Final Report

STATE-OF-THE-ART REPORT ON:

ROUNDABOUTS DESIGN, MODELING AND SIMULATION

Dr. Mohamed A. Aty, PE

Department of Civil & Environmental Engineering
University of Central Florida
Orlando, FL 32816
407-823-5657, Fax: 407-823-3315
mabdel@mail.ucf.edu

and

Dr. Yasser Hosni, PE
Department of Industrial Engineering
University of Central Florida

March 2001

EXECUTIVE SUMMARY

With the increased success of roundabout use in Europe and Australia, there is a renewed interest of their use in the US. Several States, including Florida, are now considering the use of roundabouts to solve traffic problems. A large number of diverse factors are involved in designing a roundabout. Interactions between analytical, statistical, geometrical, static, as well as dynamic traffic factors make the design of roundabouts a difficult problem. There are design guidelines, however there are no formal studies to assess the effectiveness use of roundabout in the US. On the other hand, when interactions between design factors are so complex, simulation techniques are used to support the design function.

This research investigated the state-of-the-art in roundabout design and analysis. The research team also investigated the use of a computer based simulation package for the design and analysis of roundabouts in the US. The Visual Simulation Environment (VSE) simulation tool was acquired and tested. Numerous traffic factors, and standards were found to be important in the simulation model. Three main criteria should be considered: safety, delays, and capacity. These criteria can be used to study the feasibility of using roundabouts, determine optimum design parameters, compare traffic scenarios, or compare a roundabout to an intersection, among other design functions. Our research pointed also to the significance of driver behavior. An essential element in the simulation of roundabouts is the gap acceptance process, as gap acceptance at roundabouts is likely to be different from traditional gap and lag times used for acceptance and rejections.

Although several computer programs such as SICRA, ARCADY and RODEL were identified, there is a need for simulation models that are more tailored to the US characteristics. All these programs are developed and validated in Europe or Australia, except the HCM software. As pointed above, roundabout analysis is dependent on gap acceptance and drivers' behavior, therefore there is a need for a US-based simulation model that takes into consideration US driving conditions and drivers' behavior. As more roundabouts are built in the US, data will become available to validate a US model.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION

The modern roundabout is a type of circular intersection that has been successfully implemented in Europe and Australia over the past few decades. Despite the approximately 35,000 roundabouts in operation around the world, there are fewer than 50 that exist in the United States. Until recently, roundabouts have been slow to gain support in the US. The lack of acceptance can generally be attributed to the negative experience with traffic circles or rotaries built in the earlier half of the twentieth century. Severe safety and operational problems caused these traffic circles to fall out of favor by the 1950's. However, substantial progress has been achieved in the subsequent design of circular intersections.

Modern roundabout should not be confused with the traffic circles of the past. Modern roundabout have been used successfully in many cities throughout the world, including several in the US. They have recently been built in California, Colorado, Florida, Maryland, Nevada, and Vermont. Two states, Florida and Maryland, have published guidelines for the design and justification of modern roundabouts. Modern roundabouts (Figure 1) are distinguished from traffic circles by

1. Roundabouts follow the "yield-at-entry" rule in which approaching vehicles must wait for a gap in the circulating flow before entering the circle, whereas traffic circles require circulating vehicles to grant the right of way to entering vehicles.
2. Roundabouts involve low speeds for entering and circulating traffic, as governed by small diameters and deflected entrances. In contrast, traffic circles emphasize

high-speed merging and weaving, made possible by larger diameters and tangential entrances.

3. Parking is not allowed on the circulating roadway
4. No pedestrian activities take place on the central island.

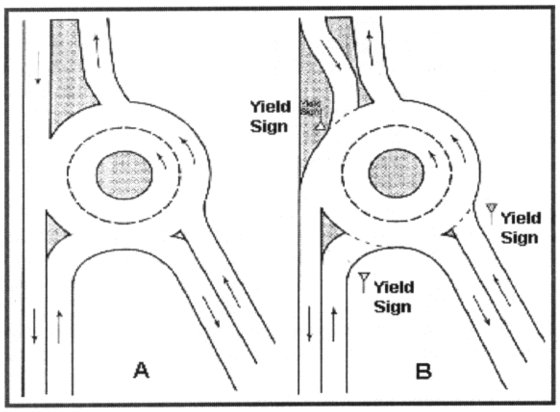

Figure 1 : Traffic circles "A" and modern roundabouts "B"
(Public Roads, Autumn 1995)

There are a large number of factors that should be considered in the design of the roundabout. In the preliminary study for this project, the following were identified as factors affecting the design and performance of the roundabout. Dimensional/ geometric factors affecting roundabout operations:

- Number of legs
- Roundabout diameter (D)
- Entry radius (r)
- Flare length (*l'*)
- Entry width (*e*)
- Approach width (*v*)

- Entry angle (M)
- Number of lanes
- Separator island and its design

The aforementioned dimensions are illustrated in Figures 2, 3 and 4.

Traffic flow factors include:

- Entering flow (ADT or pcu/hr)
- Circulating flow (ADT or pcu/hr)
- Design speed
- Traffic mix

Other factors which would affect the design of the roundabout include:

- Location (urban, suburban, or rural)
- Traffic standards
- Traffic rules
- Lighting

Combinations of these factors, and any other factors affect the performance of a roundabout. Because of the infinite number of combinations, countries have developed guidelines for roundabout design.

British, French and Australian guidelines are shown in Table 1.

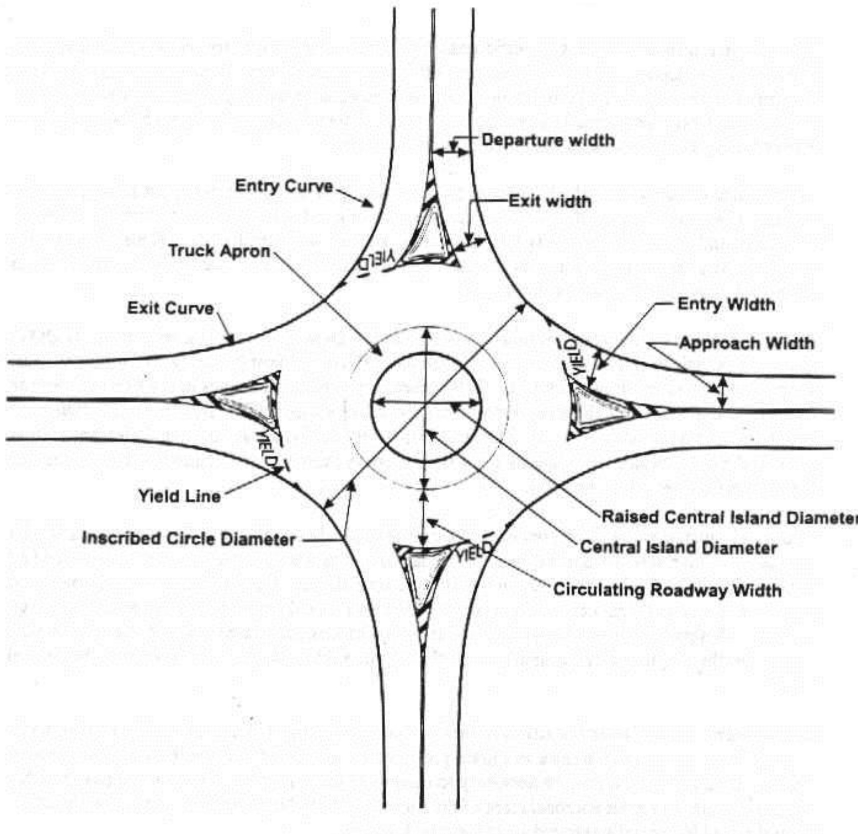

Figure 2. Basic geometric elements of roundabout (FL roundabout design guide, 1996)

