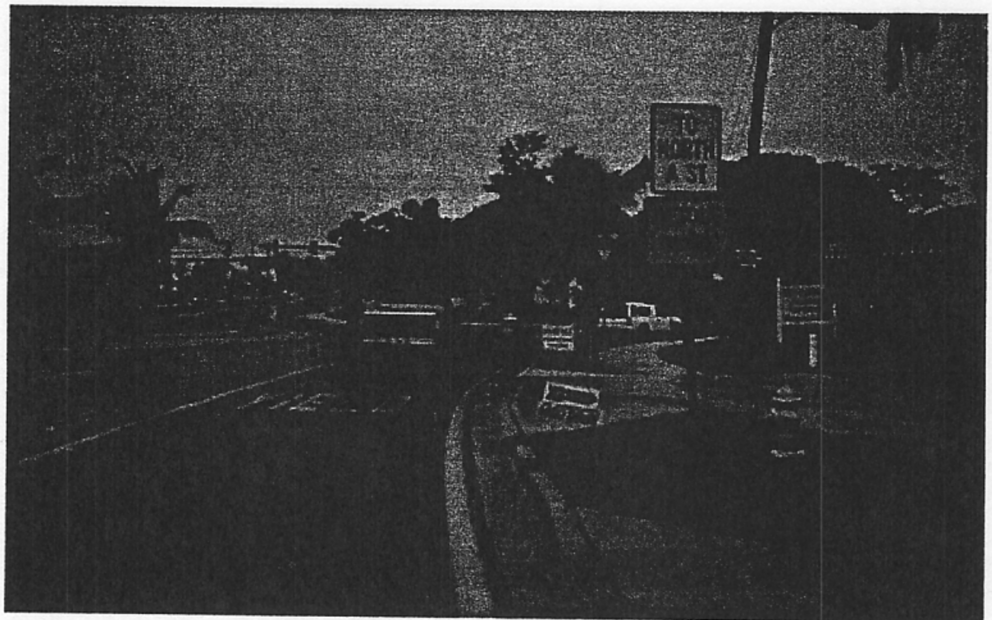

Figure 4.36 - Landscaping Obstructing Directional Signs at the Roundabout

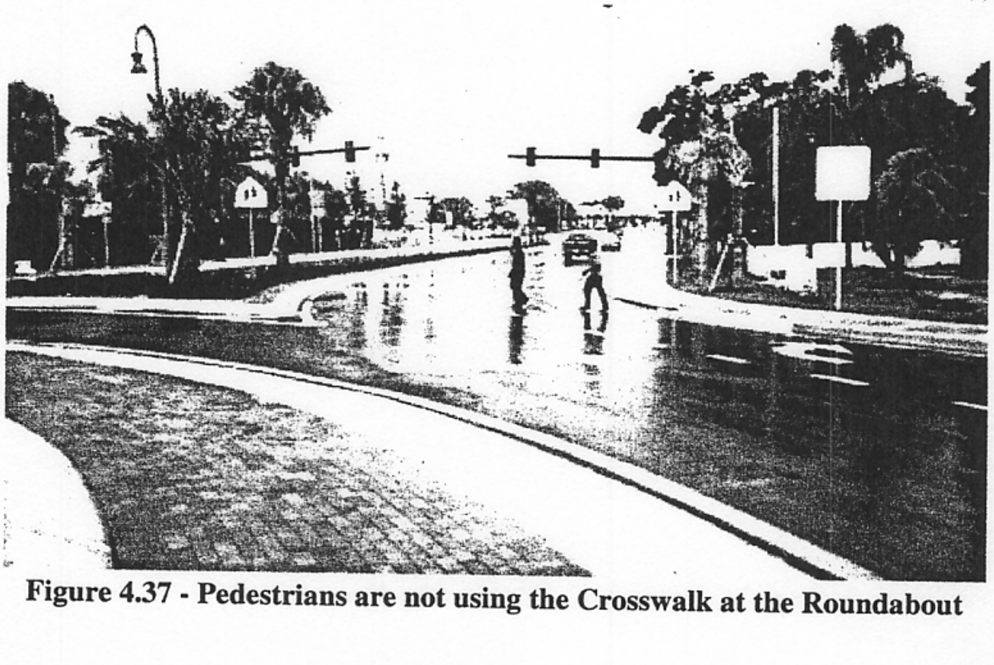

Figure 4.37 - Pedestrians are not using the Crosswalk at the Roundabout

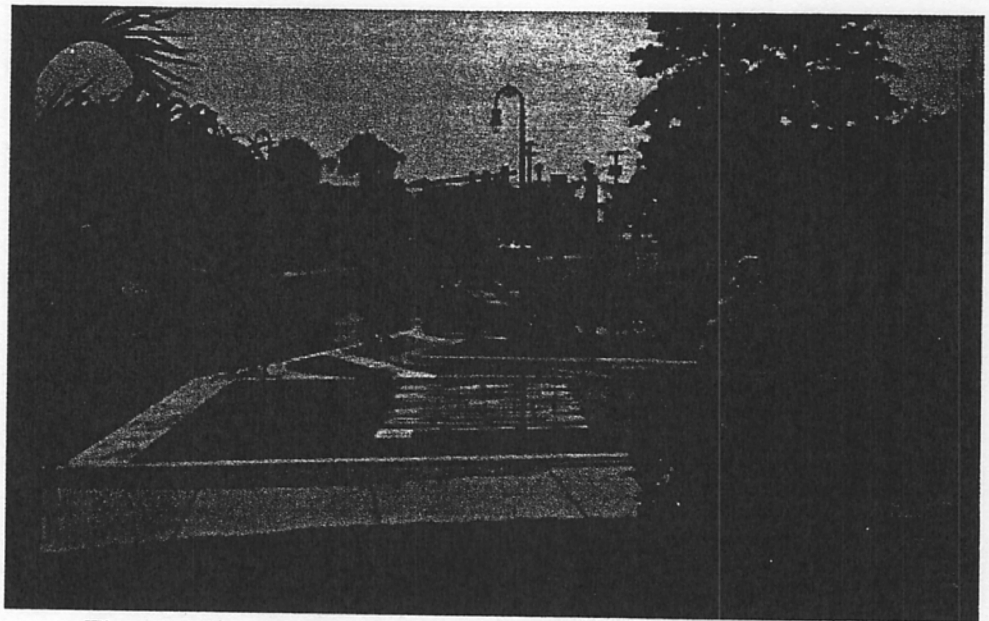

Figure 4.38 - "SCHOOL" Pavement Markings at the Exit of the Roundabout

4.2.2 Jensen Beach Blvd/Palmetto Drive, Jensen Beach

The intersection of Jensen Beach Blvd. and Palmetto Drive at Jensen Beach, Florida has been proposed to be converted into a roundabout. The area is mainly business-activity based. A railroad freight track is located 80 ft west of the intersection. The southbound of Palmetto Drive is a one-way street controlled by yield signs, while the northbound is a two-way street controlled by a stop sign. Located west of the intersection is Jensen Beach Boulevard, a two-lane, two-way street, and east of the intersection is a one-way, one-lane street heading east. The detail of the intersection is shown in **Figure 4.39**. Along the one-way portion of Jensen Beach Blvd., angle parking is provided on the north side.

Traffic data was collected automatically and manually during one weekday and one weekend day. The results of the traffic study are presented in **Tables 4.27** and **4.28**. The data was used to simulate the intersection as a roundabout. The analysis showed that the intersection will operate at a level of service "A" at all times, as shown in **Table 4.29**, **4.30**, and **4.31**. At the time of writing this report, the final drawings of the proposed roundabout were not yet finalized.

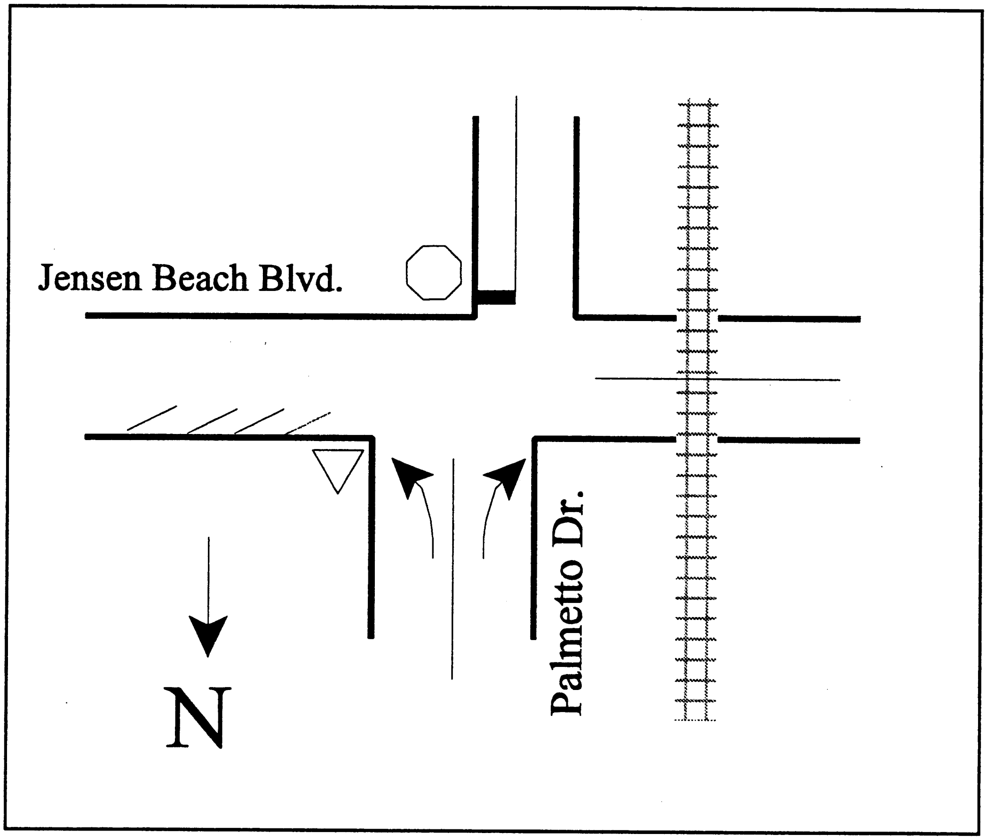

Figure 4.39 - Current Intersection Configuration at Jensen Beach Blvd. and Palmetto Dr.

