FINAL REPORT

PROJECT NYSDOT C-01-47

OPERATIONAL AND SAFETY PERFORMANCE OF MODERN ROUNDABOUTS AND OTHER INTERSECTION TYPES

Stacy Eisenman, Jessica Josselyn, and George List
Rensselaer Polytechnic Institute

Bhagwant Persaud and Craig Lyon
Ryerson University

Bruce Robinson, Miranda Blogg and Eric Waltman
Kittelson & Associates Inc.

Rod Troutbeck
Queensland University of Technology

January 24, 2004

1.0 Introduction

This project has been focused on learning about the safety and operational performance of roundabouts in the US. Operational and accident data were collected through a nationwide survey. The responses were analyzed for evidence of before-versus-after trends in operational and safety performance and tendencies in design practice. RODEL datasets were prepared from several of the survey responses to create estimates of roundabout performance. A public information brochure was prepared so that NYSDOT is better equipped to tell the traveling public about the advantages of using roundabouts where appropriate.

One of the motivations for focusing on roundabouts is their safety performance. European and Australian experience suggest that roundabouts have an ability to reduce severe accident rates at intersections by 45 to 75 percent. The survey responses suggest similar trends for the US. Of the 35 sites for which accident data were reported, 28 saw a reduction in the accident rate. Only seven sites had an increase. The average decrease in accident rate was 47%.

Prior to this study, not much was known about the performance of modern roundabouts in the United States. The survey shows that modern roundabouts have been introduced in several states including Colorado, Maryland, Florida, California, Utah, Vermont, and New York, but the number of modern roundabouts nationwide is still relatively small (about 300 according to survey). Consequently, the study has had significant merit. It has provided information about the performance of roundabouts and the differences between their performance and that of other intersection types.

This report contains eight chapters and an appendix. Chapter 2 describes the survey effort while Chapter 3 summarizes the survey responses. Chapter 4 shows the results of an operational analysis of the survey responses. Chapter 5 does the same for a broad-brush safety analysis. Chapter 6 presents accident rate models that have been developed based on the survey data. Chapter 7 talks about pedestrian issues. Chapter 8 presents the result of the RODEL analysis. Chapter 8 talks about the informational brochure. Finally, Chapter 9 discusses conclusions, recommendations, and additional work that would be a natural outgrowth of this effort.

2.0 The Survey

The survey was a critical part of the project. It provided the data on which the rest of the project was dependent. It was eight pages long and asked for the following information:

- Setting for the roundabout (e.g., urban, suburban, rural)
- Goal/purpose of the roundabout's installation (i.e. safety, operational, traffic calming)
- Unanticipated problems and ways those problems were resolved
- Configuration: number of legs (including approach angles) and number of lanes (i.e., single, multi-, etc.)
- Design parameters (e.g., inscribed diameter, approach width, entry angle)
- Before and after "as-built" plans
- Prior control (e.g., two-way stop, all-way stop, traffic circle, signal)
- Traffic volumes (e.g., turning counts, peak hour factor, percent trucks, percent buses, pedestrians)
- Operational performance (e.g., delays, queue lengths, levels of service)
- Safety performance (e.g., accident histories, including number and percentage of total, severe [fatal and injury], rear-end, overtaking, right angle, left turning, right turning, head on, wet road, pedestrian, and bicycle accidents)

The survey also said that supplementary materials such as reports, pictures, design guides, and newspaper articles could be provided. Many respondents provided these items.

To maximize the amount of information collected, the research team worked with NYSDOT to send questionnaires to the best-targeted audience possible. This included the commissioner, chief engineer, and safety director of all 50 state departments of transportation as well as many local municipalities and consultants. The research team asked for the most current information available and names of additional people to contact (e.g., in specific cities) so the most up-to-date information could be collected about roundabouts not on the state networks. FHWA also provided assistance through its regional resource centers. In conjunction with this task report, the contact database has been delivered to NYSDOT on a CD.

The research team also made maximum use of previously collected information. For example, traffic engineers nationwide have for some time been supplying roundabout-related information to the website sponsored by Kittelson & Associates [1]. They are part of the research team for the project. Use was also made of the data collected by Persaud *et al.* [2] for the Insurance Institute for Highway Safety (IIHS) study and the information assembled by Kittelson & Associates in developing the FHWA roundabout guide [3]. A fourth resource was the database assembled by Flannery [4] for her doctoral work. (Dr. Flannery is a colleague of the research team and a member of the NCHRP 3-65 research team, in which all of the members of this NYSDOT research team are also members.)

The survey form is presented in Appendix A. It asks for the kinds of data shown in Table 2-1. Some of the data is general in nature: the site name, contact person, etc. Other data describe the location: state, city, etc. A third group of items include facility descriptors: number of lanes, number of approaches, inscribed diameter, etc. The fourth and last group includes detailed pre and post construction information about the geometry, the operational performance, and the safety performance.

Table 2-1. Information Requested by the Survey

Site	State	Lanes	Pre-Geometry
Contact Person	City	Approaches	Post-Geometry
Creation Date	County	Diameter	Pre-Operational Data
Status	Zip	Design Philosophy	Post-Operational Data
Setting	Latitude	Design Guide	Pre-Accident Data
Goals	Longitude	Software	Post-Accident Data

The geometric data is intended to support the British capacity analysis
The operational data includes ADTs, peak hour volumes, and delays
The safety data includes accidents by type and severity for one or more years
Supplementary materials include pictures, reports, and drawings

The survey was sent to 247 recipients. Of these, 155 were sent by NYSDOT and 92 by the research team. The first surveys were sent out in April and May 2002. Most of the responses were received in June, July, and August 2002 and by December 2002, most of the data had been received for the operational and safety analyses.

The survey produced 98 responses. Fifty contained enough information to become part of the operational analysis while 35 could be used in the safety analysis. Sixty-one contained geometric data, 58 included drawings, 56 had photos, and 67 had accompanying reports.

3.0 Survey Results

From the survey, the research team learned about:

- Geometric design (e.g., inscribed diameter, single or multi-lane, number of legs, construction date)
- Traffic volumes (e.g., turning counts, percentages of lefts, throughs, rights, peak hour factor, use by trucks, buses, pedestrians, cyclists)
- Prior facility type (e.g., stop sign-controlled intersection, traffic circle, signalized intersection)
- Operational performance (e.g., delays, queues, levels of service)
- Safety performance (e.g., accident rates by severity and type of accidents, before-versus after trends, effects of facility configuration)

In total, the survey provided information about 288 roundabouts that had been constructed nationwide as of the last response obtained. The research team also learned that several more that were under construction, planned, or proposed.

A summary of the findings is presented in Table 3-1. It indicates how many states responded, how many sent information about roundabouts, etc.

Table 3-1. State Design Responses

	# of States
Overall Summary	
Total Responses	31
Roundabout Materials	24
No Roundabouts	7
Software Use	
RODEL [5]	4
SIDRA [6]	5
Both	3
Design Aides	
FHWA [3]	9
Other Design Guides*	7
Design Theory	
Gap Acceptance	11
Empirical Regression	6
Both	1

* Other guides included: Austroads [7] guide and state-specific guides prepared by Maryland [8], Florida [9], and Oregon [10].

Table 3-2 shows the 12 states that have the most roundabouts according to the survey responses. Colorado has the most. Other states not shown are Missouri, New York, Vermont and Wisconsin with 3 sites; Arizona and Connecticut with 2; and Alaska, Arkansas, Maine, Minnesota, Mississippi, Nebraska, New Hampshire, New Jersey, South Carolina and Texas with one. The reader should note that these statistics are constantly changing. In the case of Washington, 31 sites now exist as of the time this final report is being written, but only 25 of these sites are in the database. There are also issues about whether a few of these facilities are really roundabouts. New Jersey has nine entries in the database, but it appears that only one of these is technically a roundabout. Table 3-2 also gives a summary of the information that was received. Maryland was

Table 3-2. Sites by State

State	Sites	Useful Responses	
		Operational	Safety
CO	61	0	9
MD	37	19	13
WA	31	5	0
FL	29	2	4
KS	19	5	1
UT	19	0	0
NV	18	3	0
OR	18	1	1
CA	14	6	0
MI	6	1	0
IN	5	0	0
NC	4	0	0

the largest contributor for both the operational and safety data. Useful operational data was also received from Maine, Mississippi, New York, Vermont, and Wisconsin. Useful safety data was also received from Maine, South Carolina and Vermont.