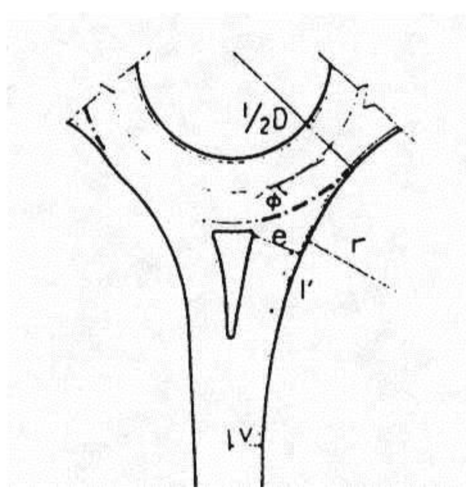

Figure 3. Geometric factors of roundabout approach (Bared *et al*, 1997)

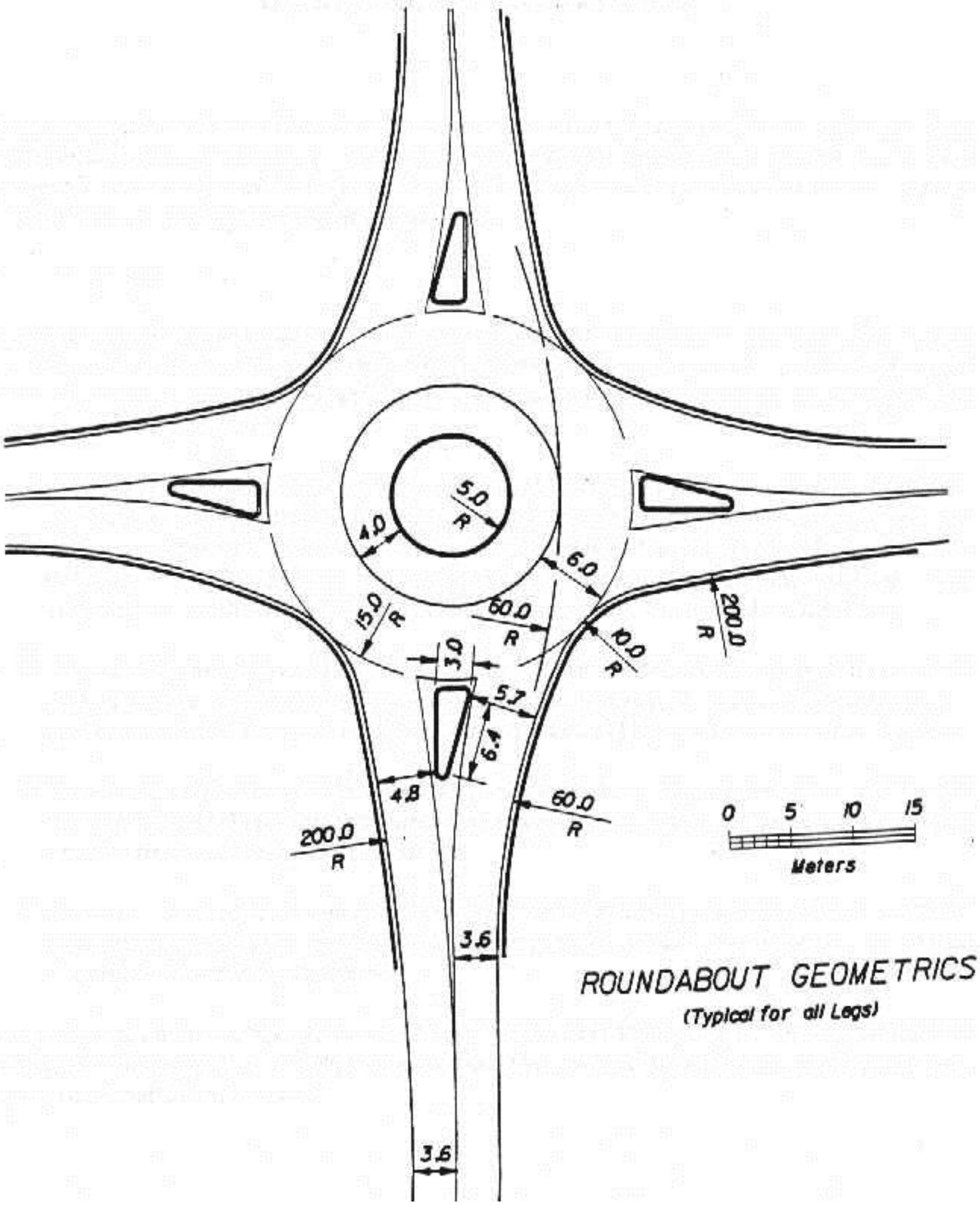

Figure 4. Minimum configuration for a simple roundabout
(FL roundabout design guide, 1996)

Table 1. Design Elements Stated by Three Guidelines (Bared *et al*, 1997)

DESCRIPTION	BRITISH	AUSTRALIAN	FRENCH
Central Island diameter (at the non-mountable curbs)	Min. 4m	Min. 5m, Recommend 10m Typical 20-30m	Min. 7m
Width of circulatory travel-way (curb to curb)	Max. 15m	-------------------	Min. 6.5 - 8.5m Max. 9m
Inscribed circle diameter	Min. 15m Max. 100m	-------------------	-------------------
Cross-Section (X-tion) of circulatory travel-way	Adverse and crowded X-tion recommend 2-2.5%	Adverse X-section Min. 2.5 - 3%	Adverse X-section recommend 1-2%
Entry width (Curb to Curb)	Min. 4m Max. 15m	Min. 5m	Recommend 5m for 1-In approach 8m for 2-In approach
Entry Radius	Min. 6m Recommend 20m	-------------------	Recommend 10-15m entry radius<= inscribed radius
Exit width (curb to curb)	Recommend 7-7.5m	Min. 5m	Recommend 5-6m for 1-In, 8m for 2-In
Exit Radius	Min.20m, desirable 40m	-------------------	Min. 15m, Max. 30m Exit rad. > central Isl. radius
Length of separator island	20-50m	Comfortable deceleration length (high speed)	= to radius of inscribed circle
Lighting	Required	Required	1. Required if approach is already lighted 2. Otherwise not required in rural areas

While the guidelines are useful, the diversity in the values between countries, and within each factor, as well as the fuzziness of the terms used limit its use only as guidelines. In addition the guidelines are particular to specific country, and it is not inclusive to all factors.

There is a need for an efficient tool that would enable traffic analysts to evaluate different combinations of design and traffic factors and propose efficient designs in a timely manner. When interactions between design factors are so complex, such as the case of roundabout design; simulation techniques proved to be the most efficient tools to support the design function.

GEOMETRIC DESIGN ELEMENTS

There is no uniform design guidance in the U.S. for modern roundabouts. However, the Federal Highway Administration is planning to develop guidelines, and information on roundabouts will also be introduced in the next edition of AASHTO's Policy on Geometric Design of Highways and Streets. The design practices currently used in the US are generally based on either the British or the Australian guidelines.