Table 4.27 - AM Peak TMC at Jensen Beach Blvd./Palmetto Dr, Jensen Beach (February 1999)

Time	Jensen Beach Blvd. (Eastbound)		Palmetto Dr. (Southbound)		Palmetto Dr. (Northbound)	
	TH	RT	LT	RT	LT	RT
9:00	159	4	13	221	0	3
9:15	155	7	8	206	0	4
9:30	164	7	16	235	1	13
9:45	155	6	20	236	0	1
Total Hour	633	24	57	898	1	21

Table 4.28 - PM Peak TMC at Jensen Beach Blvd./Palmetto Dr, Jensen Beach (February 1999)

Time	Jensen Beach Blvd. (Eastbound)		Palmetto Dr. (Southbound)		Palmetto Dr. (Northbound)	
	TH	RT	LT	RT	LT	RT
4:15	226	8	7	257	0	2
4:30	208	6	5	252	2	3
4:45	251	9	12	211	0	7
5:00	228	7	20	216	0	3
Total Hour	913	30	44	936	2	15

Table 4.29 - AM Peak Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec.)	LOS
Jensen Beach Blvd	811	1,839	0.441	5.3	A
Palmetto Dr. (South)	232	1,708	0.136	5.3	A
Palmetto Dr. (North)	1,011	1,975	0.512	5.2	A
Intersection	2,054	5,522	0.512	5.3	A

Table 4.30 - PM Peak Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec.)	LOS
Jensen Beach Blvd	933	1,884	0.527	5.3	A
Palmetto Dr. (South)	18	1,191	0.015	5.8	A
Palmetto Dr. (North)	1,032	1,977	0.522	5.1	A
Intersection	2,043	5,052	0.527	5.2	A

Table 4.31 - Weekend Mid-day Peak Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
Jensen Beach Blvd	1,637	1,846	0.887	7.4	A
Palmetto Dr. (South)	42	348	0.121	16.6	B
Palmetto Dr. (North)	1,249	1,920	0.653	5.2	A
Intersection	2,928	4,114	0.887	6.6	A

4.2.3 Indian River Drive/Jensen Beach Blvd., Jensen Beach

This location is at the intersection of SR 707 and SR 732. SR 732 is a causeway connecting the mainland to Hutchinson Island. It is a single-lane "T" intersection with left turning lanes. The primary traffic at the intersection comes from the traffic that travels in and out of the Island. A bascule bridge is located 400 ft (122 m). east of the intersection of the causeway. During the time when the bridge opens, traffic is disturbed and the intersection fails, especially during the peak hours.

Traffic Data was collected automatically and manually during one weekday and one weekend. The results of the traffic study are presented in **Tables 4.32**. The analysis of the p.m. peak hour, using the Highway Capacity software, indicates that the intersection has a level of service "C" with an average delay of 29.1 seconds.

A four-approach, single-lane roundabout was installed in this same location. The intersection layout after the installation of the roundabout is shown in **Figure 4.40**. Traffic data collection was performed for the p.m. peak period after the installation of the roundabout, and the results are shown in **Table 4.33**. The SIDRA analysis, shown in **Table 4.34**, shows that the level-of-service improved to "A" after the installation of the roundabout and that the average delay is 3.1 seconds. Also, field observation indicated that during the time when the bridge opens, traffic is not disturbed as before implementation. The traffic flow is expected to improve at the roundabout location after the residents become familiar with the new intersection configuration. It was also observed that several drivers stop on the circulating lanes to allow other approaching drivers to enter the roundabout.

Table 4.32 - PM Peak TMC at SR 707/SR 732 T-Intersection, Jensen Beach (1999)

Time	SR 732 (Westbound)		SR 707 (Southbound)		SR 707 (Northbound)	
	LT	RT	LT	TH	TH	RT
9:00	165	69	32	56	77	164
9:15	147	49	23	56	87	137
9:30	116	68	26	66	104	139
9:45	117	60	24	51	122	138
Total	545	246	105	229	390	578

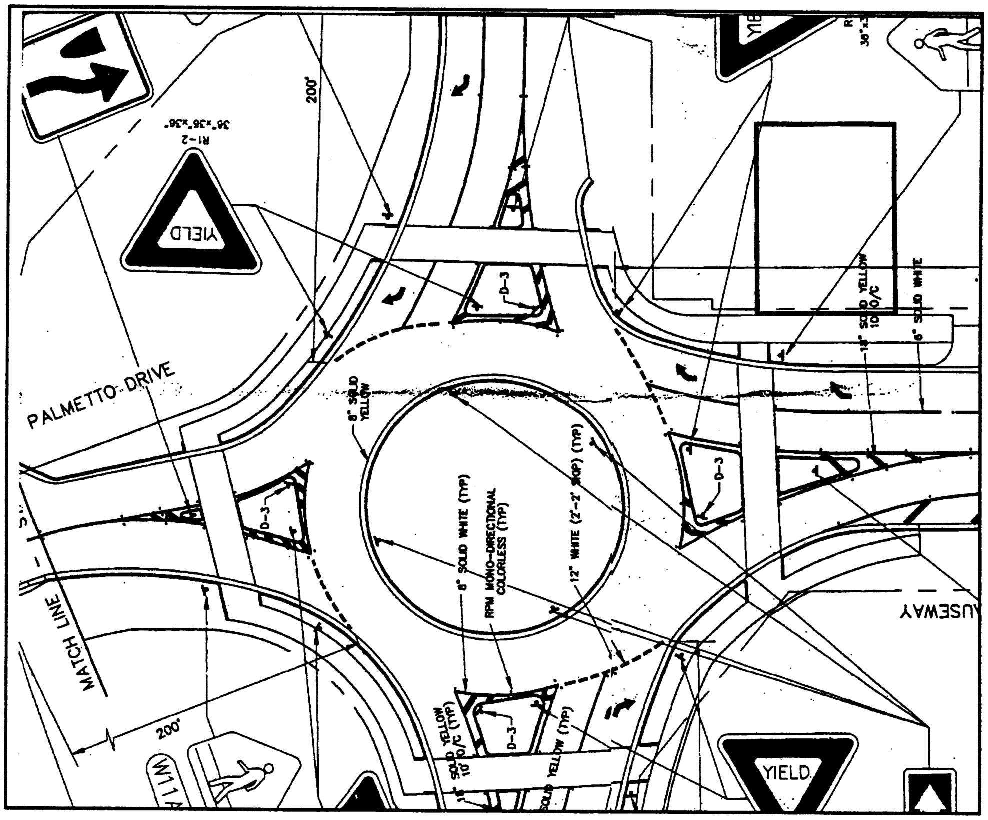

Figure 4.40 - Jensen Beach Roundabout

Table 4.33 - PM Peak TMC at SR 707/SR 732 Roundabout, Jensen Beach (1999)

Time	SR 732 (Eastbound)			SR 732 (Westbound)			SR 707 (Southbound)			SR 707 (Northbound)		
	LT	TH	RT	LT	TH	RT	LT	TH	RT	LT	TH	RT
Total Hour	4	32	0	215	351	214	128	85	93	28	255	474

Table 4.34 -PM Peak Capacity and Level of Service

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
SR 732 (Westbound)	867	1,829	0.474	3.3	A
SR 732 (Eastbound)	40	900	0.044	3.6	A
SR 707 (Southbound)	339	1,264	0.268	5.8	A
SR 707 (Northbound)	841	2,310	0.364	1.7	A
Intersection	2,087	7,264	0.474	3.1	A

4.2.4 US 1/Roosevelt Blvd, Key West

The entrance to Key West, Florida is proposed to be converted to a roundabout. The current intersection configuration is shown in **Figure 4.41**. The current T-intersection is controlled by traffic signals. The four-lane divided US 1 serves as the only entrance and exit to and from Key West and ends at Roosevelt Blvd. Roosevelt Blvd., which runs north and south, is a four-lane undivided roadway. Several hotels are located along Roosevelt Blvd.

Traffic data was collected before construction, both manually and automatically, and the results are shown in **Tables 4.35** and **4.36**. North Roosevelt Blvd has the highest pedestrian and bicycle volume crossing during weekdays, as well as weekend during peak hours, with an average of 22 ped./bic. for each peak hour. The ADT information for the Key West entrance location is presented in **Table 4.37**.

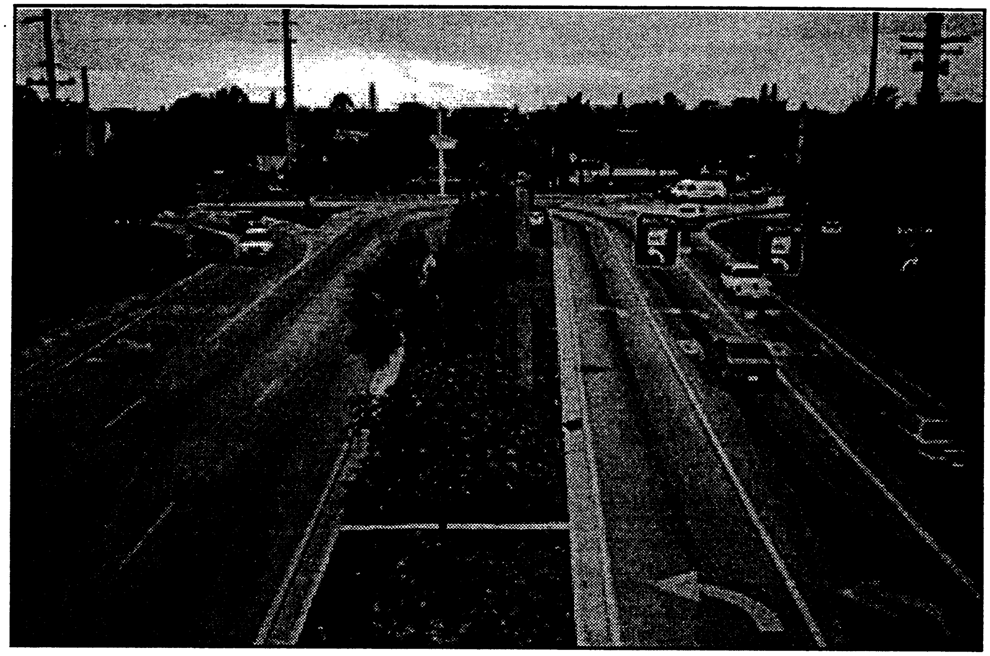

Figure 4.41 - Current Configuration for the Key West Entrance

Table 4.35 - AM TMC for US 1/Roosevelt Blvd. at Key West (December 1998)