Sixteen of the 288 sites are in rural settings, 159 are suburban and 106 are urban. (The remaining 8 are in unknown settings.)

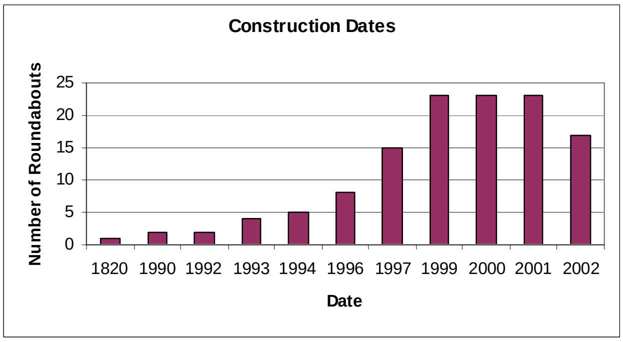


Figure 3-1. Construction Date Trends

As Figure 3-1 shows, most of the roundabouts have been built since 1990. In fact, the roundabouts built since 1995 account for more than 90% of the total roundabouts in the U.S.

Table 3-3 shows the previous control type where it is known (150 sites). Of those, 40 are new (the intersection didn't exist before the roundabout was built), 47 were previously two-way stop controlled intersections, 31 were one-way stop controlled (these are either T intersections or ramp terminals at freeway interchanges),

Table 3-3. Breakdown of Prior Control by Legs and Roundabout Type

Legs	Type	OWSC	TWSC	3WSC	AWSC	Signal	Circle	None
3	Single	18	3		2			10
4	Single	7	29		10	6		21
5	Single		2	1	2			
3	Multi	2						
4	Multi	1	10		1	4	2	9
5	Multi	1	3			3		
6	Multi	2				1		
Total		31	47	1	15	14	2	40

15 were all-way stop controlled intersections, and 14 were signalized intersections. Two were previously traffic circles and one was a three-way stop controlled intersection.

Figure 3-2 illustrates the distribution of prior control types. The figure shows that a large number of the roundabouts have been installed at locations that were previously one-way or two-way stop controlled intersections.

Table 3-4 shows the distribution of roundabouts based on the number of legs and type. The most prevalent kind of

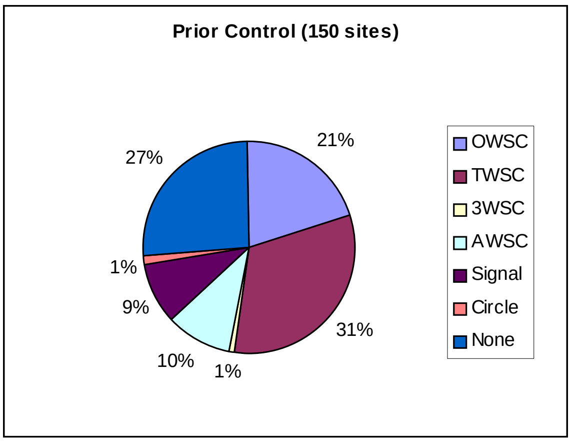


Figure 3-2. Distribution of Prior Control

roundabout is a single lane facility with four legs. The other common types of roundabouts are: single lane - three legs; and multiple lanes - four legs.

Table 3-4. Distribution by Legs and Type

Legs	Type	Sites
2	Single	2
3	Single	60
4	Single	141
5	Single	10
2	Multi	1
3	Multi	7
4	Multi	49
5	Multi	7
6	Multi	3

Table 3-5 shows, based on the data in the database, that the total intersecting traffic (AADT) values for roundabouts tend to increase with both the number of legs and the number of lanes.

Table 3-5. AADT Trends

		AADT		
Legs	Type	Avg	Max	Sample
3	Single	11577	28060	13
4	Single	10966	23000	34
5	Single	15533	20000	3
3	Multi	16000	16000	1
4	Multi	20752	35000	16
5	Multi	25890	38000	5

Table 3-6 shows the breakdown of facility diameter by number of lanes (single, multi) and number of legs. The inscribed diameter is a major attribute of every roundabout and an influential variable in determining many other geometric attributes. It is clear that the diameter tends to increase as the number of legs increases and as the type switches from single to multi-lane. The most common size category for a single lane roundabout is 25-35 meters. (It is important to note that roundabouts smaller than 30m diameter can have difficulty accommodating larger vehicles and tend to function more as a residential traffic calming device.) In the case of multilane roundabouts the most common size category is 45-55 meters. The largest roundabout in the database is 140 meters in diameter (Long Beach, CA).

Table 3-6. Distributions of Diameters by Legs and Roundabout Type

		Diameter (meters)										
Legs	Type	10	20	30	40	50	60	70	80	90	100	Total
3	Single		12	20	6	2						40
4	Single	2	23	47	19	14	3				1	109
5	Single		1	2	1	5						9
Single totals		2	36	69	26	21	3	0	0	0	1	158
3	Multi		1		1	2	2	1				7
4	Multi			3	5	13	8	4	8	1		42
5	Multi				1	4	1	1				7
6	Multi				1		1	1				3
Multi totals		0	1	3	8	19	12	7	8	1	0	59
Total		2	37	72	34	40	15	7	8	1	1	217

Note: Plus a multi-lane, 4-leg roundabout at 140 meters

The overall trends in the response can be characterized as follows:

- Almost 300 roundabouts are known to exist.
- The states with the most roundabouts in the database are Colorado, Washington, Maryland and Florida.
- Two-thirds of the roundabouts are single lane facilities and the rest are multilane.
- More than 90% of the roundabouts have been built since 1995.

- About a quarter of the roundabouts are new and the rest have replaced a wide variety of previous intersection controls including two-way stop control, all-way stop control, and signalization.
- The AADT tends to increase with the number of legs.
- The most common diameter is 25-35 meters for single lane facilities and 45-55 meters for multilane facilities.
- The diameter tends to increase with both the number of lanes and the number of legs.

4.0 Operational Analysis

Operational data for 50 sites could be incorporated from the survey responses into a database. The data items included in the database are summarized in Table 4-1.

Table 4-1. Operational Database Characteristics

Site	Before Volumes (AM & PM)
State	After Volumes (AM & PM)
Legs	Before Delays (AM & PM)
Lanes	After Delays (AM & PM)
Diameter	
The database also includes calculations of by approach, of approach volumes, conflicting volumes, capacities, average queues, 95% queues, and estimated delays.	

The first five fields in each record are for the site: its name, state, legs, and lanes, and diameter. (Unfortunately, a lot of other geometric information was not provided. Drawings were sent only for a few of these sites.)

The next 64 fields are for volume data: vehicles per hour for each turning movement on each approach, and total, for the AM and PM peak hour, before and after construction. (Sometimes only the total volumes were supplied.) In cases where the volumes were provided for the before condition only, it was assumed that the after condition was the same as the before.

The last 64 fields are for delay data: the average delay per vehicle, in the AM and PM peak hours, before and after construction, for each turning movement on each approach and for each approach overall. (Most of the time only the average delay for the approaches was specified. But in some cases, movement specific delays were included.)