The basic principle of roundabout design is to restrict the operating speed within the intersection by deflecting the paths of entering and circulating vehicles. Safety and capacity benefits can be fully achieved only if vehicles are physically unable to traverse the roundabout at speeds higher than approximately 40 km/h. The major elements of a roundabout are shown in Figure 5. 5and are described as follows:

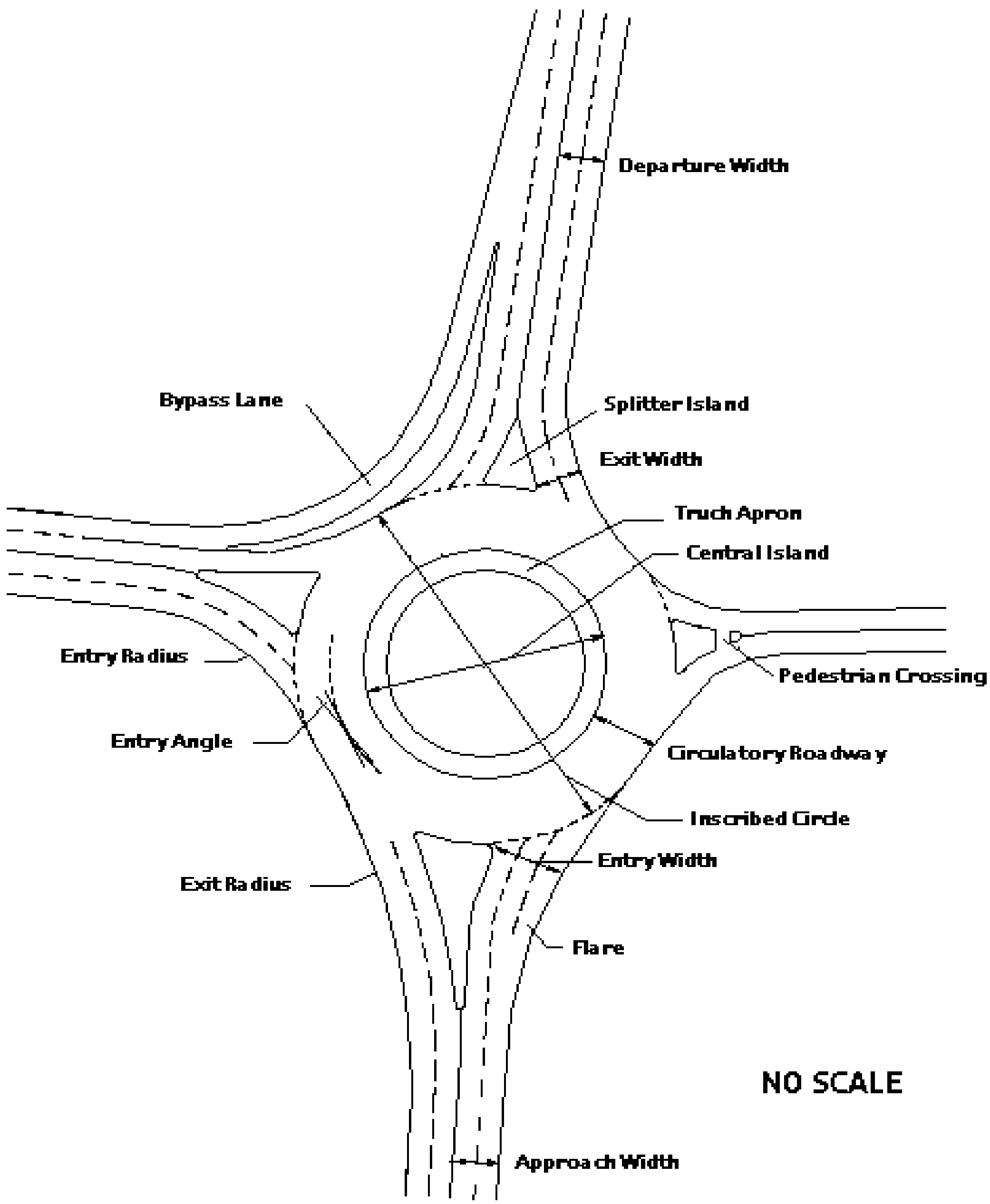

Figure 5. Design elements of roundabouts (Bared *et al*, 1997)

Inscribed Circle

The diameter of the inscribed circle may range between 15 m and 100 m. A minimum diameter of 37 m is required for roundabouts on the State highway system, because smaller circles do not adequately accommodate truck movements. However, the safety advantages of a roundabout may begin to diminish when the diameter of the inscribed circle exceeds 75 m.

Circulatory Roadway

The width of the circulatory roadway depends mainly on the number of entry lanes and the radius of vehicle paths. The roadway must be at least as wide as the maximum entry width, and lane lines within the circle should not delineated. The pavement may be either crowned or sloped to one side, depending on the need to facilitate drainage or minimize adverse crossfalls for vehicle paths.

Central Island

The central island is usually delineated by a raised curb, and its size is determined by the width of the circulatory roadway and the diameter of the inscribed circle.

Truck Apron

A truck apron may be needed on smaller roundabouts to accommodate the wheel path of oversized vehicles. The apron is usually designed as a mountable portion of the central island.

Splitter Island

This splitter island is placed within the leg of a roundabout to separate entering and exiting traffic. It is usually designed with raised curb to deflect entering traffic and to provide a refuge for pedestrian crossings.

Bypass Lane

A bypass lane may be warranted for heavy right turn volumes.

Pedestrian Crossing

The location of pedestrian crossing is generally recommended to be one to three vehicle lengths behind the yield line. Bringing crossings closer to the circle would reduce roundabout capacity, while placing them further away would expose pedestrians to higher speeds.

Approach Width

This approach width refers to the half of the roadway that is approaching the roundabout.

Departure Width

This departure width refers to the half of the roadway that is departing the roundabout.

Entry Width

The entry width is the perpendicular distance from the right curb line of the entry to the intersection of the left edge line and the inscribed circle.

Exit Width

The exit width is the perpendicular distance from the right curb line of the exit to the intersection of the left edge line and the inscribed circle.

Flare

A flare may be used to increase the capacity of a roundabout by providing additional lanes at the entry. Because flared entries tend to increase the potential for accidents, they should be used only when required by traffic volumes.

Entry Angle

To provide the optimum deflection for entering vehicles, the angle of entry should be approximately 30 degrees. Smaller angles reduce visibility to the driver's left, while larger angles cause excessive braking on entry and a resulting decrease in capacity.

Entry Radius

The entry radius is the minimum radius of curvature measured along the right curb at entry. The practical entry radius is approximately 20 m. Smaller radii may decrease capacity, while larger radii may cause inadequate entry deflection.

Exit Radius

The exit radius is the minimum radius of curvature measured along the right curb at exit. The desirable exit radius is approximately 40 m.

TRAFFIC OPERATIONS

Capacity

Roundabout capacity is defined as the sum of all entering approach capacities. Capacity of each entry is defined as the maximum number of vehicles that can enter the roundabout within 1 hour; this is defined for a given volume of circulating vehicles. This is similar in concept to the analysis method of the Highway Capacity Manual HCM "Chapter 10" for unsignalized intersection capacity, whereby the capacity of each minor traffic stream is defined separately, depending in the critical gap and the conflicting traffic-stream volume. Linear regression equations have been developed to describe the relationship between the entry capacity (Ve) of an approach and the circulating traffic volume (Vc). **Error! Reference source not found.**6 presents these parameters.