Time	Roosevelt Blvd (SB)			Roosevelt Blvd (NB)			US 1 (WB)		
	TH	LT	Ped/Bic	RT	TH	Ped/Bic	RT	LT	Ped/Bic
7:00	18	128	5	90	24	4	224	108	1
7:15	31	161	2	113	25	8	232	147	1
7:30	36	164	2	145	19	4	305	188	0
7:45	24	192	3	177	27	7	320	182	3
8:00	28	171	3	119	22	6	316	220	3
8:15	25	186	0	122	34	3	298	196	1
8:30	30	154	2	113	29	3	251	144	0
8:45	46	169	0	113	46	7	265	146	3

Table 4.36 - PM TMC for US 1/Roosevelt Blvd. at Key West (December 1998)

Time	Roosevelt Blvd (SB)			Roosevelt Blvd (NB)			US 1 (WB)		
	TH	LT	P&B	RT	TH	P&B	RT	LT	P&B
4:00	34	263	1	183	28	3	268	164	5
4:15	39	289	3	177	32	7	259	128	6
4:30	47	295	2	187	32	3	273	170	4
4:45	37	264	5	178	36	9	254	169	12
5:00	44	300	5	225	30	2	275	168	2
5:15	55	290	0	244	25	8	236	163	4
5:30	49	302	0	239	25	2	207	123	1
5:45	47	303	0	162	32	1	229	115	0

Table 4.37 - Daily Traffic Volumes at the Entrance of Key West (December 1998)

Location	ADT	AM Peak		PM Peak	
		Volume	Hour	Volume	Hour
US 1 (WB)	22,451	2,181	7:30	1,696	4:15
US 1 (EB)	24,301	1,545	7:45	2,090	4:45
Roosevelt Blvd (NB)	9,983	673	7:30	943	4:15
Roosevelt Blvd (SB)	22,312	1,542	11:30	1,850	4:30

A total of 206 accidents were reported at SR-A1A & SR-5 (Key West), from January 1992 to January 1995. The accident study before construction shows that 11% of the accidents involved bicycles and pedestrians. The results of the accident study are shown in **Table 4.38**.

The current intersection is proposed to be converted to a single-lane roundabout as shown in the **Figure 4.42**. The collected traffic data wase used to simulate the current intersection as a roundabout. The analysis shows that the roundabout will operate at a level of service "D" during the weekday PM periods, due to the high volume of left turns from Roosevelt Blvd. southbound. The result of analysis is shown in **Table 4.39**.

Table 4.38 - Accident Summary SR 5 and SR A1A, Key West

Location	Date	Type of Accident	Contributing Cause	Pedestrian/Bicycle Action
SR - 5	2/92	Collision w/pedestrian	Careless driving	Crossing not at intersection
	2/92	Collision w/pedestrian	Failed to yield R-O-W	Pedestrian violation
	4/92	Collision w/bicycle	Failed to yield R-O-W	N/A
	7/92	Collision w/bicycle	Careless driving	N/A
	11/92	Collision w/bicycle	Failed to yield R-O-W	N/A
	1/93	Collision w/bicycle	Disregarded traff. signal	N/A
	4/93	Collision w/bicycle	Failed to yield R-O-W	N/A
	6/93	Collision w/pedestrian	Failed to yield R-O-W	Crossing not at intersection
	6/93	Collision w/bicycle	Failed to yield R-O-W	N/A
	9/93	Collision w/bicycle	Disregarded stop sign	N/A
	9/93	Collision w/pedestrian	Failed to yield R-O-W	Crossing not at intersection
	10/93	Collision w/pedestrian	DIU	N/A
	11/93	Collision w/bicycle	Failed to yield R-O-W	N/A
	4/94	Collision w/ped/bike	Excess. speed	N/A
	5/94	Collision w/ped/bike	Careless driving	N/A
	5/94	Collision w/ped/bike	Careless driving	N/A
	8/94	Collision w/pedestrian	Failed to yield R-O-W	N/A
	10/94	Collision w/ped/bike	Failed to yield R-O-W	Improper passing
	12/94	Collision w/pedestrian	Failed to yield R-O-W	Pedestrian violation
	10/94	Collision w/ped/bike	Careless driving	N/A
SR - A1A	4/94	Collision w/bicycle	Failed to yield R-O-W	N/A
	4/94	Collision w/bicycle	Failed to yield R-O-W	N/A

Table 4.39 - PM Capacity and Level of Service of the Proposed Roundabout at Key West

Approach Name	Total Flow (veh/hr)	Total Capacity (veh/hr)	Degree of Saturation (v/c)	Average Delay (sec)	LOS
US 1 (IN)	1,596	3,558	0.525	5.9	**A**
Roosevelt Blvd (NB)	1,034	2,227	0.482	5.3	**A**
Roosevelt Blvd (SB)	1,463	1,441	1.275	127.5	**F**
Intersection	4,093	7,226	1.275	49.2	**D**

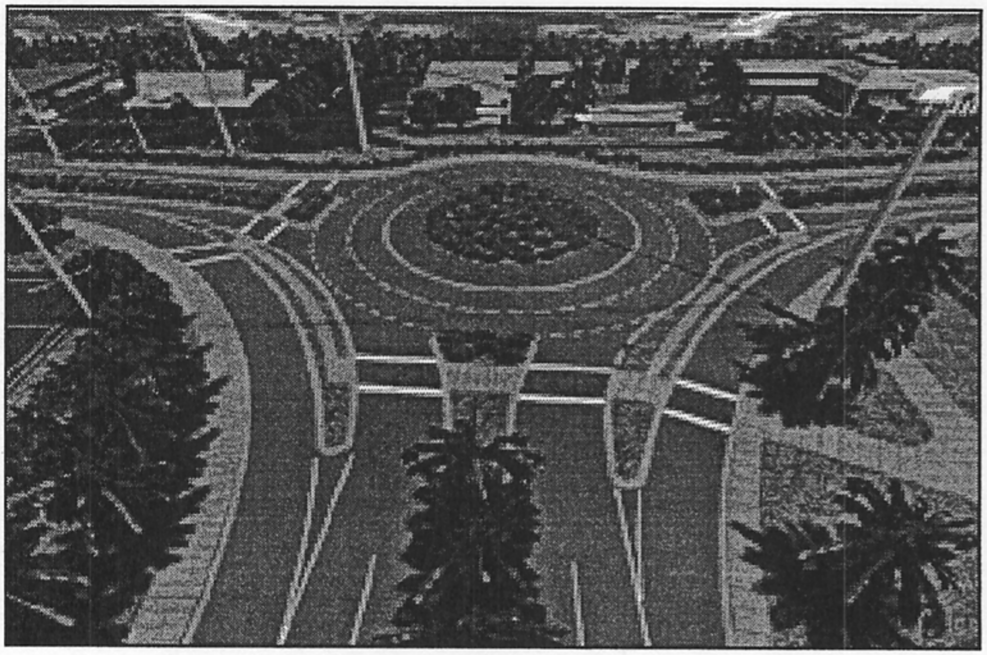

Figure 4.42 - Proposed Roundabout at Key West

5.0 PEDESTRIAN AND BICYCLE SIMULATION AT ROUNDABOUTS

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 that handle pedestrian and bicycle traffic. Four models were developed for that purpose. The first model simulates a roundabout without pedestrian and cyclist traffic. The second model simulates a roundabout with mixed flow bicycles. The third model simulates a roundabout with a combined pedestrian and bicycle crossing 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 a one car length, then shifted to two and three car lengths. The fourth model simulates a bicycle lane that is installed at the outer perimeter of the circulating lane of the roundabout. All four models output the number of served vehicles, with the average vehicle waiting time yielding to pedestrians and cyclists at each approach, as well as the average waiting time when yielding to other vehicles before entering the roundabout. The number of queued vehicles, queue length, and the service time matrix are provided as well. The models described in this chapter are discrete, event-based models where vehicle, pedestrian and bicycle volumes were increased gradually in order to measure the performance of the simulated roundabout under each bicycle and pedestrian treatment.

5.1 GEOMETRIC ASSUMPTIONS

1- The dimensions of the roundabout used for the simulation are based on an actual roundabout located in Boca Raton, Florida, at the intersection of SW 18th Street and 12th Avenue.

2- Splitter islands are provided at all approaches of the roundabout. The size of the splitter island should be large enough to store the maximum number of pedestrians arriving at one time.

3- All approaches to the roundabout are controlled by yield signs and all traffic is forced to move in one direction at the roundabout.

5.2 DEVELOPMENT OF THE SIMULATION MODELS

The models described in this chapter are based on field observations and traffic data collected at a single-lane roundabout in Boca Raton, Florida. The roundabout consists of four approaches and is located in a residential area. The inscribed diameter of the roundabout is 160 ft (49 m). The east and the west entries of the roundabout are equipped with raised splitter islands, while the splitter islands on the north and south entries are painted. Traffic data was collected at the roundabout for a period of 24 hours during a regular weekday. Data collected includes volume counts, vehicle speed and gaps at 12 points of the roundabout (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 1,193 vehicles during the a.m. peak, and 1,383 vehicles during the p.m. peak. Moreover, the roundabout was videotaped to determine the interaction among different users.

Due to low pedestrian and bicycle volume at this roundabout, pedestrian and bicycle behaviors were observed at Cartagena Plaza Circle Located in Miami-Dade County. Pedestrian and bicycle observation were performed at an approach that is controlled by a "Yield" sign and equipped with a splitter island.

5.2.1 Operational Assumptions

1- The average initial approach speed for vehicles is 25 mph (40 km/hr), while the average circulating speed is 15 mph (25 km/hr).

2- Vehicles arriving at the yield line proceed without stopping if a suitable gap exists. Otherwise, they must wait for a suitable gap that is considered to be approximately 3.0 seconds.

3- 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.

4- Pedestrians, bicyclists and vehicles arrive at crosswalks independently and randomly. Pedestrians cross a road of given width with a speed of 4 ft/sec (1.22 m/sec), and bicyclists with eight mph.

5- Any vehicle that stops at the crosswalk takes a constant time to pass through it (function of the crosswalk width and acceleration rate).