Table 4-2. Operational Database Site Configuration Distribution

Legs	Type	Sites
3	Single	9
4	Single	23
5	Single	1
3	Multi	0
4	Multi	12
5	Multi	3
6	Multi	2

Table 4-2 shows that 33 of these sites are single lane facilities and 17 are multi-lane. The most common configuration is a single lane facility with four legs. The next most common is a multi-lane facility with four legs.

The information in the operational database was used to perform three main operational analyses. The first was a study of the peak hour volumes and how they broke down in terms of turning movements. The second had to do with capacity, examining the relationship between circulating volume, approach volume, and estimated capacity for 10 sites. (Since the survey responses had limited geometric information, geometric parameter defaults from the FHWA method [3] were used in the capacity calculations.) The third analysis was a study of the delay trends. This analysis examined relationships of the before and after delays, as well as a few instances of estimated delays.

4.1 Operational Trends

Of the various things that can be learned by examining the operational attributes of the roundabouts, one relates to the entering volumes and the turning movements. This analysis specifically examines the four-leg, single lane roundabouts.

The first observation of note is that the roundabouts have a high percentage of left turns, more than one would expect for a “typical” intersection. (This might be consistent with the observation that traffic engineers seem inclined to use roundabouts where the left turns are predominant.)

Figure 4-1 presents evidence of this for the four-leg, single-lane sites in the operational database. It plots (on the X axis) the total intersecting volume for a given site in a given time period (e.g., the AM peak) against (on the Y axis) the percentage of left turns for the same site in the same time period. The labels are interpreted as follows: BAM is the AM peak hour in the before condition, BPM is the PM peak hour in the before condition, AAM is the AM peak hour in the after condition, and APM is the PM peak hour in the after condition. So the diamonds plot all the left turn percentage vs. total volume for the AM peak hour volume in the before condition.

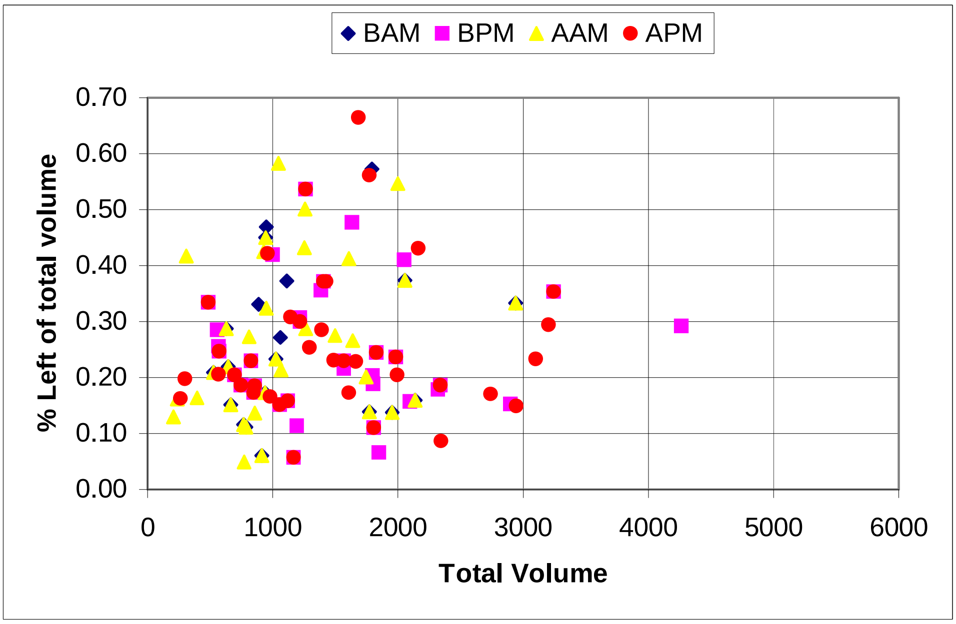


Figure 4-1. Distributions of total left turning movements plotted against of the total entering volumes

In looking at Figure 4-1, several things are evident. First, a lot of variation exists in the total volumes and the percentage of left turns among the sites and time periods. Second, the percentage of left turns ranges up to 65%, which is high. At such a percentage, two out of every three vehicles entering the intersection makes a left turn. There is not just one of these situations in the database, but several. In a number of them, the percentage of left turns is higher than 50% (one in every two). There are more where the percentage is above 40% (two out of five), and significantly more where it is about 30% (one in every three). This trend exists in both the before and after conditions and the AM and PM peaks. (The latter result is due in part to the fact that for some sites it was necessary to assume that the after volumes were the same as the before volumes, e.g., for purposes of doing capacity assessments.)

The high percentage of left turns should be compared to the left turn percentages of several signalized intersections. Figure 4-2 adds two more scatter plots to those in Figure 4-1. AMSig and PMSig are plots of total intersecting volume and percentage of left turns for three typical signalized intersections. (These intersections were studied as part of a statewide signal timing enhancement project funded by the New York State Energy Office [11] between 1988 and 1991 and their volumes are typical of the volumes seen by the authors in that project.) None of these signalized intersections have left turn percentages that are as high as those observed for the roundabouts. There are a few instances where the percentage of left turns is as high as 30%, but for the most part, the values are in the 10-20% range. So it seems there is a significant difference between the roundabouts and normal signalized intersections.

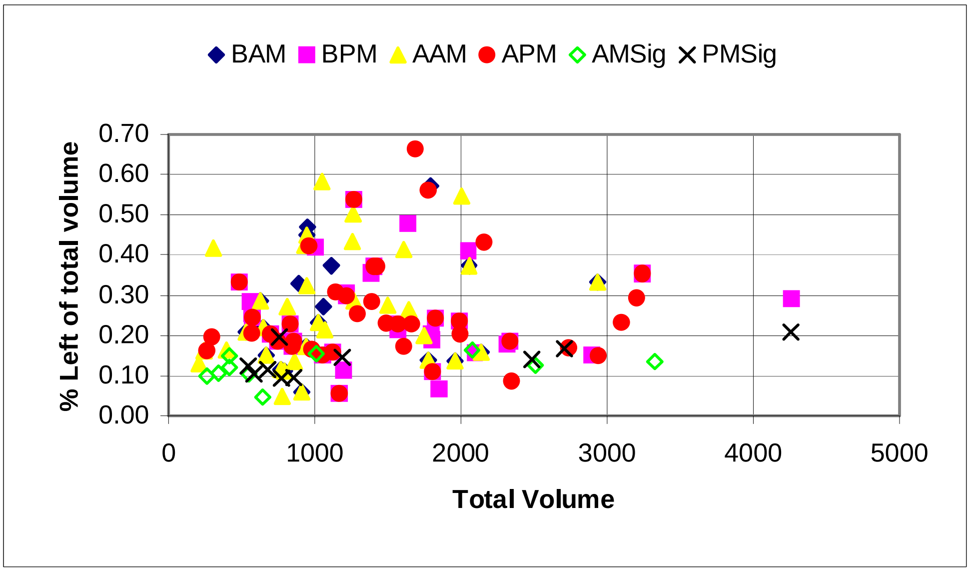


Figure 4-2. Comparison with Signalized Intersections

While the samples of both roundabouts and signalized intersections are both quite small, this trend seems consistent with the fact that roundabouts are being touted as a useful control treatment when the left turns are heavy. The figure also shows that as the total entering volumes increase the percentage of left turns tends to be higher.

Figure 4-3 makes the point about the high percentage of left turns in a slightly different way. (The legend is the same as for Figure 4-1.) It shows the fraction of sites that have a given percentage of left turns in the AM and PM peak hours before and after introduction of the roundabout. For example, for the AM peak hour, 27% of the sites (the y-axis) have 10-19% left turns (the x-axis). The most common range for the percentage of left turns is 20-29% (the highest set of bar heights). As a point of comparison, for the three signalized intersections whose data appeared in Figure 4, about 20% had left turn percentages in the range of 0-9%, about 75% were in the range of 10-19%, and 5% were in the range of 20-29%.