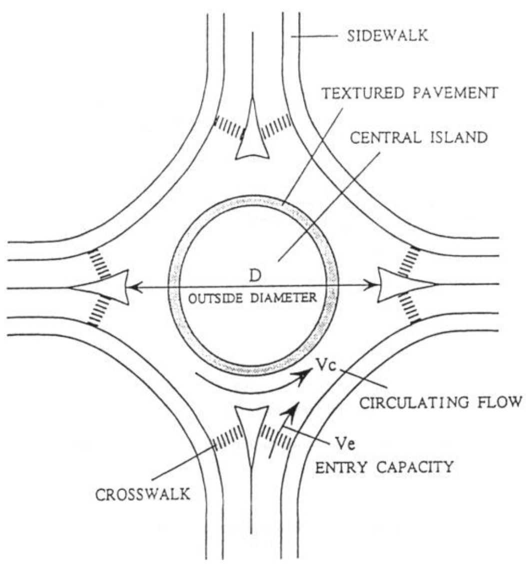

Figure 6. Entry capacity and circulating flow parameters (Polus and Shmueli, 1997)

Generally, there are two approaches to calculating the capacity of a roundabout. The British method involves an empirical formula based on measurements at saturated roundabouts, whereas the Australian method uses an analysis based on gap acceptance. A draft update of the Highway Capacity Manual (HCM) includes a procedure for determining the capacity of single-lane roundabouts using the gap acceptance approach. For analyzing multi-lane roundabouts, the draft HCM suggests the use of software programs, but no specific program is mentioned. It is recognized that there are advantages to using empirical models to develop relationships between geometric design characteristics and roundabout performance. However, given the current lack of field data in the United States, the draft HCM recommends using the analytical approach. Although both approaches are currently acceptable, the fundamental differences between the empirical and analytical methods may sometimes produce inconsistent results. The two methods are described as follows:

Empirical (British) Method

In the British method, the capacity formula is based on the relationship between entry capacity and various geometric parameters. For example, the capacity of each approach to a roundabout decreases linearly as the entry angle increases. Other parameters include entry width, approach width, entry radius, and inscribed circle diameter. Two computer software packages commonly used to calculate capacities, queues, and delays in accordance with the British formula are ARCADY (Assessment of Roundabout CApacity and DelaY) and RODEL (ROundabout DELay). Statistical tests have been performed to confirm the suitability of the geometric parameters used to predict capacity, and the output of both computer programs have been verified through direct field observations.

Analytical (Australian) Method

In the Australian method, the capacity of a roundabout is calculated using a traditional gap acceptance approach that is similar to the process described in the HCM for analyzing two-way stop-controlled intersections. It is assumed that drivers need a minimum "critical gap" in the circulating flow before entering the roundabout. As the available gaps become larger, more than one driver can enter with subsequent headways equal to the "follow-up time". The capacity formula calculates the capacity of each approach as a function of the circulating flow, the critical gap, and the follow-up time. SIDRA (Signalized and unsignalized Intersection Design and Research Aid) is the computer software package commonly used for predicting the performance of roundabouts by applying the gap-acceptance methodology.

Comparison between Roundabout Capacity Models

Given that no capacity models are yet developed in the United States, equations from foreign sources may temporarily be used to conduct capacity analysis. **Error! Reference source not found.**7 shows models developed in England, Australia, Switzerland, and Germany. English and Australian models include the outside diameter "D" (see **Error! Reference source not found.**6). The German and Swiss models do not depend on the diameter and therefore, they can be adopted only for general planning rather than for detailed designs.

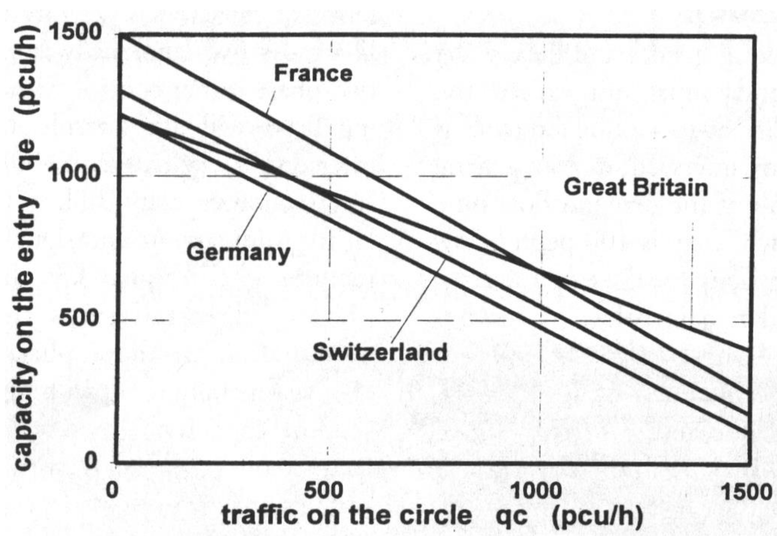

Figure 7. International comparison of entry capacities for single-lane roundabouts (Brilon and Vandehey, 1998)

Brilon and Vandehey (1998) found that entry capacity is significantly affected by human behavior, particularly personal attitudes and experience. Because all these behavior elements are variable, capacity at roundabouts is generally expected to be much more variable than for signalized intersections. Table 2 summarizes modeling effort done by Brilon (1998, Germany).

Table 2. Entry Capacity Equations for Roundabouts (Brilon and Vandehey, 1998)

Number of Lanes		
Entry	Circle	Entry Capacity Equations
1	1	$q_e = 1{,}218 - 0.74q_c$
1	2 to 3	$q_e = 1{,}250 - 0.532q_c$
2	2	$q_e = 1{,}380 - 0.50q_c$
2	3	$q_e = 1{,}409 - 0.42q_c$

Note: The linear equations are for the calculation of entry capacities (q_e) at roundabouts in Germany [q_c = traffic flow on the circulating roadway immediately upstream of the entry. All traffic volumes are given in pcph where 1 bus or truck = 1.5 passenger car unit (pcu); 1 truck plus trailer or articulated bus = 2 pcu; and 1 motorcycle or bicycle = 0.5 pcu.]

Based on applications in Germany, compact single-lane roundabouts have many advantages for intersection with traffic volumes of up to 25,000 vpd. However, this amount can be increased by using a right-hand “bypass” or “slip” lane for high-volume, right turn flow (see **Error! Reference source not found.**8).

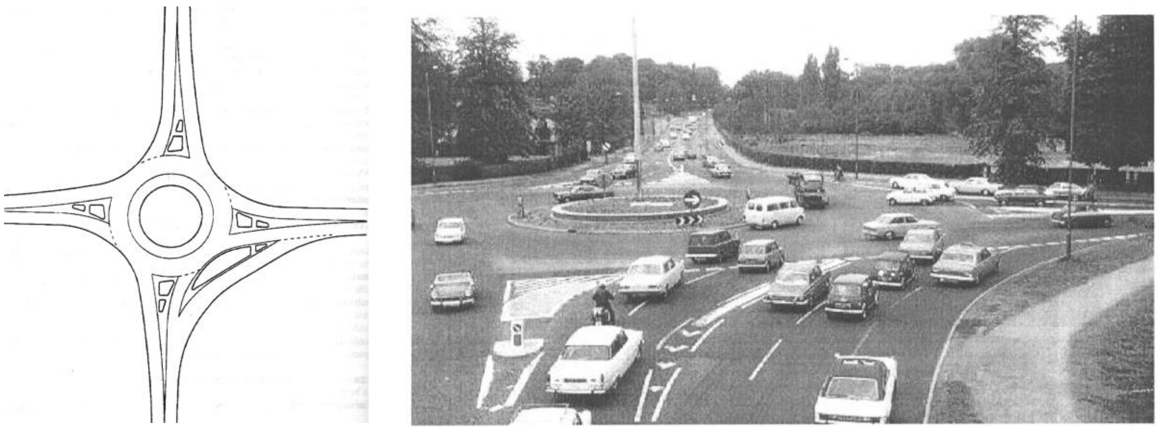

Figure 8. Roundabout with right-turn bypass lane
(Public Roads, Autumn 1995)

Delay

Roundabout delay is defined separately for each entry approach. The delay for any entry approach is composed of two distinct components: queuing and geometric delay. Queuing delay occurs when drivers are waiting for an appropriate gap in the circulating traffic. Geometric delay results from vehicles slowing down as they traverse the roundabout (i.e., driving through circulating lane).

To avoid long queues and delays, traffic demands must not exceed the design capacity for all entry approaches, as is the case at any intersection. **Error! Reference source not found.**9 shows average delay versus reserve capacity. Reserve capacity is an indication for how busy the entry approach. Based on this figure if the demand flow of a given approach entry is 100 pcph below the design capacity, average delay should remain below 35 seconds per vehicle.