6- 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 (cars that can decelerate and stop before the crosswalk). Otherwise, pedestrians and cyclists must wait for the car to pass.

7- 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.

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

9- 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.

10- 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.

11- 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.

12- If there are vehicles at the conflict point of the entry (see **Figure 5.1**), the vehicles at the entry cannot enter.

13- 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 5.1**).

14- The follow-up time was found to be 2.5 seconds.

5.2.2 Model 1 - Roundabout without Pedestrian and Bicycle Traffic

This model simulates the vehicular traffic at a single-lane roundabout. Vehicles will approach the roundabout at a speed of 25 mph. The deflection at the entry of the roundabout will force the vehicles to reduce the speed to 15 mph. Before the vehicle arrives at point "g"(see **Figure 5.2**), 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. When the vehicle reaches the exit conflict, the driver has to make a choice to exit the roundabout or to continue until they reach the destination exit. When the vehicle exits the roundabout, the driver can accelerate up to a speed of 25 mph.

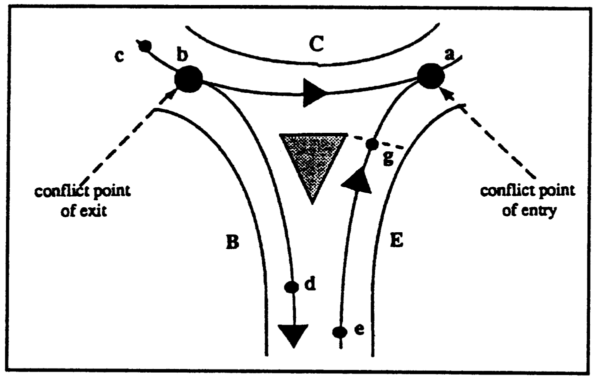

Figure 5.1 - Conflict Points at the Entrance and Exit

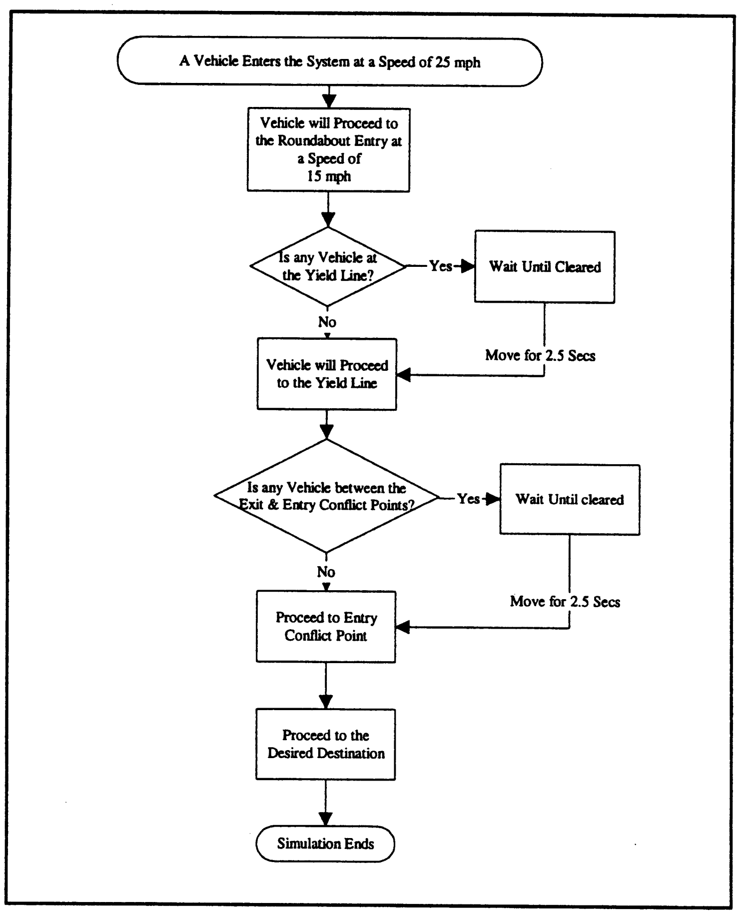

Figure 5.2 - Model 1 Processing Logic

5.2.3 Model 2 - A Roundabout with Mixed Flow Bicycles

This model simulates bicycles with mixed-flow traffic at a single-lane roundabout. Vehicles will approach the roundabout at an average speed of 25 mph (40 km/hr), and bicycles at a speed of 8 mph (13 km/hr). At point "e", vehicles will reduce speed to 15 mph (25 km/hr), and bicycles will maintain the speed of 8 mph (13 km/hr). At this point, 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 between points "b" and "a", then 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. When the vehicle or the bicycle reaches the exit conflict point "b", the driver has to make a choice to exit the roundabout or continue until they reach the destination exit. When the vehicle exits the roundabout at point "d," the driver can

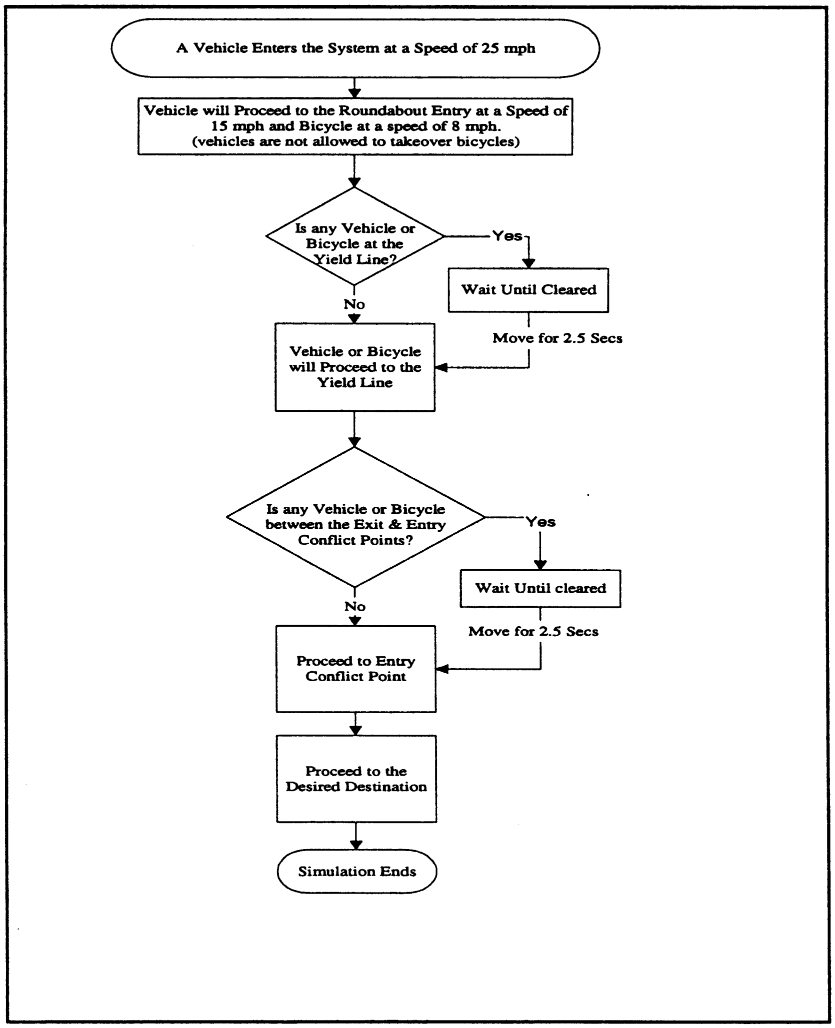

Figure 5.3 - Model 2 Processing Logic.

overtake a preceding bicycle and accelerate up to a speed of 25 mph (40 km/hr). The processing logic model is presented in **Figure 5.3**.

5.2.4 Model 3 - Roundabout with a 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 approach to the roundabout at a distance of one car length from the yield line. Vehicles approach the roundabout at a speed of 25 mph (40 km/hr), then reduce to 15 mph (25 km/hr) before reaching the entry side crosswalk. If a driver observes a pedestrian or a bicyclist attempting to cross, or sees a pedestrian on the entry side crosswalk, the driver yields to the pedestrian or bicyclist.

If another pedestrian or bicyclist arrives when there are others in the crosswalk, they cross without delay. If a pedestrian or a bicyclist arrives and finds that a vehicle is about to pass through the crossing, the pedestrian or the bicyclist waits until the vehicle completes its passage, and consequently, the next vehicle yields to the pedestrian or bicyclist. If there are no other pedestrians or bicyclists on the entry side crosswalk, vehicles can proceed and merge with the circulating traffic.

When the driver arrives to the desired exit and observes a pedestrian or bicyclist on the exit side crosswalk, the driver yields to them. 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 a speed of 15 mph (25 km/hr) until they pass the crosswalk. After the crosswalk, the driver can accelerate to a speed of 25 mph (40 km/hr). At the time when the vehicles stop at the exit 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 5.4**.