Not only is the percentage of left turns high, but a single left turn often seems to account for a high fraction of the left turning volume. Figure 4-4 displays the distribution of the ratio of the heaviest left to the total lefts. (The legend is again the same as Figure 4-1.) For example, in the AM peak in the before condition, about 27% of the cases have a left turn that is 40-49% (almost half) of the total left turn volume. In fact, for nearly half of the observations, the heavy left is 60% or more of the total left turn volume. (This can be seen by adding together the percentage occurrences for categories 60-69%, 70-79%, 80-89%, and 90-99%.)

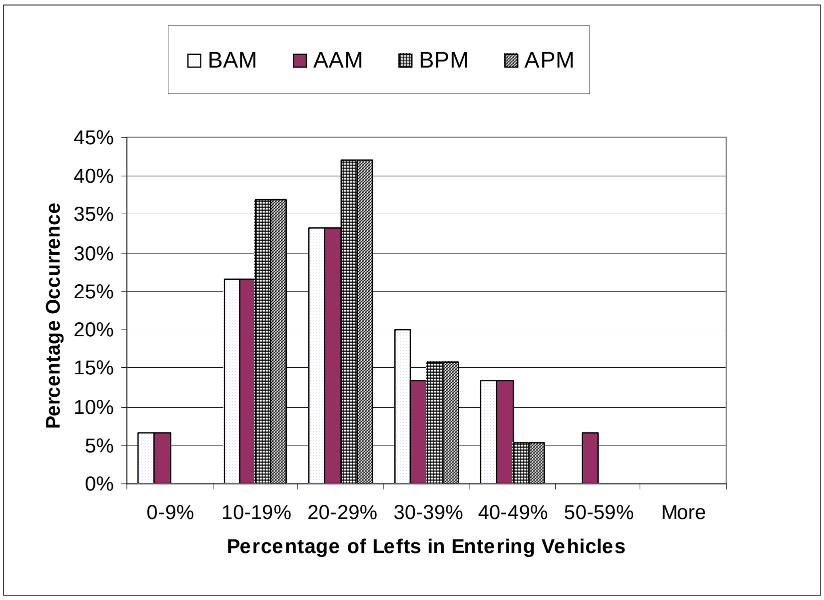


Figure 4-3. Percentage occurrence of left turn percentages

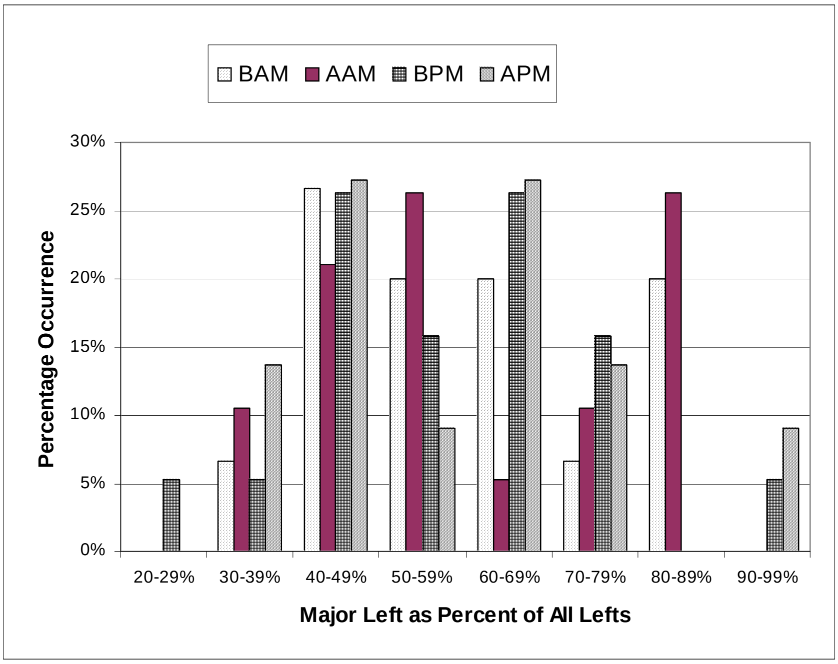


Figure 4-4. Relationship of the heaviest left turning movement to the total left turning volume

4.2 Capacity Issues

The operational database is also structured to allow an examination of capacity issues. Capacity for a roundabout is not a single value, but a set of values, one for each approach in each time period. It is generally accepted that the capacity of a given approach in a given time period depends on the conflicting volume or circulating traffic – the vehicle flow rate on roundabout in front of the approach – and the approach geometry, especially, the entrance width. The less conflicting traffic there is, the greater the capacity is for a given geometry, and the wider the approach is, the more capacity the approach has for a given conflicting volume.

The capacity relationship that best describes the performance of roundabouts in the US is more of an unknown than a known at the present time. No definitive study of roundabout capacity has been done in the US for the past 50 years. The NCHRP 3-65 project [12] now underway will be the first.

What is known is that there are capacity models that have been developed for roundabouts in other countries, especially Great Britain, Germany, Australia, and France. These models predict the capacity of a given approach for a given condition using geometric and/or behavioral relationships.

The British empirical model [13] is the one used in this report. It estimates the capacity of a given approach based on a set of equations that depend on the geometric characteristics of the approach and the conflicting volume. The British model is the one on which RODEL [5] is based. (RODEL is the performance model being used by NYSDOT for designing roundabouts.) The equations in the British model can be entered into a series of cells in one line of a spreadsheet. (RODEL provides slightly lower capacity estimates based on exactly the same formulas, see the Task 4 report.) The model requires the geometric parameters shown in Table 10 plus the inscribed diameter. The inscribed diameter is the only one of these parameters available for all of the sites and it has been used in the capacity assessment. The other parameters have been set to the values shown in Table 4-3, which lists the defaults in the FHWA design guide, Appendix A [3].

Table 4-3. Default parameters for capacity calculation

Parameter	Single Lane	Double Lane
Entry radius, r (m)	20	20
Entry angle, phi (deg)	30	30
Approach half width, v (m)	4	8
Entry width, e (m)	4	8
Effective flare length, l' (m)	40	40

In the analysis presented here, the capacity of each approach in each time period is computed and then contrast with the volume on that approach (and the resulting volume-to-capacity, v/c, ratio). For the single lane sites, this has been done for 256 instances (i.e., an approach for a specific site in a given time period). For the multi-lane sites, it has been done for 150 instances.

Figure 4-5 shows the results of the capacity analysis for the 72 instances where a comparison of the flows against capacity could be made for single lane sites with three approaches (a given approach in a specific time period). The diamonds are the combinations of approach volume and conflicting volume that are in the operational database and the X's are the capacity estimates that were computed based on the conflicting volumes. This means two points are plotted for each

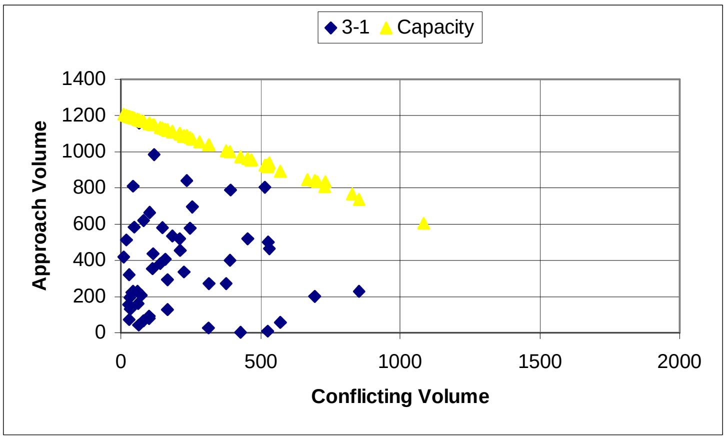


Figure 4-5. Three leg single-lane roundabout approach volumes vs. conflicting volumes, compared with approach capacities

approach / time period. One is the combination of approach volume and conflicting volume that was observed / reported and other is the capacity estimate for the conflicting volume and the approach geometry. The downward sloping trend in capacity is due to the fact that the British empirical model predicts a negative, linear relationship between conflicting volume and capacity. As the conflicting volume increases, the approach capacity decreases. It is also possible to see that the observed approach volumes are all less than the estimated capacities, except possibly, for one instance.