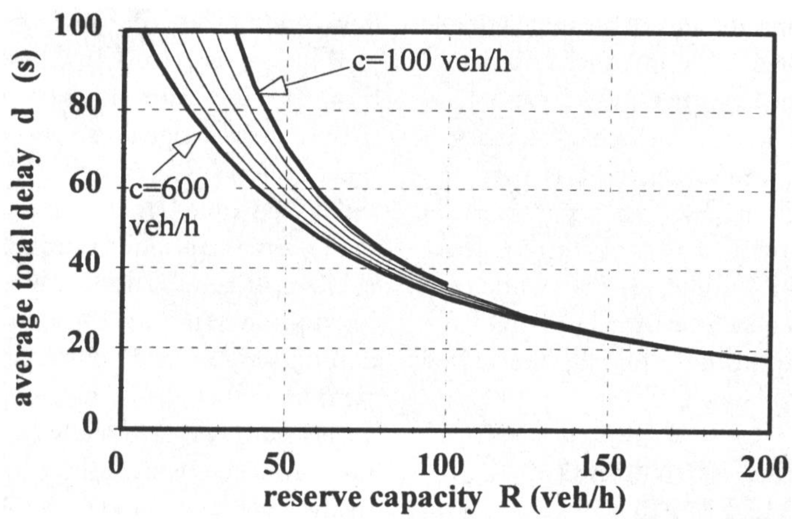

Figure 9. Average delay versus reserve capacity (Brilon and Vandehey, 1998)

When comparing a roundabout's operation with that of a traffic signal, it is important to recognize that outside the intersection's peak hours (i.e., traffic demands are lower), roundabouts result less delay to motorists, whereas a signal will always result more delay, even under extremely low flow conditions.

Safety

Reduced speeds at roundabouts have been shown to be the primary cause of improving safety. Another factor is the reduced number of conflict points as compared to conventional intersection.

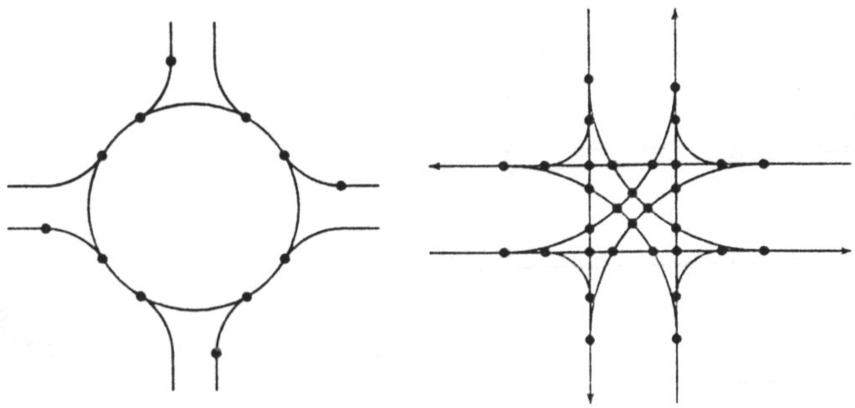

Figure 10. Potential conflict points between an intersection and a roundabout

(Bared *et al*, 1997)

Accident predication models for roundabouts have been developed in terms of entering traffic, circulating traffic, and geometric features such as entry path curvature, entry width, circulating width, and central diameter. Accident models are classified by accident types for a given entry approach. Bared *et a* (1997) presented the following accident model for roundabouts.

$$A = kQ^{a}(\text{or } Q_e^{\alpha} Q_c^{\beta})\exp(\sum b_i X_i)$$

where

A = accidents (fatal and injury) per leg or approach,
k = estimated coefficient determined by regression analysis,
α, β = estimated coefficients corresponding to traffic flows,
Q = entering ADT × circulating ADT,
Q_e = entering ADT,
Q_c = circulating ADT, and
$b_i X_i$ = geometric variables X_i and their estimated coefficients b_i .

Error! Reference source not found.11 provides examples for these accident models. This figure confirms that roundabouts experience fewer and lower severity than stop and signalized intersections. The most safety sensitive design elements of roundabouts are entry width and circulating width. Widening of both entry and circulating widths increases accident frequency. However, capacity of roundabout does increase as entry and circulating widths increases. Keep in mind, that capacity often conflicts with safety.

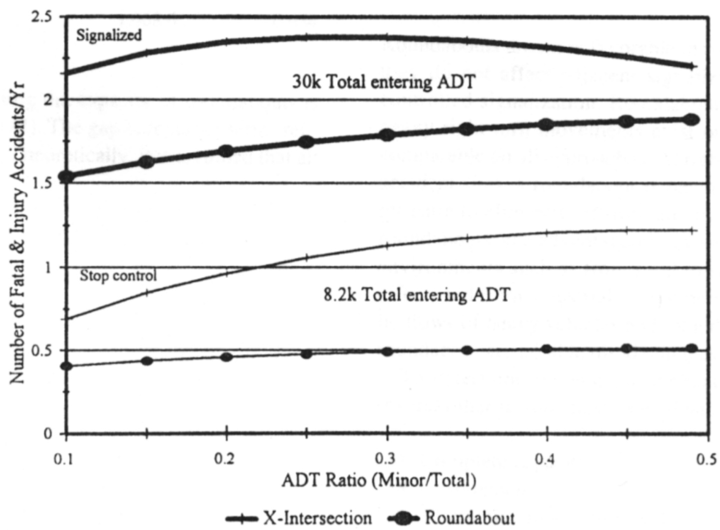

Figure 11. Examples for accident models for roundabout and signalized intersections (Bared *et al*, 1997)

ADVANTAGES OF ROUNDABOUTS

Less Serious Accidents

Head-on and angle collisions are virtually non-existent because of the circular rather than opposing flow of traffic. The angles of traffic interaction and slower speed through the interchange reduce the severity of accidents. Roundabouts in the USA and other countries have achieved a 50 to 90 percent reduction in collisions compared to intersections using 2- or 4-way stop control or traffic signals (http://www.islandnet.com/ITE_BC/No95_Roundabout.html).

Construction, Operating, and Maintenance Costs

A simple signalized intersection costs about $3,000 (US) per year for electricity, maintenance of loops, controller, signal heads, timing plans, etc. In addition, signal heads and controllers have to be replaced and completely rebuilt on a regular basis. Larger signalized intersections are more expensive to maintain. The only maintenance costs for a roundabout are for landscape maintenance and occasional sign replacement.

Small roundabouts only cost several thousand dollars. Larger roundabouts can cost as much or more than a set of traffic signals. Even if the construction cost of a roundabout is higher than traffic signals, a life cycle economic analysis including construction, operation, maintenance and collision cost reduction of each type of control will usually show that a roundabout has a higher benefit/cost ratio than signalized intersection.

Self Regulating

Traffic flows change with time and development. To provide optimum operation, traffic signals need to be retimed regularly. As traffic volumes increase, especially cross-traffic volumes, additional intersection lanes need to be added so the intersection capacity can approach that of the mid-block segment. In most cases the whole road is widened. In contrast, the capacity of a roundabout can approach the mid-block capacity of the intersecting roads. Although as the cross-traffic volumes increase, short approach lanes and/or an additional circulating lane may be added. The resulting roadwork and right-of-way requirements are much less than for the signal controlled intersection. Generally a well-designed roundabout closely matching approach and mid-block capacity, rarely needs altering, except where the road is widened and the number of approach lanes increased.

Environmental benefits

Brilon (1998) mentioned that German and other countries indicate that roundabouts account for a reduction in noise levels. Roundabout also can be expected to result in a lower pollutant output as the result of fewer vehicle stops and starts.

DISADVANTAGES OF ROUNDABOUTS

Flat Area

Roundabouts should be considered only in areas that can accommodate an acceptable outside diameter and other appropriate geometric design elements. To provide adequate sight distance for approaching drivers to perceive the layout of the intersection, the roundabout should be preferably located either on level terrain or at the bottom of a sag vertical curve. The topography should also allow the circle of the roundabout to be constructed on a flat plateau to provide visibility within the intersection.