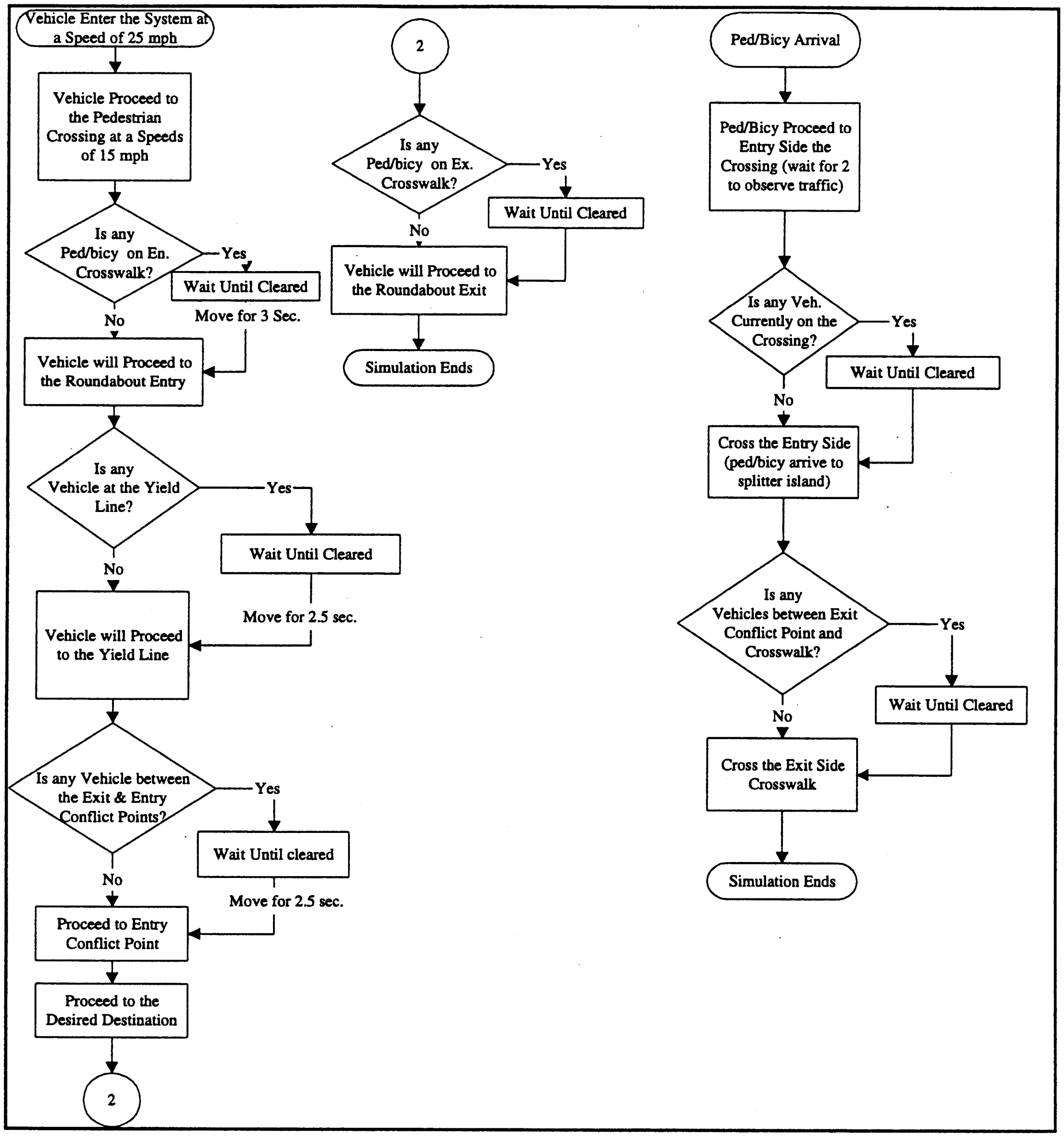

Figure 5.4 - Model 3 Processing Logic

5.2.5 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. 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. Bicycles approaching a crosswalk are treated as vehicles. The speed of the bicycles is considered to be eight mph (11.7 ft/sec, 3.6 m/sec). As vehicles which are exiting the roundabout must 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 **Figure5.5**.

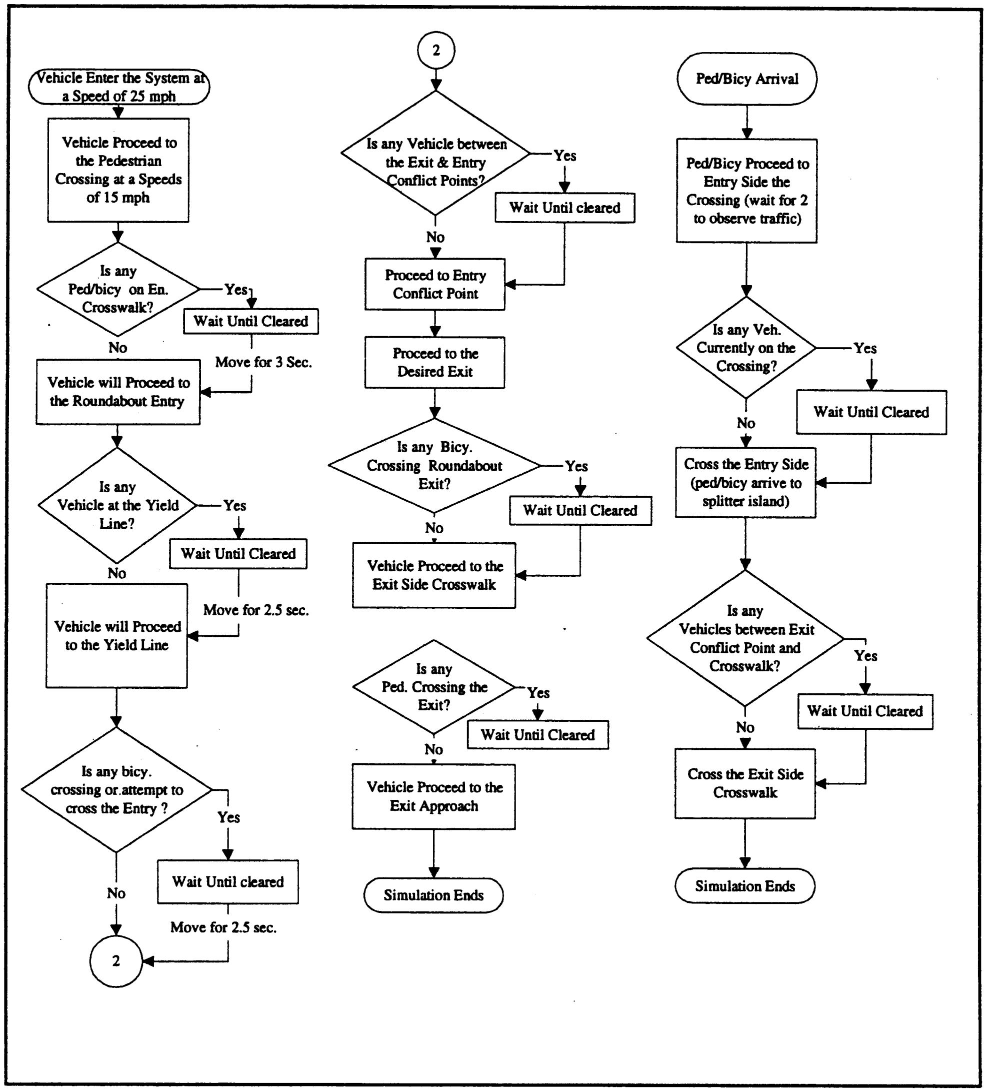

Figure 5.5 - Model 4 Processing Logic

5.3 SIMULATION RESULTS AND FINDINGS

The results obtained from the four simulation models are summarized in this section. For all models, it was considered that pedestrians and/or bicycles cross only on the crossing facility of the westside of the roundabout. The four measured indicators described below are used to compare the performance of a single lane roundabout under various conditions.

- *Maximum Contents:* compares the maximum number of vehicles in queue when incrementing the pedestrian and/or bicycle volumes.

- *Percentage Utilization:* compares the percentage of time when a certain location is occupied by incrementing the pedestrian and/or bicycle volumes.

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

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

Table 5.1 and **Figures 5.6, 5.7 and 5.8** show a comparison of the basic model, which only simulates vehicle movements at roundabouts, and the combined pedestrian and bicycle model. When pedestrian and bicycle crossings are added to the basic model, all measured indicators show significant increment for the west approach, and a variable reduction for the other locations. Because the location of the crossing is on the west approach only, the cars that stop for pedestrians and/or bicycles that are crossing the approach create a gap that is utilized by the entities at the other locations of the roundabout.

Table 5.1 - Basic Model Vs. Combined Pedestrians and Bicycles Path Model

Maximum Contents			
Location	**Basic**	**Combined Crossing**	**% Change**
North App.	3.30	3.10	*(6.00)*
West App.	4.60	5.90	*28.00*
South App.	2.60	1.90	*(27.00)*
East App.	3.50	2.90	*(17.00)*
West Cir. Queue	2.10	2.00	*(5.00)*
North Cir Queue	2.00	2.00	*0.00*
South Cir. Queue	2.20	2.40	*9.00*
East Cir. Queue	2.80	2.50	*(11.00)*
Average Seconds In System			
Entity Name	**Basic**	**Combined Crossing**	**% Change**
North	18.20	17.80	*(2.00)*
West	18.40	20.40	*11.00*
South	16.00	14.90	*(7.00)*
East	16.40	15.30	*(7.00)*
Average Delays			
Approach	**Basic**	**Combined Crossing**	**% Change**
North	6.20	5.50	*(11.00)*
West	6.40	8.40	*31.00*
South	6.60	5.40	*(19.00)*
East	7.60	6.10	*(20.00)*