Figure 4-6 shows the 184 instances where the operational database has an approach volume and a conflicting volume for a four leg, single lane roundabout. Again, the squares plot the approach volume / conflicting volume combinations and the X's plot the capacity estimate from the British model based on the conflicting volume and the inscribed diameter. Comparing Figure 4-6 with Figure 4-5, the four leg single lane roundabouts seem to have slightly lower approach volumes and larger conflicting volumes than the 3-leg roundabouts.

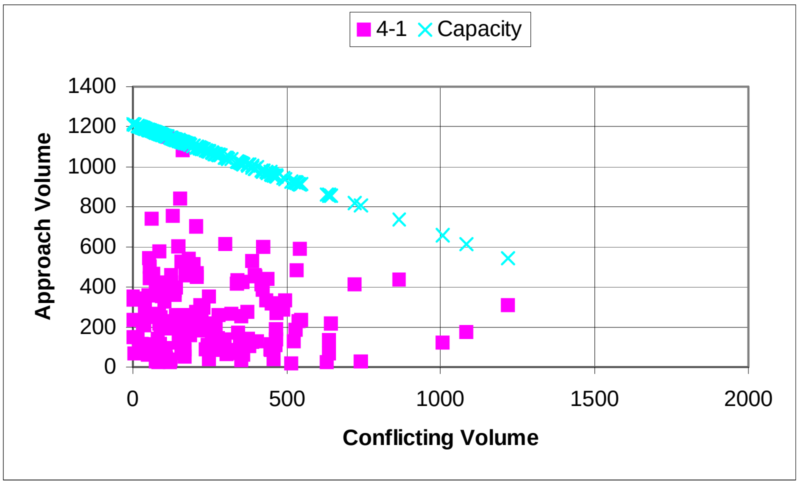


Figure 4-6. Four leg single-lane roundabout approach volumes vs. conflicting volumes, compared with approach capacities

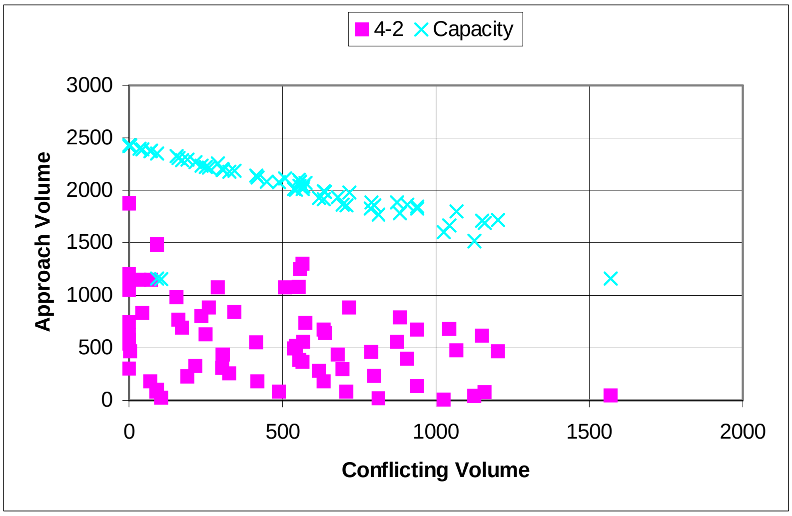


Figure 4-7. Four leg multi-lane roundabout approach volumes vs. conflicting volumes, compared with approach capacities

The 88 instances of conflicting volume / approach volume for four leg multi-lane sites are shown in Figure 4-7. Notice that these approach volumes are larger than for the single lane cases. Notice also that the capacities are larger. This latter shift is due to the change in the approach width and other geometric parameters used in the capacity calculation. The difference can be seen if the capacity points in Figure 9 are compared with those in Figure 4-6. In fact, if the four-leg, single-lane capacity curve were to be plotted on Figure 4-7, a large number the approach values would exceed the capacity curve. Therefore, it appears that the design of these roundabouts as multi-lane facilities was appropriate for the volumes being handled.

Figures 4-5, 4-6, and 4-7 suggest two things. The first is that the capacity models (e.g., in this instance, specifically the British empirical model) may be providing capacity predictions that are meaningful for US conditions. That is, the capacity estimates are not ***below*** the observed approach volumes nor are they significantly above them. The second is that the design engineers seem to be appropriately matching the design features (e.g., single or multi-lane) to the volumes being handled.

Figure 4-8 shows a plot of the approach volumes against the conflicting volumes for all of the multi-lane roundabout configurations whether they are four-leg, five-leg or six-leg. The approach volumes do not seem to increase with the additional legs. This might be expected since each leg ought to add volume to the overall total. In general, though, the conflicting volumes are higher than they were for the single-lane roundabouts.

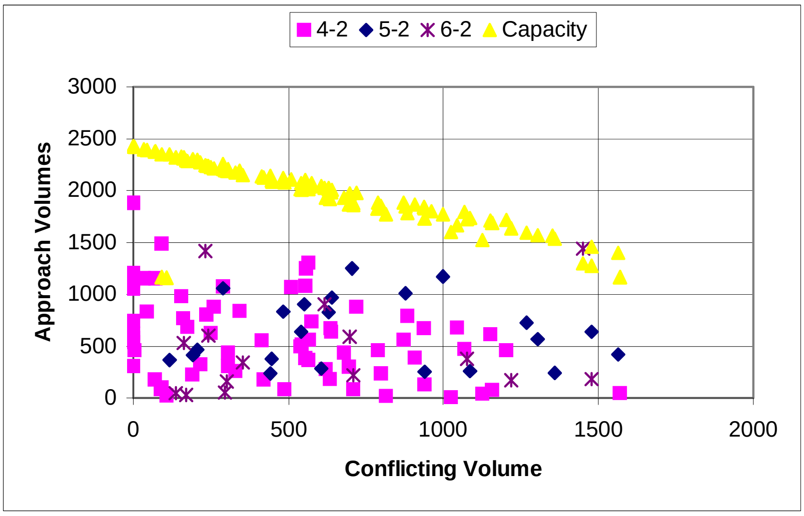


Figure 4-8. Multi-lane roundabout approach volumes vs. conflicting volumes, compared with approach capacities

4.3 Delay Characteristics

One of the key features of roundabouts is its approach to delay reduction. A roundabout aims to reduce delays and stops by replacing the interrupted spatial and temporal discharge of vehicles on conflicting paths with slow-speed merges and diverges for vehicles moving in the same direction. Consequently, it is useful to see what the survey responses show about changes in the average delay per vehicle at the roundabout sites.

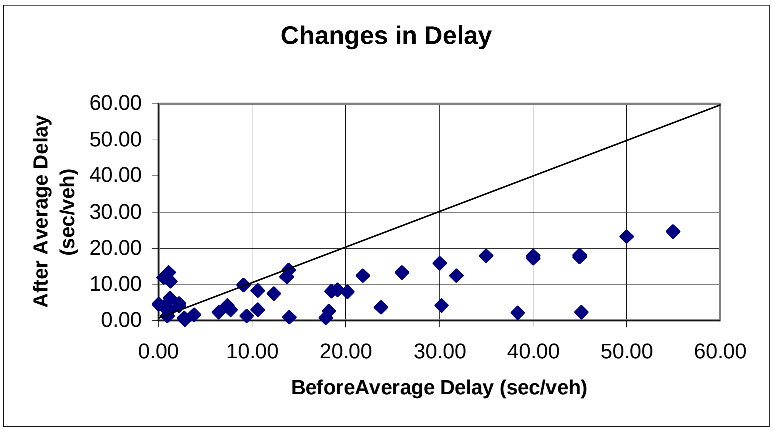


Figure 4-9. Observed delays: before & after condition comparison

Figure 4-9 shows the before / after delay comparisons for the 10 sites that have field data for both conditions. These data tend to show that the introduction of the roundabout reduces delay. Notice that almost all of the delays in the after condition are less than half of what they were in the before condition. There are only a few instances in which delays increase. The increases could be because the prior facility was a two-way stop controlled intersection: substantial delays for the minor movements and insignificant delays for the major flows were changed to small delays for all vehicles.