Signal Coordination

Roundabouts are not suitable in areas with a coordinated traffic signal system, because such systems break down when the progression of platoons is disrupted by the unregulated movement of a roundabout. Conversely, a roundabout should not be constructed at a location where the flow of vehicles leaving the intersection would be obstructed by queues from downstream traffic controls.

Unbalanced Flow

Roundabouts may not be effective at intersections where entry flows are unbalanced. When the volume on the major road is much heavier than that on the minor road, the equal treatment of approaches may cause undue delay to the major road. Also, if the major road carries a heavy stream of through-traffic, the lack of adequate gaps in the dominant flow may prevent the minor flow from entering the roundabout.

Pedestrians / Bicyclists Safety

Additional assessment is warranted prior to constructing roundabouts in areas where pedestrian or bicycle activity is expected. With the absence of conventional crossing controls, many pedestrians do not perceive roundabouts to be safe. Despite this perception, accident records indicate that with the use of proper design elements, a pedestrian is at least as safe at a roundabout as at a conventional intersection. However, the safety record for bicyclists appears to be more problematic.

MODELING AND SIMULATION

The theory of gap-acceptance leads to complex assumptions regarding driver behavior. Various simplifications need to be made in order to obtain less complicated model. Although simulation models have many advantages, it should be noted that the need for data is great. Since simulation models are dependent on driver behavior, the criticism directed at gap-acceptance models is also valid.

Simulation techniques involving complex computer programs have been developed in the last decade, which require considerable computing power. These are used in a number of countries to model behavior at non-signalized intersections, but only some have been adapted to roundabouts. The earlier role of simulation models of entry capacity, delay, and accident risk is changing from an instrument of scientific research towards a practical tool for the traffic engineer.

Simulation models have been developed or investigated in Australia, France, Germany, England and Switzerland. The development of a simulation model (INSECT) in Australia has indicated that fixed gap times are not applicable, and there are differences of gap-acceptance characteristics between sign controlled intersections and roundabouts, where gaps acceptance depends on waiting time. The model attempts to simulate the movements of individual vehicles every second. It contains five sub-models: drivers, vehicle generation, lane selection, standard conflict resolution, and roundabout conflict resolution. The latter considers also the closest approach on the right. Gap-acceptance methods are used to resolve the conflicts. Small roundabouts are not modeled very well. Results, surveyed and simulated queue delays, confirms that for most cases the model predictions are reasonably accurate. Further development in the field of crash prediction is possible.

Compute Programs

Since roundabout design is fairly new, there are very few programs developed that are used for analysis of roundabouts. Modifying the results of present day intersection analysis programs form many of these programs. Some of the more popular programs are RODEL, ARCADY, SIDRA, KREISEL, GIRABASE, and HCM (Highway Capacity Manual). Of these programs, SIDRA is the most commonly used.

SIDRA

The SIDRA (Signalized & unsignalized Intersection Design and Research Aid) package has been developed by ARRB Transport Research in Australia, as an aid for design and evaluation of the following intersection types:

- Signalized intersections
- Roundabouts
- Two-way stop control
- All-way stop control
- Yield sign control

Recent Australian research shows that if there is more than one entry lane, the traffic flow differs between the lanes. The lane with the greatest flow is called the dominant stream and the other lanes are termed the sub-dominant streams.

The gap-acceptance parameters are calculated in the following order:

- The follow up time in the dominant stream is estimated as a function of the circulating flow and the inscribed circle diameter;
- The follow up time in the sub-dominant stream is calculated as a function of the ratio of flows between the lanes considered and the dominant-stream follow up time;

- The critical gap is calculated as a function of the follow up time, the major flow, the number of effective circulating lanes and the entry lane width.

All capacity estimates are based on gap acceptance modeling. SIDRA computes the capacity of each approach lane separately. This method allows for capacity losses due to lane under-utilization and allocated the largest degree of saturation in any lane movement (Kerenyi, 1998).

SIDRA requires site specific data covering traffic volumes by movement, number of entry and circulating lanes, central island diameter, and circulating roadway width. It uses several parameters for which reasonable default values are offered.

One parameter of particular importance is the practical capacity of roundabouts. The default value of 85% of the possible capacity (i.e. v/c = 0.85). The SIDRA documentation points out that roundabout operation at near capacity levels is less predictable than signal operation. This is because signal control is more positive, and therefore less dependent on drivers' behavior. Therefore, more caution is urged in dealing with roundabouts that operate above the practical capacity. The concept of geometric delay is added to the queuing delay. Geometric delay is the delay experienced by drivers within the roundabout due to a negotiation speed that is slower that the approach speed. SIDRA offers the option to include or exclude the geometric delay from computations. Technically, a delay that includes the geometric delay provides a more realistic assessment of roundabout performance (FDOT, 1996).

RODEL

RODEL is an interactive program intended for the evaluation and design of roundabouts. This program was developed in the Highways Department of Staffordshire County Council in England. RODEL is based on an empirical model developed by Kimber at the Transport and Road Research Lab (TRRL) in the UK. The empirical model was chosen over the gap acceptance model because it directly related capacity to detailed geometric parameters. RODEL is an interactive program in which simultaneous display of both input and output data is shown in a single screen. There are two main modes of operation. In mode 1, the user specifies a target parameter for average delay, maximum delay, maximum queue, and maximum v/c ratio. RODEL generates several sets of entry geometrics for each approach based on the given input. Depending on site specifics and constraints, the generated geometrics can be used for design purposes. Mode 2 focuses more on performance evaluation using specified values of the geometric and traffic characteristics.

ARCADY

ARCADY is a British roundabout analysis program which has the same theoretical background as RODEL. This program also incorporates Kimber's model which is based on the rule of circulating vehicles having priority over entry vehicles. Kimber used the idea of entry geometry affecting the capacity and related the equation to several site-specific parameters. The model also assumes a linear relationship between the circulating flow and the maximum entry flow. The ARCADY input data requirements are similar to RODEL since both programs follow the same methodology. The input parameters include entry width, inscribed circle diameter, flare length, approach road width, entry radius, and entry angle. Like RODEL, ARCADY deals in the concept of confidence level. The main difference is that the confidence level may be specified for RODEL, but is embedded in the ARCADY model at 50 percent.

KREISEL

Developed in Germany, it offers many user-specified options to implement the full range of procedures found in the literature from Europe and Australia. KREISEL gives the average capacity from a number of different procedures. It provides means to compare these procedures.

GIRABASE

Is a French method. Capacity, delay, and queuing projections based on regression. Sensitive to geometric parameters. Gives average values.

HCM Software

US HCM method. Limited to capacity estimation based on entering and circulating volume. Optional gap acceptance parameter values provide both a liberal and conservative estimate of capacity. The data used to calibrate the models were recorded in the US. The two curves given reflect the uncertainty from the results. The upper bound average capacities are anticipated at most roundabouts. The lower bound results reflect the operation that might be expected until roundabouts become more common.

SUMMARY AND CONCLUSIONS

Modern roundabouts are circular intersections that have been successfully implemented in Europe and Australia over the past few decades. Despite the approximately 35,000 roundabouts in operation around the world, there are fewer than 50 that exist in the United States. Modern roundabouts are distinguished from traffic circles by; (1) the "yield-at-entry" rule in which approaching vehicles must wait for a gap in the circulating flow before entering the circle, (2) parking is not allowed on the circulating roadway, and (3) no pedestrian activities take place on the central island.

Roundabout capacity is defined as the sum of all entering approach capacities. Capacity of each entry is defined as the maximum number of vehicles that can enter the roundabout within 1 hour; this is defined for a given volume of circulating vehicles. Linear regression equations have been developed to describe the relationship between the entry capacity (Ve) of an approach and the circulating traffic volume (Vc).