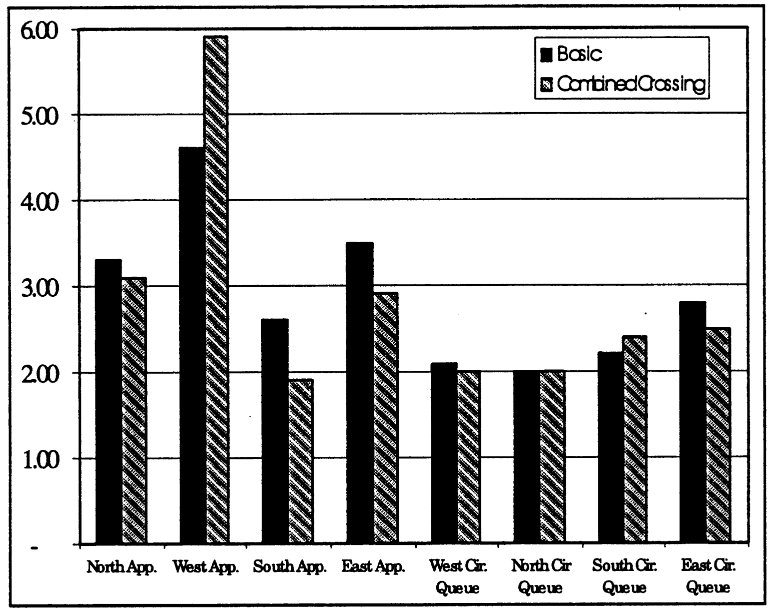

Figure 5.6 - Comparison of Queue Lengths after Installing a Crossing Facility

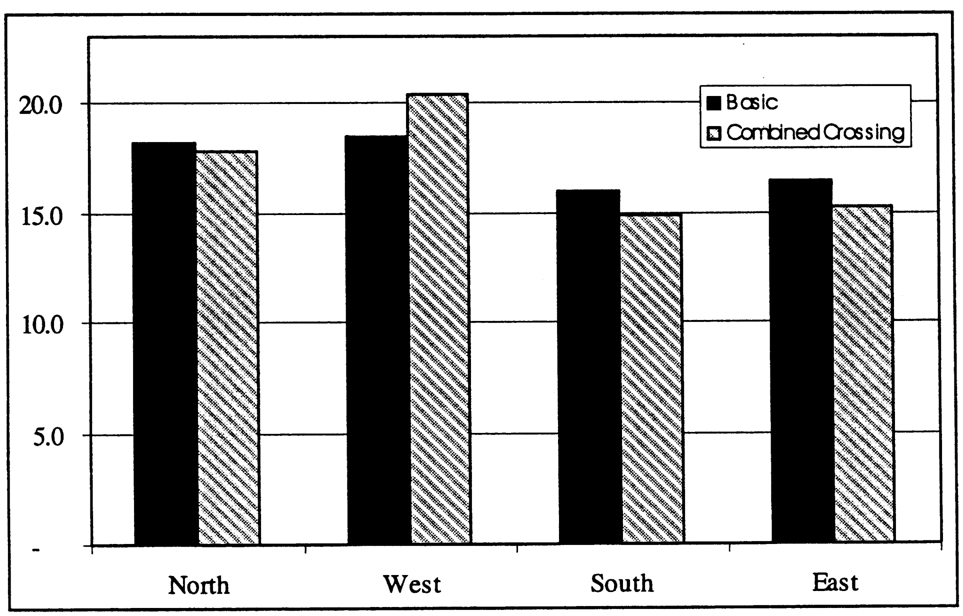

Figure 5.7 - Comparison of Time a Vehicle Needs to Negotiate the Roundabout after Installing a Crossing Facility

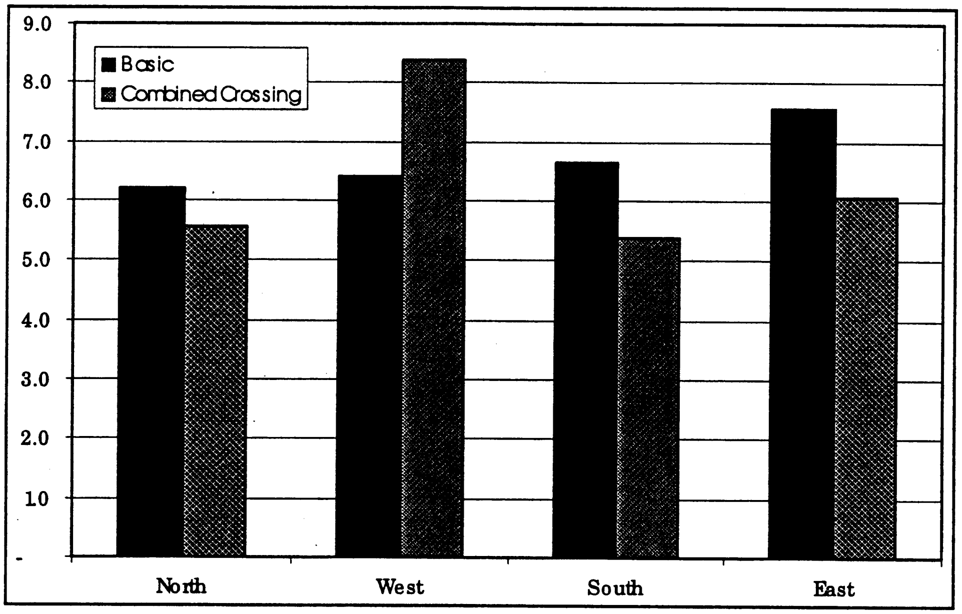

Figure 5.8 - Comparison of Average Delays after Installing a Crossing Facility

Table 5.2 and **Figures 5.9, 5.10 and 5.11** illustrate the results obtained from the bicycle with mixed flow and bicycle lane models. The bicycle volume was considered to be ten percent of the vehicle volume and then increased to 20 percent and 30 percent, respectively. The results showed that the introduction of bicycle lanes reduces the average overall times in the roundabout for the vehicles on the north and south approaches, while the overall time for the vehicles on the west and east approaches tend to increase.

The introduction of bicycle lanes at the roundabout greatly benefits the pedestrians that cross the approaches of the roundabout, since bicyclists have priority over the vehicles; as a result, the exiting vehicles are forced to reduce speed or wait for the bicyclists by the exit approach of the roundabout. This situation creates a greater gap for pedestrians crossing this approach.

Table 5.2 - Mixed Flow Model Vs. Bicycles Lanes Model

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.	18.50	18.20	*(1.46)*	19.30	18.20	*(5.95)*	20.40	18.30	*(9.97)*
West App. Veh.	21.00	19.60	*(6.43)*	23.10	20.00	*(13.64)*	25.60	20.00	*(21.78)*
South App. Veh.	15.60	16.80	*7.56*	16.60	17.10	*3.00*	17.50	17.50	*(0.23)*
East App. Veh.	15.80	16.70	*5.75*	16.30	17.00	*3.92*	17.00	17.10	*0.23*
North App. Bicy.	30.00	36.00	*20.15*	30.40	36.50	*19.92*	30.40	36.30	*19.50*
West App. Bicy	33.70	38.00	*12.77*	34.80	38.20	*10.01*	36.60	38.10	*4.32*
South App. Bicy.	25.20	24.50	*(2.83)*	26.90	26.20	*(2.57)*	27.40	28.20	*2.88*
East App. Bicy.	26.00	32.40	*24.45*	26.80	32.00	*19.55*	27.10	32.30	*19.47*
Ped. SN	15.40	13.60	*(11.66)*	15.70	3.80	*(76.04)*	15.90	13.80	*(13.61)*
Ped. NS	15.40	13.70	*(10.85)*	15.40	13.60	*(12.00)*	15.90	13.60	*(14.75)*
Average Delay Value									
Approach	**10%**			**20%**			**30%**		
	Mixed Flow	**Bicycle Lanes**	**% Change**	**Mixed Flow**	**Bicycle Lanes**	**% Change**	**Mixed Flow**	**Bicycle Lanes**	**% Change**
North	5.80	6.20	*5.82*	6.20	6.20	*1.30*	6.50	6.30	*(4.13)*
West	8.40	7.80	*(7.96)*	9.90	8.00	*(19.45)*	11.90	8.00	*(32.83)*
South	6.00	7.40	*22.76*	6.70	7.70	*14.80*	7.60	8.10	*5.78*
East	6.60	7.60	*15.17*	7.10	7.70	*8.44*	7.60	7.80	*2.78*

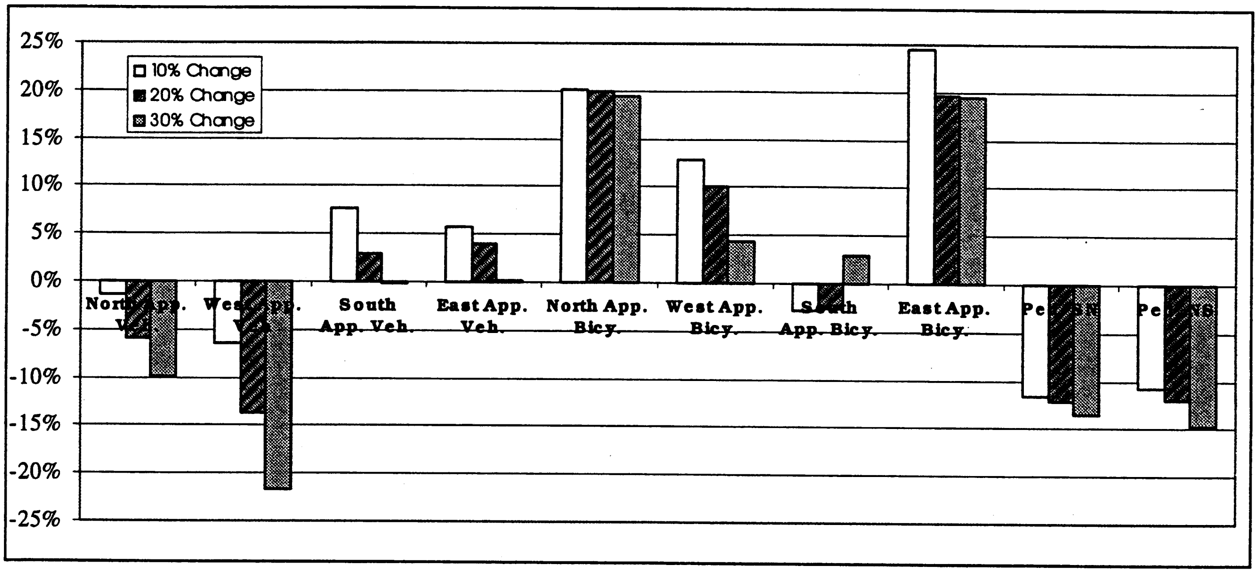

Figure 5.9 - The Effect of the Bicycle Lane on the Time Needed to Negotiate the Roundabout

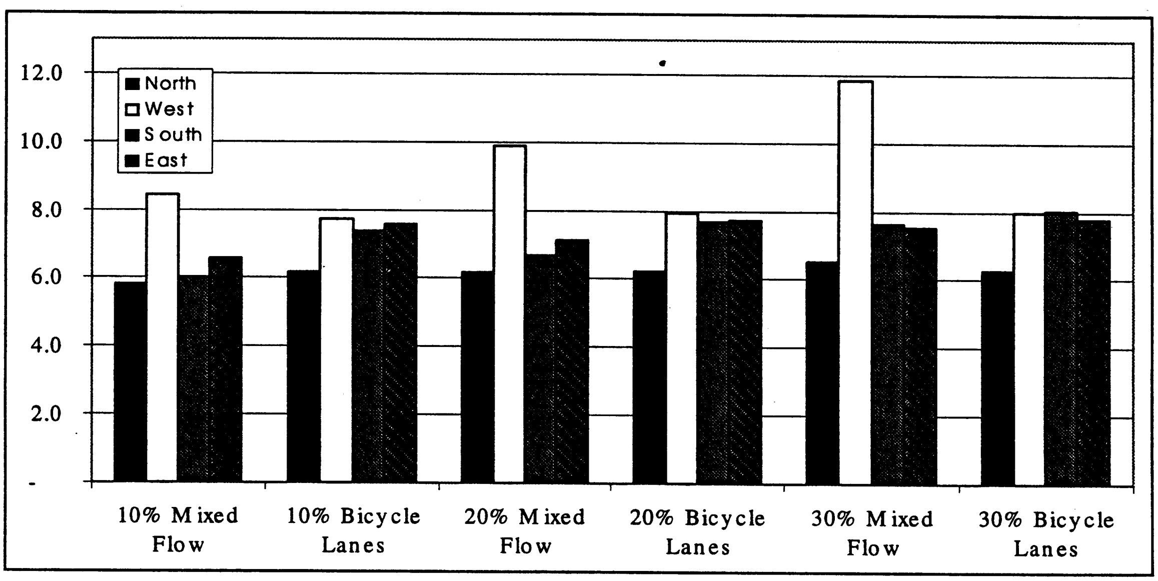

Figure 5.10 - Comparison of Time a Vehicle Needs to Negotiate the Roundabout after Installing a Bicycle Lane