Figure 4-10 includes five additional sites for which estimated delays were supplied for the after condition. The traffic engineers (or the models they use) seem to overestimate the delays that roundabouts produce. Notice that the estimated delays (the purple squares) are much larger than the observed delays for sites / conditions with similar delays in the before condition.

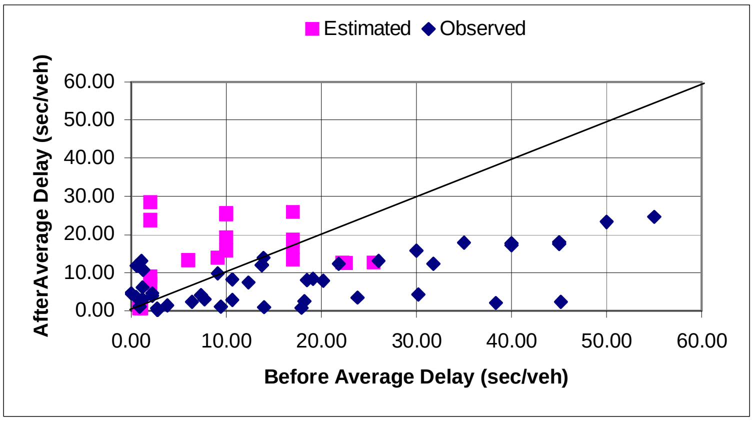


Figure 4-10. Estimated and Observed delays: before & after condition comparison

Overall, this analysis seems to indicate that if a roundabout is well designed, it can significantly reduce delays.

5.0 Safety Trends

The safety database contains accident data for 35 roundabouts. In this section, the safety trends are examined including all of those sites. (Two of these 33 sites previously had all-way stop control and could not be used in the safety analysis presented in Section 6.) As Table 5-1 shows, sites 1-3 are single lane sites, sites 4-24 are 4-leg, single lane sites, etc.

Table 5-1. Distribution of roundabouts in the safety database

ID #	#Sites	# Legs	Lanes
1-3	3	3	single lane
4-24	21	4	single lane
25-26	2	3	multilane
27-35	9	4	multilane

Figure 5-1 shows the trends in total accidents per year for the before and after conditions where the sites have been sorted in descending order based on the number of total accidents per year in the before condition. The horizontal axis shows the site numbers (based on the numbering scheme in Table 5-1). The vertical axis shows the total accidents per year, both before and after construction of the roundabout. If one counts the number of sites with an accident reduction, there are 28, out of the 35 sites. Only seven have increases. Put another way, 80% of the sites show a decrease in the number of total accidents per year. The average decrease, which cannot be computed easily from the figure, is 47%. The conclusion that these data suggest is that these sites have had significant decreases in the number of accidents per year, just as other countries around the world have experienced.

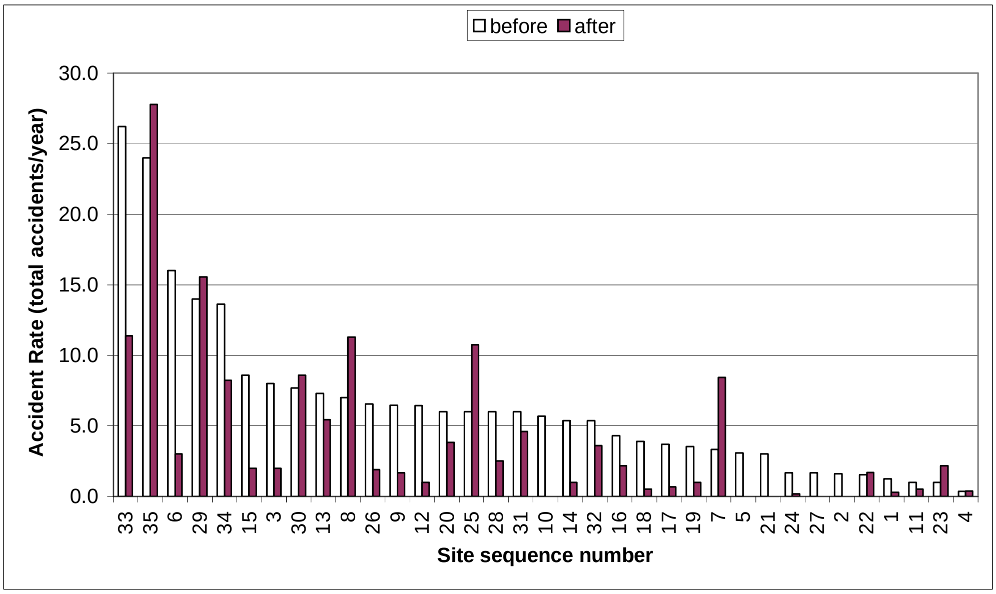


Figure 5-1. Before-After comparison of total accidents per year

Figure 5-2 displays exactly the same data as in Figure 5-1 but groups the sites first by type (see Table 5-1) and then by number of accidents per year in the before condition. For the 3-leg, single-lane sites (#1-#3), notice how the relatively large accident rate in the before condition (about 7 per year) for site #3 drops significantly to about 1 accident per year in the after condition. These sites have the lowest accident rates in either the before or after condition, and in all three cases, a substantial reduction in the accident rate occurs. For the 4-leg, single-lane sites (#4-#24), four have an accident rate increase - two are substantial – and the rest have major declines, to zero in several cases. These sites have accident rates that are lower than the multi-lane sites, and in all but a few instances, a substantial reduction in the accident rate takes place. The 3-leg, multi-lane sites (#25-#26) have lower accident rates in the before condition than the 4-leg, multi-lane sites, but that may be an artifact of the sites in the sample. At one of the 3-leg, multi-lane sites, the accident rate decreases substantially while at the other one it increases. The 4-leg, multi-lane sites (#27-#35) seem to have the highest accident rates. Moreover, the impact of the roundabout on the accident rate is substantial only for three of the sites.

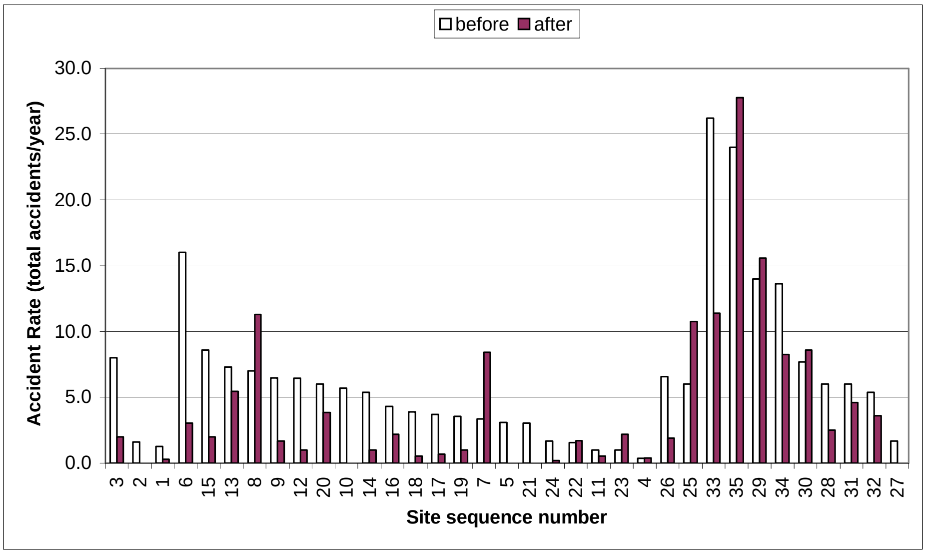


Figure 5-2. Before vs. After: Total Accidents per Year by Type and Number of Legs