Because roundabouts have only begun to appear in the U.S., there is a lack of empirical data regarding the volume at which a roundabout begins to break down. Until further data is available, roundabouts on the State highway system should be considered only at intersections where volumes generally do not exceed 5000 vehicles per hour. Regardless of whether the proposal involves a new facility or an operational improvement, the design of a roundabout should be based on estimated traffic 20 years after the completion of construction.

Our investigation showed many advantages to roundabouts, including safety and delay benefits. It is therefore suggested that roundabouts be considered as alternatives to intersections that experience or expected to experience high crash rates or delay levels. Developing a simulation tool for roundabouts is recommended to evaluate existing roundabouts or comparing roundabouts to intersections.

There is a need for an efficient tool that would enable traffic analysts to evaluate different combinations of design and traffic factors and propose efficient designs in a timely manner. When interactions between design factors are so complex, such as the case of roundabout design; simulation techniques proved to be the most efficient tools to support the design function. The simulation program will need to include a model of driver behavioral patterns, including the gap acceptance process. The definition of delay is critical during the validation of the program. If delays are taken as those incurred by vehicles on the approaches to the roundabout, then delays from queues observed will need to be compared to the simulated delays.

BIBLOGRAPHY

Bared, J., Prosser, W., and Esse, C., (1997) “State-of-the-art design of roundabouts”, *Transportation Research Record* 1579.

Brilon, W., Vandehey, M., (1998) "The state of the art in Germany", *ITE journal*

Florida roundabout guide, Florida Department of Transportation, 1996.

Kerenyi L (1998) “A Comparison of a Traffic Signal Controlled Junction and a Roundabout Solution at the Sluppen Bridge Junction in Trondheim”, Master’s thesis, Norwegian University of Science and Technology.

Polus, A., and Shmueli, S., (1997) “Analysis and evaluation of the capacity of roundabouts”, *Transportation Research Record* 1572

Public Roads (Autumn 1995), http://www.tfhrc.gov/pubrds/fall95/p95a41.htm

http://www.islandnet.com/ITE_BC/No95_Roundabout.html

http://roundabouts.kittelson.com/crossref.html

APPENDIX

ROUNDABOUTS IN THE U.S.

Status: Existing

State	County	City	Intersection	Type
	N/A	(unincorporated)	inv.cgi?site_id=140	
CA	Alameda	Berkeley	Marin Ave./Los Angeles Ave./Del Norte St./Arlington Ave.	
CA	Humboldt	Arcata	West End @ Spear	Single-Lane
CA	Los Angeles	Long Beach	Los Alamitos Circle (Hwy. 1/Hwy 19/Los Coyotes Diagonal)	Multi-Lane
CA	Santa Barbara	Santa Barbara	Alameda Padre Serra/Montecito St./Salinas St./Sycamore Canyon Rd.	Single Lane
CO	N/A	Avon	Avon Rd./Beaver Creek Blvd.	Multi-Lane
CO	N/A	Avon	Avon Rd./Benchmark Rd.	Multi-Lane
CO	N/A	Avon	Avon Rd./I-70 EB Ramps	Multi-Lane
CO	N/A	Avon	Avon Rd./I-70 WB Ramps	Multi-Lane
CO	N/A	Avon	Avon Rd./US 6	Multi-Lane
CO	N/A	Nederland	Hwy 72/Hwy 119/2nd St./Bridge St.	Single Lane
CO	N/A	Vail	Chamonix Rd./I-70 EB Ramps/South Frontage Rd.	Multi-Lane
CO	N/A	Vail	Chamonix Rd./I-70 WB Ramps/North Frontage Rd.	Multi-Lane
CO	N/A	Vail	Vail Road/I-70 EB Ramps/South Frontage Rd.	Multi-Lane
CO	N/A	Vail	Vail Road/I-70 WB Ramps/North Frontage Rd./Spraddle Cr. Rd.	Multi-Lane
DC	N/A	Washington	Chevy Chase Circle (Conn. Ave./Western Ave.)	
DC	N/A	Washington	Dupont Circle (Mass Ave./Conn. Ave./New Hampshire Ave.19th St./P St.)	
DC	N/A	Washington	Grant Circle (New Hampshire Ave./Illinois Ave./NW 5th St.)	

State	County	City	Intersection	Type
DC	N/A	Washington	Logan Circle (Rhode Isl. Ave./Vermont Ave./13th St./P St.)	
DC	N/A	Washington	Scott Circle (Mass. Ave./Rhode Isl. Ave./16th St./N St.)	
DC	N/A	Washington	Sheridan Circle (Mass Ave./23rd St./R St.)	
DC	N/A	Washington	Sherman Circle (Kansas Ave./Illinois Ave.)	
DC	N/A	Washington	Tenley Circle (Conn. Ave./Nebraska Ave.)	
DC	N/A	Washington	Thomas Circle (Mass Ave./Vermont Ave./14th St./M St.)	
DC	N/A	Washington	Ward Circle (Mass. Ave./Nebraska Ave.)	
DC	N/A	Washington	Washington Circle (Penn. Ave./New Hampshire Ave./23rd St./K St.)	
DC	N/A	Washington	Westmoreland Circle (Mass. Ave./Dalecarlia Pkwy/Western Ave.)	
FL	Alachua	Gainesville	SE 7th Street/SE 4th Avenue	Single Lane
FL	Broward	Hollywood	Hollywood Blvd./26th Ave.	Multi-Lane
FL	Broward	Hollywood	Hollywood Blvd./Rainbow Dr.	Multi-Lane
FL	Broward	Hollywood	Hollywood Blvd./S. Federal Hwy. (US 1)/Harrison St./Tyler St.	Multi-Lane
FL	Collier	Naples	7th St. N./11th Ave. N.	Single Lane
FL	Collier	Naples	7th St. N./12th Ave. N.	Single Lane
FL	Collier	Naples	7th St. N./3rd Ave. N.	Single Lane
FL	Collier	Naples	7th St. N./7th Ave. N.	Single Lane
FL	Collier	Naples	8th St. S./12th Ave. S.	Single Lane
FL	Hillsborough	Tampa	North Blvd./Country Club	Single Lane
FL	Lake	Lady Lake	()	Multi-Lane
FL	Lake	Lady Lake	()	Multi-Lane
FL	Lake	Tavares	Main St./Disston Ave./Lake Dora Dr.	Single Lane
FL	Leon	Tallahassee	Killarney Way/Shamrock Drive	Single Lane
FL	Manatee	Bradenton Beach	SR 789/Bridge Street	Single Lane
FL	Martin	Stuart	Federal Hwy (US 1)/SR 76/SR A1A	Single Lane