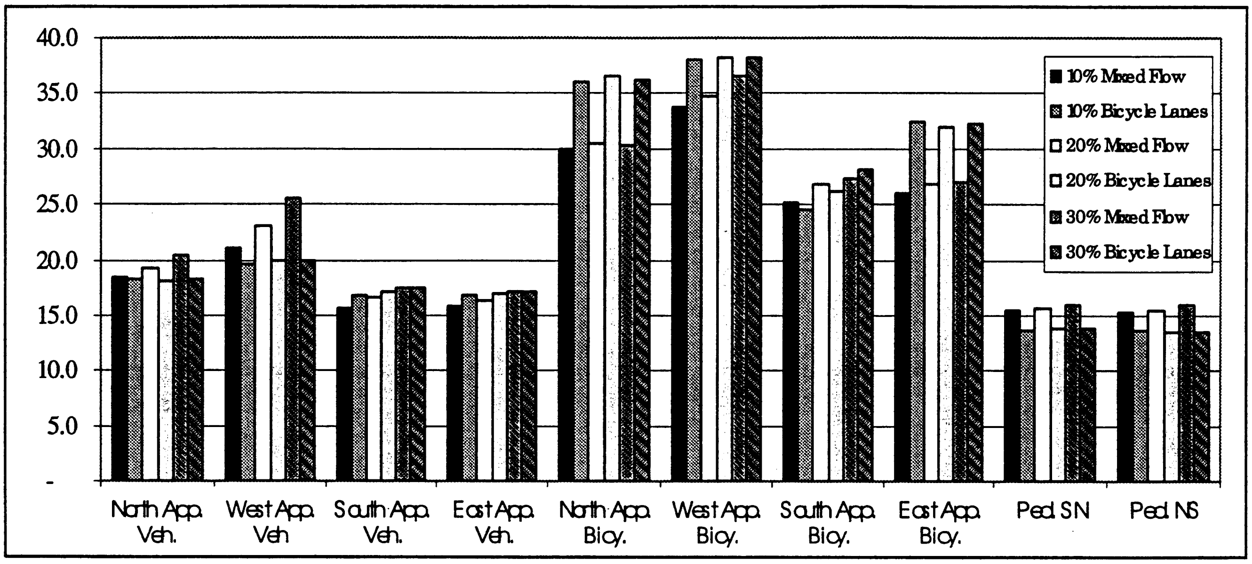

Figure 5.11 - Comparison of Delays after Installing a Bicycle Lane.

The installation of a pedestrian crossing on the west approach of the roundabout increased the maximum queue length by 28%, while the average delay time of vehicles by 31% on the same approach. Furthermore, the maximum queue length and the average delay of vehicles using other approaches decreased, as shown in **Figure 5.12**. The reason for this decline is when pedestrians cross the west approach, more gaps are created on the circulating lane of the roundabout, which allows other vehicles to enter the roundabout.

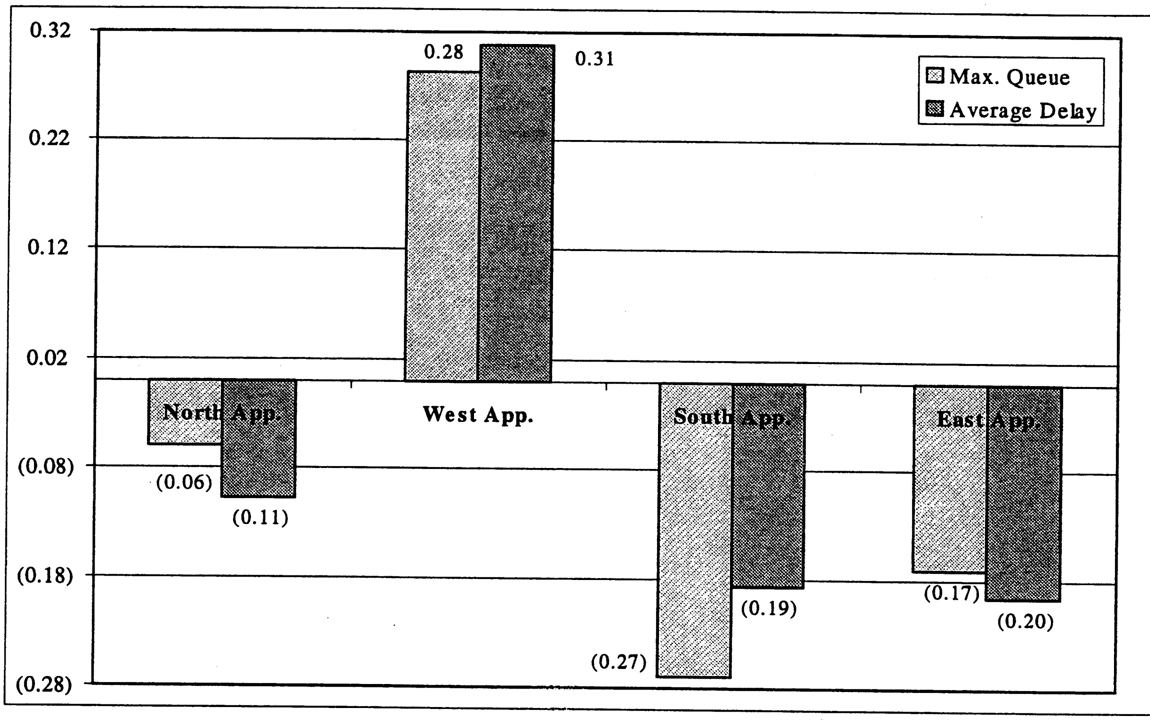

Figure 5.12 - Effect of Installing a Pedestrian Crossing on Queue Length and Average Delay

It was also found that when the pedestrian crossing is located at a one car length from the yield line of the roundabout, the time required for pedestrians and bicyclists to cross the approach is less than when locating the crossing at two or three car lengths from the yield line (see **Figure 5.13**). This is because at two car lengths, pedestrian and bicyclists must observe the vehicles at the exit conflict point of the approach, which is the same situation when locating the crossing at one car length. On the other hand, when locating the crossing at three car lengths, pedestrians and bicyclists observe vehicles that are already on the exit side of the approach. In addition, the queue length on the west approach decreases as the pedestrian crossing is placed at two or three car lengths, and the number of vehicles in queues on the other approaches increase. The reason is that as the crossing is placed at three car lengths, the delays caused by pedestrians start to diminish.

The effect of changing the traffic volume and the crossing location has a negligible effect on the north and east approaches, while the same change has a greater effect on average delays on the west and south approaches, as shown in **Figure 5.14**. The developed model was used successfully to understand the effect of placing of the pedestrian crossings on the operation and performance of the roundabout. It was concluded that placing the crossing at a distance of two car lengths causes more delays to pedestrians, especially when crossing the exit side of the roundabout. Splitter islands should be spacious enough to provide refuge to pedestrians.

The effect of the pedestrian crossing location to vehicles exiting the roundabout was minimum, as pedestrians and bicyclists must yield to exiting traffic.