Figure 5-3 shows the injury accident rates per year for the before and after conditions. The sites are sorted first by type (based on Table 5-1) and then in descending order by the injury accident rate for the before condition. All of the 3-leg, single lane sites have significant drops in their accident rates; two become zero. Of the 4-leg, single-lane sites, the first four have accident rates that fall to zero. Of the first 10 in this group (up through site #9), only one does not have a substantial drop in its accident rate. Only four of these sites have an increase in their accident rates. Of the 3-leg, multi-lane sites, one has an accident rate of zero in both the before and after condition, while the other has a rate of zero in the before condition and a non-zero rate (slightly above 0.5) in the after condition. For the 4-leg, multi-lane sites, eight of the nine have substantial reductions in their accident rates. Four have accident rates that fall to zero. Three more have substantial reductions in their accident rates and one has an increase.

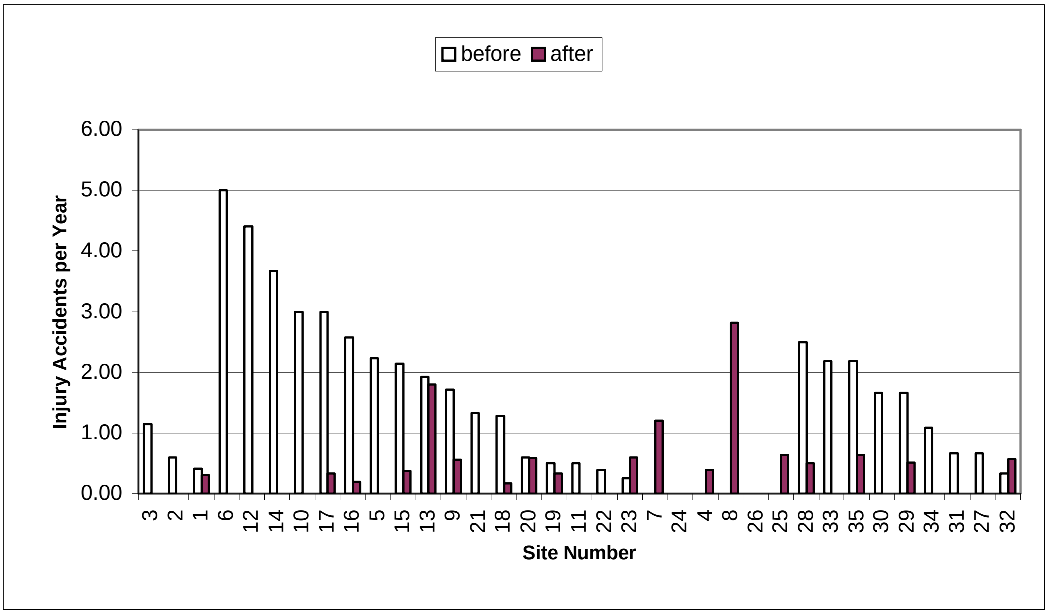


Figure 5-3. Before-After comparison of injury accidents per year

Figure 5-4 shows the trends in property-damage-only (PDO) accidents per year for the before and after conditions. The experience of countries elsewhere has been that PDO accident rates tend to remain constant or slightly increase when roundabouts are introduced, and this trend may be prove to be the case in the US, but the limited data from these 35 sites suggests that PDO accident rates may also be decreasing. The sites in Figure 16 are sorted first by facility type (per Table 11) and then in descending order by the property damage rate in the before condition. For

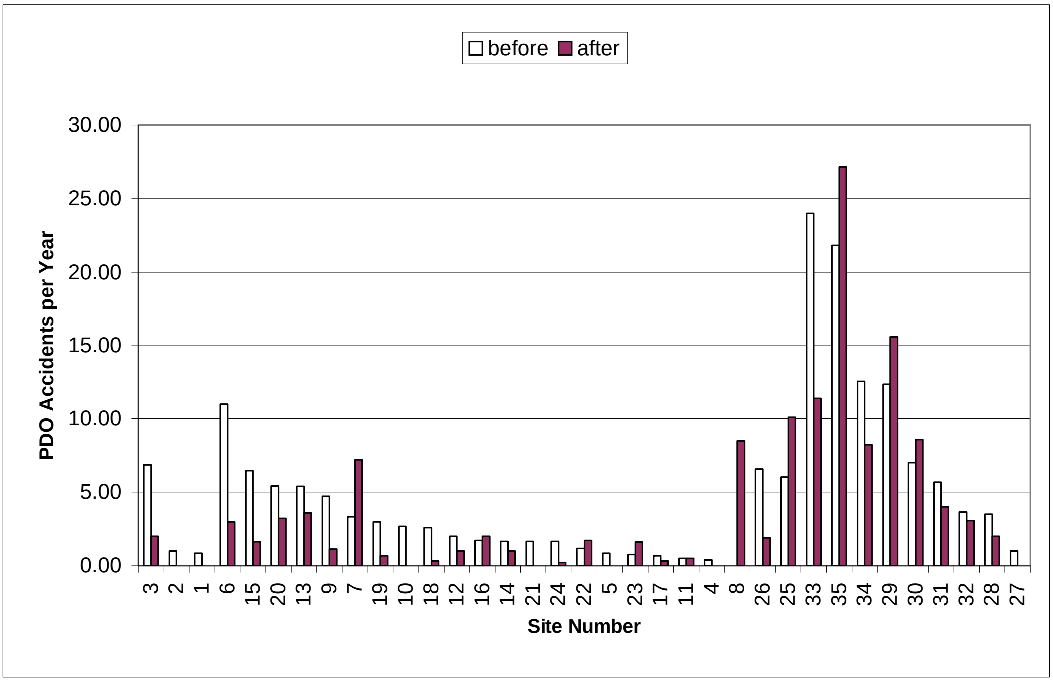


Figure 5-4. Before-After comparison of property damage only accidents per year

the 3-leg, single-lane sites, all three have significant drops in their PDO accident rates; two become zero. For the 4-leg, single-lane sites, the first five have accident rates that drop by 30-70%. Among the first 10 (up to site 12), only one does not have a drop in its PDO accident rate. Moreover, only five of these sites have increases in their PDO accident rates (including site number 24 which has a substantial increase). For the 3-leg, multi-lane sites, one has a decrease in its accident rate while the other has an increase. Of the nine 4-leg, multi-lane sites, six have decreases in their accident rates while three have increases.

A separate examination of the broad-brush geometric design of the 288 sites in the overall database suggests that such accident performance improvements appear reasonable.

Eisenman and List [14] have developed a metric that seems useful in assessing the vulnerability of sites to accidents. It focuses on the differences in speeds that might exist at a given site. The metric was developed to help pre-screen sites for field data collection in NCHRP 3-65.

The "accident-proneness" metric developed by Eisenman and List [14] is based on the following set of ideas. The first is that it is possible to deduce useful information about the likelihood that a roundabout might have a safety problem simply by looking at an aerial photograph. The notion was that the geometry influences the speeds at which vehicles can traverse the roundabout and differences in speed can be a major factor in causing accidents. Hence, if, in an aerial photograph it is obvious that some movements can be made without a speed reduction while others cannot, it is likely that the roundabout will have a propensity for accidents.