State	County	City	Intersection	Type
FL	Martin	Stuart	N. Colorado Ave./E. Osceola St.	Single Lane
FL	N/A	(unincorporated)	inv.cgi?site_id=138	
FL	Okaloosa	Fort Walton Beach	Hollywood Blvd./Doolittle Blvd.	Single Lane
FL	Palm Beach	Boca Raton	SW 18th St./Juana Rd. (SW 12th Ave.)	Single Lane
FL	Palm Beach	West Boca Raton	Lakes at Boca Raton/Cain Blvd.	Single Lane
FL	Sarasota	Sarasota	South Gate Circle (Tuttle Ave./Siesta Dr.)	Multi-Lane
FL	Sarasota	Sarasota	St. Armands Circle (SR 780/Blvd. of the Presidents/John Ringling Blvd.)	Multi-Lane
MD	Anne Arundel	Lothian	MD 2/MD 408/MD 422	Single Lane
MD	Baltimore	Towson	MD 45/MD 146/Joppa Rd./Allegheny Ave.	Multi-Lane
MD	Carroll	Taneytown	MD 140/MD 832	Multi-Lane
MD	Cecil	Leeds	MD 213/Leeds Road/Elk Mill Road	Single Lane
MD	Harford	Bel Air	Tollgate Rd. & Marketplace Dr.	Single-Lane
MD	Howard	(unincorporated)	Baneker Rd.	
MD	Howard	(unincorporated)	MD 103/MD 100 EB Ramps	Single Lane
MD	Howard	(unincorporated)	MD 103/MD 100 WB Ramps	Single Lane
MD	Howard	(unincorporated)	Trotter Rd.	
MD	Howard	Lisbon	MD 94/MD 144	Single Lane
MD	Montgomery	Gaithersburg	Longdraft Rd./Kentlands	Multi-Lane
MD	Prince George's	(unincorporated)	Ft. Washington Rd.	
MD	Washington	Cearfoss	MD 63/MD 58/MD 494	Single Lane
ME	N/A	Gorham	Rte. 202/Rte. 4/Rte. 237	
MS	Hinds	Jackson	MS 475/Airport Rd./Old Brandon	Single Lane
NV	N/A	Las Vegas	Lake South/Crystal Water Way	Single Lane
NV	N/A	Las Vegas	Michael/Harmony Way	Single Lane
NV	N/A	Summerlin	North Roundabout (Village Center Circle/Town Center Drive/Library Hill Drive?)	Multi-Lane

State	County	City	Intersection	Type
NV	N/A	Summerlin	South Roundabout (Village Center Circle/Hill Center Drive/Meadow Hills Drive?)	Multi-Lane
OR	Multnomah	Portland	NE 39th Ave./Glisan St.	Multi-Lane
OR	Washington	Beaverton	SW Teal Blvd./155th Ave./Nutcracker Ct.	Single Lane
SC	N/A	Hilton Head	Whooping Crane/Main Street	Single Lane
TX	N/A	Addison	Mildred St./Quorum Dr.	Multi-Lane
VT	N/A	Montpelier	Keck Circle (Main St./Spring St.)	Single Lane
WA	Kitsap	Port Orchard	Mile Hill Dr. (Hwy 166)/Bethel Avenue	Single-Lane

Status: Planned

State	County	City	Intersection	Type
CA	Humboldt	Arcata	Samoa @ Buttermilk	Single-Lane
CA	Humboldt	Arcata	Samoa @ Crescent	Single-Lane
CA	Humboldt	Arcata	Samoa @ Union	Single-Lane
CA	Placer	Truckee	Donner Pass Rd./I-80 Ramps	
FL	Palm Beach	Lake Worth	Lake Worth Ave. (SR 802)/South A Street	Multi-Lane
KS	N/A		Rice Rd./I-70 EB Ramps	
KS	N/A		Rice Rd./I-70 WB Ramps	
MD	Anne Arundel	(unincorporated)	Arundel Beach Road/Leelynn Drive	Single Lane
MD	Anne Arundel	Annapolis	Gateway Circle (West St./Taylor Ave./Spa Rd.)	Multi-Lane
MD	Anne Arundel	Glen Burnie	Quarterfield Road (MD 174)/I-97 SB Ramps	Multi-Lane
MD	Baltimore	(unincorporated)	Charles St./Bellona Ave.	Single Lane
MD	Baltimore	(unincorporated)	MD 372/Hilltop Rd.	
MD	Caroline	Federalsburg	MD 307/MD 318	Single Lane
MD	Cecil	(unincorporated)	MD 291/US 301 NB Ramps	Single Lane
MD	Cecil	(unincorporated)	MD 291/US 301 SB Ramps	Single Lane
MD	Frederick	Brunswick	MD 17/A St./B St./Maryland Ave.	Single Lane

State	County	City	Intersection	Type
MD	Harford	Abingdon	Tollgate Pkwy. & Singer Rd.	Single-Lane
MD	Howard	(unincorporated)	Hopkins-Gorman Rd./US 29 SB Ramps	Multi-Lane
MD	Howard	(unincorporated)	MD 104/MD 100 WB Ramps	Multi-Lane
MD	Howard	(unincorporated)	MD 216/US 29 NB Ramps	Multi-Lane
MD	Howard	(unincorporated)	MD 216/US 29 SB Ramps	Multi-Lane
MD	Howard	(unincorporated)	Snowden River Pkwy./MD 100 WB Ramps	Single Lane
MD	Howard	Lisbon	MD 94/Old Frederick Rd.	
MD	Prince George's	Mt. Rainier	US 1/34th St.	Multi-Lane
MD	Prince George's	Ritchie	Ritchie-Marlboro Rd./I-95 NB Ramps	Multi-Lane
MD	Prince George's	Ritchie	Ritchie-Marlboro Rd./I-95 SB Ramps	Multi-Lane
NJ	N/A	Southampton	Red Lion Circle	
NJ	N/A	Wall	Brielle Circle	
VT	N/A	Bennington	Rte. 67A	
VT	N/A	Brattleboro	Rte. 9/Rte. 5	
VT	N/A	Manchester	Rte. 7A/Equinox	
VT	N/A	Manchester	Rte. 7A/Grand Union	Single Lane
VT	N/A	Richmond	Rte. 2/Rte. 117/I-89	
VT	N/A	Stow	Rte. 108	

Status: Proposed

State	County	City	Intersection	Type
CA	Alameda	Berkeley	Gilman St./I-80 Ramps	
CA	Humboldt	Arcata	11th @ D	Single-Lane
CA	Humboldt	Arcata	Alliance @ Foster	Single-Lane
CA	Humboldt	Arcata	Guintoli @ Heindon	Single-Lane
CA	Humboldt	Arcata	US101NB @ 14th	Single-Lane
CA	Humboldt	Arcata	US101NB @ Sunset & LK Wood	Single-Lane
CA	Humboldt	Arcata	US101NB @ Guintoli	Single-Lane

State	County	City	Intersection	Type
CA	Humboldt	Arcata	US101SB @ Sunset	Single-Lane
CA	Humboldt	Arcata	US101SB @ Guintoli	Single-Lane
CA	Los Angeles	Castaic	NorthLake Blvd./D St.	Single Lane
CA	Los Angeles	Long Beach	Lakewood Blvd. (Hwy 19)/Outer Circle Dr.	Multi-Lane
CA	N/A	Calabasas	Lost Hills Road/Agoura Rd	Multi-Lane
CA	N/A	Calabasas	Lost Hills Road/US 101 NB Ramps	Multi-Lane
CA	N/A	Carlsbad	Lego Dr./Armada Dr.	Multi-Lane
CA	N/A	Fresno	Fresno St./N. Fresno St./Divisadero St.	Multi-Lane
CA	Nevada	Grass Valley	Hwy 49/McKnight Rd.	
CA	Orange	(unincorporated)	Conroy-Windermere Rd./Apopka-Vineland Rd.	Multi-Lane
CA	Santa Barbara	Santa Barbara	Milpas St./US 101 WB Ramps/Carpinteria St.	Multi-Lane
CA	Sonoma	Sonoma	Hwy 12/Napa Rd.	
MD	Anne Arundel	Glen Burnie	Quarterfield Road (MD 174)/I-97 NB Ramps	Multi-Lane
MD	Harford	(unincorporated)	MD 165/MD 23	Single Lane
MD	Harford	(unincorporated)	MD 165/MD 24	Single Lane
MD	Washington	Ringgold	MD 64/MD 418	Single Lane
MD	Worcester	Ocean City	US 113/MD 589	

Status: Removed

State	County	City	Intersection	Type
FL	Palm Beach	West Palm Beach	S. Quadrille Blvd. (El Campeon Blvd.)/Fern St.	Single Lane
FL	Volusia	Daytona Beach	Seabreeze Circle(Seabreeze Bridge/Mason Ave./Ballough Dr.)	Multi-Lane