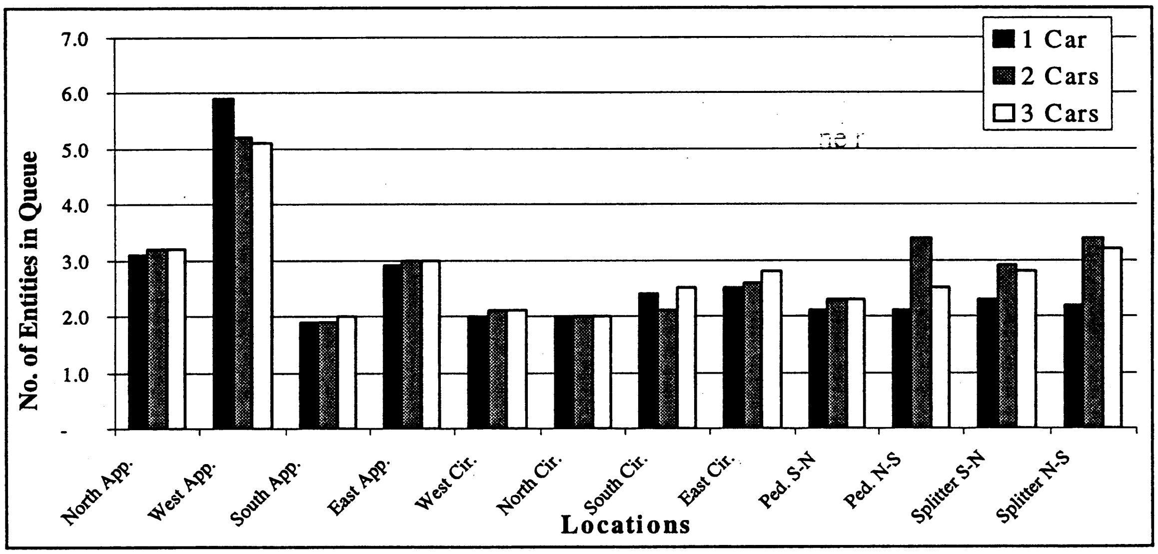

Figure 5.13 - Changes in Queue Length Due to Changes in Crossing Location

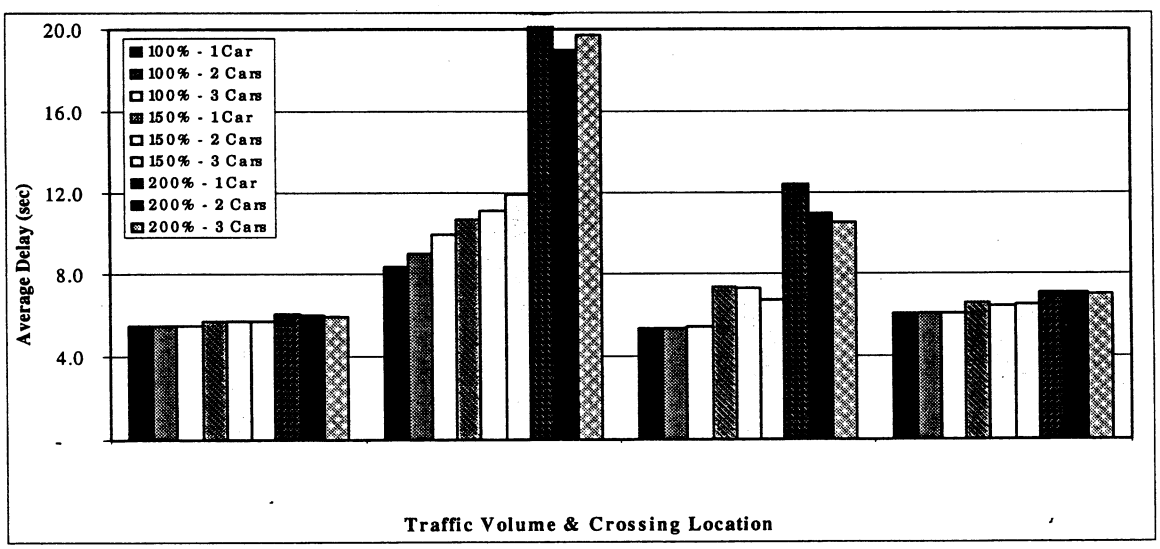

Figure 5.14 - Average Delays Due to Change in Traffic Volumes and Crossing Location

5.4 MODEL VERIFICATION, CALIBRATION AND VALIDATION

In order to ensure that the developed models are free from any errors, it is not possible to reflect the real-world system precisely; as a result, 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 adjustments, and so on. On the other hand, model validation is also a process of determining whether the conceptual models correctly reflect the real system.

5.4.1 Model Verification

Model verification utilizes the comparison of the conceptual model to the computer representation which 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 or intention of modeling and are harder to detect. Often they are logical errors that cause the models to behave in a different manner than originally intended.

In order to verify the developed models, the following preventive measures were taken into consideration in 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*** - the models were built with complexity being progressively added. 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 are built correctly:

- Code reviews were conducted continuously to check for errors and inconsistencies, and models were tested in both top-down and bottom-up fashions.

- Model animations were examined for correct behaviors of the models and several counters were placed to monitor the number of vehicles at each segment of the roundabout to ensure that the vehicle distribution is similar to the real system.. Animation was also examined to identify problems in order to discover the cause of the problems.

- The built-in trace and debug options were used to provide textual feedback of what takes place during simulation. The results offer an in-depth view and understanding of what happens inside the simulation process.

5.4.2 Model Calibration

During the several visits made to the study's roundabout site to calibrate the basic model, critical gaps, as well as the drivers' follow-up times were re-measured in order to ensure that the predicted queue lengths and delays on each approach were accurate.

5.4.3 Model Validation

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

Watching Animation - The visual animation of the operational behavior of the model was compared to the real system by placing several counters to record the number of the vehicles passing the queue length, as well as the waiting time on each approach, and to provide 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 in order to determine the effect of models' behavior on the simulation output. The PM traffic data was used to run the basic model, and the simulation output was compared to the filed observations. The results of running the basic model, using PM traffic data, are shown in **Tables 5.3**. The results show that as the traffic volume changes with time, the queue length and the average delay time change. 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 5.4** that the volume and queue length of the same approach are directly proportional. On the other hand, the delay is proportional to the volume of the upstream approach. If the upstream volume approach increases, drivers will experience more delays, as there will be shorter gaps between circulating vehicles.

Table 5.3 - 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 5.4 - 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%

6.0 CONCLUSIONS

6.1 SUMMARY AND CONCLUSIONS

Over the past three decades, the use of roundabouts in cities worldwide has increased due to their benefits, in comparison with traditionally controlled intersections. Roundabouts are often the primary choice because they are associated with low accident rates, low construction and operating costs, and can accommodate reasonable traffic capacities with acceptable delay. The main conclusions in this research effort can be summarized as follows:

- The introduction of roundabouts leads to a slight reduction in pedestrian casualty accidents, yet increases bicycle casualty accidents.

- When applied correctly, roundabouts are both a safe form of intersection control and an effective method of reducing various types of accidents. Casualty accident rates are reduced by 68% following the installation of roundabouts.

- Roundabouts effectively reduce right-angled accidents by 87%, with a 47% reduction in overall reported accidents.

- There is a slight reduction in accidents involving pedestrians after the installation of roundabouts.

- Bicycle accident rates at roundabouts are 15 times those of cars, and pedestrian accident rates are equivalent to those of cars.

- Bicycle accidents account for 13% - 16% of all accidents, while pedestrian accidents represent 4% - 6% of all accidents, and motorcycles account for 30% - 40% of all accidents.

- In the processes of planning and designing roundabouts, special attention should be given to the movement of pedestrians and bicycles. Accident studies found that multi-lane roundabouts are more stressful to bicyclists than single-lane roundabouts.

- In comparison, multilane roundabouts are not as safe as single-lane roundabouts, since pedestrians have to cross a larger distance. In most situations, single-lane roundabouts provide a satisfactory level of safety for bicyclists compared to other types of controlled intersections. This is due to the lower speeds of vehicles, as well as fewer conflict points, compared to multi-lane roundabouts or other types of intersections.

- Existing literature tends to advise ***against*** using roundabouts in high pedestrian/bicycle locations. Accordingly, several roundabout guidelines offer recommendations about the safest location and/or position of the pedestrian crossings at roundabouts.

- Special provisions for bicyclists are not normally required at roundabouts. Several guidelines recommend the provision of a special bicycle facility in case of high bicycle volume at the ***outer perimeter*** of the roundabout, if space permits.

- Other roundabout guidelines recommended that bicyclists should use the roundabouts, as drivers of vehicles would.

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

- In addition, the majority of roundabout design guidelines recommend off-setting the pedestrian crossing by one to three car lengths from the yield line of the roundabout. This will allow the motorists that are approaching the roundabout to yield to pedestrians that are crossing the approaches, which will then cause motorists to look for an acceptable gap in order to merge with the circulating flow.

- Crossing provisions are preferable, in association with splitter islands, either as an unmarked crossing place with curb cuts or incorporated into a marked crossing.

- The yield line pavement marking should be aligned with the edge of the splitter island.

- Avoid over signing at roundabout locations to avoid confusion when driving.

- Landscaping should not obstruct the drivers' line of sight, as well as any of the warning and directional signs at roundabouts.

- "SCHOOL" pavement markings should be avoided between the yield and the pedestrian crossing at both the entries and exits, as this may cause pedestrians to become confused with the difference between the "SCHOOL" pavement marking and the crossing.

- Educational material should be available to introduce the priority rules at roundabouts to drivers, pedestrians, and bicyclists.

- A roundabout is not a panacea for all traffic problems. Caution must be exercised when roundabouts are being used to replace an existing traffic signal, to ensure that the safety of pedestrians and bicyclists are not jeopardized.

- There are several powerful traffic analysis packages that are capable of analyzing roundabouts. Existing software packages provide estimates of capacity and performance characteristics such as delay, queue lengths, stop rates, effects of heavy vehicles, accident frequencies, geometric delays, as well as fuel consumption, pollutant emissions and operating costs for roundabouts.

- Existing software packages are not capable of determining the effect of various pedestrian crossing locations, including the effects of different bicycle treatments on the performance of roundabouts.

- Thus, there is a need to develop a simulation model which would be capable of determining the effect of different pedestrian and bicycle considerations at single-lane roundabouts. The proposed models presented in **Chapter 5** are capable of determining the effect of different bicycle and pedestrian considerations at single-lane roundabouts. The performance measures presented are average delay time, queue length and overall service time.

- When pedestrian and bicycle crossings are added to an approach of a roundabout, all measured indicators show a significant increment to that approach, as well as a variable reduction for the other approaches. Because the location of the crossing is on one approach only, the vehicles that stop for pedestrians and/or bicycles crossing the approach create a gap, that is in turn, utilized by the entities at the other locations of the roundabout.

- The introduction of bicycle lanes reduces the average overall times in the roundabout for the vehicles on the north and south approaches, while the overall time for the vehicles on the west and east approaches tends to increase.

- The introduction of bicycle lanes at the roundabout greatly benefits the pedestrians that are crossing the approaches of the roundabout, since the bicyclists have priority over the vehicles, thus, the exiting vehicles are forced to reduce speed or wait for the bicyclists by the exit approach of the roundabout. This situation creates a greater gap for pedestrians crossing this approach.

- When the pedestrian crossing is located at a one car length from the yield line of the roundabout, the time required for the pedestrians and bicyclists to cross the approach is less than when locating the crossing at two or three car lengths from the yield line.

- The developed models were helpful in understanding different bicycle and pedestrian considerations at single-lane roundabouts.

6.2 FUTURE WORK

Due to the dearth of modern roundabouts in South Florida, several observations were made at traffic circles. Also, the values for average speeds and follow-up time were observed at only one roundabout located in Boca Raton, Florida. Thus, further work is recommended to precisely determine the impact of different bicycle and pedestrian treatment at roundabouts.

- Intensive data collection should be performed at modern roundabouts with different geometries and different traffic conditions. Accurate vehicle data collection is needed in order to simulate vehicle arrival instead of assuming the arrival distribution.

- More complexity should be added to the proposed model. Entry points, as well as entry and exit conflict points should be dynamic to model variable gaps.

- Multi-lane roundabouts should be modeled.

- Further validations of the models are needed before using these models to measure the performance of a roundabout with various bicycle and pedestrian treatments. Validation of the models should be done by collecting data at roundabouts throughout the United States. Also, interaction between vehicles, pedestrians, and bicyclists should be studied carefully.

- It should be noted that the simulation package that was used to create the proposed models was not primarily developed for transportation purposes; however, several transportation applications were developed using it. For example, it was used to model a toll plaza, the John F. Kennedy Airport terminal, and the Salt Lake City International Airport.

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