Looking at Figure 5-5, consider the situation where a vehicle enters at A and exits at B (the next leg). The vehicle may not have to slow down if the entry and exit angles are very shallow. Now consider the situation where a vehicle enters at A and exits at C (the next downstream leg). Again, a vehicle may not have to slow down if the inner circle has a small diameter. At a three-leg roundabout, the A-to-B move may be a right-turn or a through depending upon which entry is being considered. If Approach D is absent in the roundabout in Figure 5-5, then Approach A could have two high-speed possibilities (AB and AC). Approach B could have one (BC), and approach C could have one (CA).

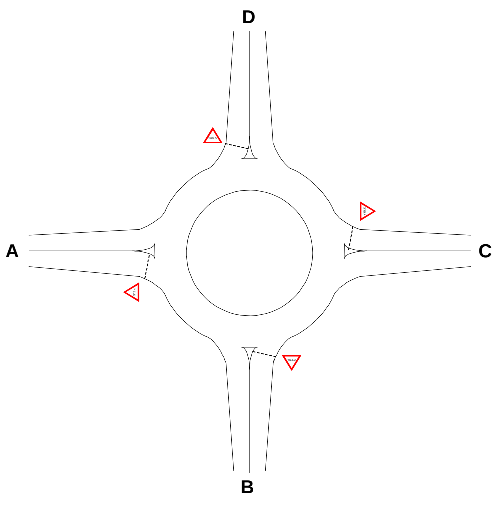


Figure 5-5. Illustrative Roundabout

Based on these ideas, a "number" can be developed that "measures" the accident-proneness of any site. It can be written as NN.MM where NN is the number of AC-type approach combinations that can be traversed at high speed and MM is the number of AB-type approach combinations for which high speed is possible. It is not really a decimal. The decimal point is used to separate the two thoughts. The order is important, though, because the metric asserts that the AC-type high-speed moves are likely to cause more accidents than the AB-type moves.

If one assumes the Eisenman-List metric is useful, then sites such as those in the database can be evaluated in terms of their accident proneness. The results of this assessment are shown in Table 5-2. One hundred and ninety-one of the sites in the database could be evaluated in terms of this safety metric. Of those, the research team senses that 108 may have geometries that are “safe”.

Table 5-2. Distribution of Safety Metric by Legs and Lanes

		Safety Metric																
Lanes	Type	0.0	0.1	0.2	0.3	0.4	1.0	1.1	1.2	1.3	1.4	2.0	2.1	2.2	2.3	2.4	3.0	4.0
3	Single	22	2	2	3			2	2			1						
4	Single	56	8	6		1	1	5	2	1		1	1	1				11
5	Single	2					2										1	
3	Multi	3	1		1							1						
4	Multi	21	2	3	1	6		3	4				1				1	
5	Multi	2	1				1		2			1						
6	Multi	2															1	
Total		108	14	11	5	7	4	10	10	1	0	4	2	1	0	0	3	11

That is, no high speeds are possible and the speed differentials should be small. All movements through the facility involve slowing down and checking for conflict with other movements. The most prevalent “mistake” in design seems to be allowance for one of the AB-type movements to occur at high speed (the 14 sites with an evaluation of 0.1). The next most prevalent conditions are two such AB-type movements (metric of 0.2) or all four of the AC-type movements being possible at high speed (the metric of 4.0). The research team’s observation is that these sites have central islands with a diameter that is too small. The vehicles making “through moves” can pass through the roundabout without slowing down. The next most prevalent conditions are 1.1 and 1.2, which means that one of the AC-type moves can be made at high speed as well as one or two of the AB-type moves. This seems to happen at three-legged roundabouts where the “through” moves (e.g., from A to C or C to A in Figure 5-5, assuming approach D is not present) do not require slowing down.

The conclusions from Table 5-2 are twofold. First, more than half of the roundabouts that were evaluated (108 of 191) are likely to be quite safe, at least from a vehicular standpoint, because passage without speed reduction is difficult. Another 37 suffer mostly from a lack of speed reductions for one or more AB-type moves (0.1, 0.2, 0.3 or 0.4). Another 25 allow high-speeds for one AC-type move and some combination of AB-type moves (1.0, 1.1, 1.2, 1.3, 1.4). Only 11 cases (about 5%) have high speeds possible for all through moves.

6.0 Safety Model Development

The objective of the safety analysis was to use accident and other data to conduct a statistically defendable before-after study to estimate/ demonstrate safety benefits of installing roundabouts in the US. While such a study was already done for the Insurance Institute for Highway Safety (IIHS) [2], the idea was to build on that study using a database that was richer, in terms of the number of intersections, the diversity of prior intersection types and geometries, and the number of years of data. In so doing the hope was that the research team could gain insights into conditions that favor roundabout installation from a safety perspective.

The intent was to see how the safety effect estimates vary with:

- traffic volumes
- type of control before – signal or stop
- crash history
- number of approaches
- single or multi lane designs
- urban/rural environment
- pedestrian activity

6.1 Methodology

The empirical Bayes before-after procedure [15] was employed to properly account for regression to the mean while normalizing for differences in traffic volume between the before and after periods. The method is now the accepted standard [16] for conducting before-after observational safety studies where appropriate expertise and data are available, such as were for this analysis.

6.1.1 Theoretical Basics

The change in safety at a converted intersection for a given crash type is given by:

$$B-A,$$

where B is the expected number of crashes that would have occurred in the after period without the conversion and A is the number of reported crashes in the after period.

Where sites have been selected for improvement because of a randomly high accident count or where there are traffic volume changes resulting from the improvement or otherwise, it is unacceptable to use the count of accidents in the before period as an estimate of the number of crashes expected in an equivalent after period without treatment. In such cases, and even where uncertainty exists as to whether these conditions exist, an empirical Bayes procedure is used. For this project, there were traffic volume changes resulting from roundabout installations (on average there was a 20% increase in entering volumes between the before and after periods) and the extent to which sites were selected because of a randomly high count is not known.

Therefore, it seemed natural to use the empirical Bayes methodology for estimating B in the above equation.

In the empirical Bayes procedure, a regression model is used to first estimate the annual number of crashes (P) that would be expected at sites with traffic volumes and other characteristics similar to the before period condition for the site being analyzed. The regression model estimate is then combined with the count of crashes (x) in the n years before conversion to obtain an estimate of the expected annual number of crashes (m) at the intersection before conversion. This estimate of m is:

$$m = w_1(x) + w_2(P),$$

where the weights w_1 and w_2 are estimated from the mean and variance of the regression estimate as $w_1 = P/(k + nP)$ and $w_2 = k/(k + nP)$, where $k = P^2/Var(P)$ is a constant for a given model and is estimated from the regression calibration process.

Factors then are applied to account for the length of the after period and differences in traffic volumes between the before and after periods. The result is an estimate of B. The procedure also produces an estimate of the variance of B. The significance of the difference (B-A) is established from this estimate of the variance of B and assuming, based on a Poisson distribution of counts, that:

$$Var(A) = A$$

In the estimation of changes in crashes, the estimate of B is summed over all intersections in the converted group and compared with the count of crashes during the after period in that group. The variance of B is also summed over all conversions. The variance of the after period counts, A, assuming that these are Poisson distributed, is equal to the sum of the counts.

The estimate of safety effect, the Index of Effectiveness (θ) is estimated as:

$$\theta = (A/B) / \{1 + [Var(B)/B^2]\}.$$

The percent change in crashes is in fact 100(1-θ); thus a value of $\theta = 0.7$ indicates a 30 percent reduction in crashes.

The variance of θ is given by:

$$\mathrm{Var}(\theta) = \theta^2\{[Var(A)/A^2] + [Var(B)/B^2]\} / [1 + Var(B)/B^2]^2.$$

6.1.2 Regression Models Used

The regression models used in the empirical Bayes procedure are the same as those used in the IIHS study and represent the best available in the judgment of the investigators. Some were specially calibrated for that study, while others were obtained from sources believed to be representative of the study sites. The paper based on the IIHS study [17] discusses the selection of regression models in more detail. There are three independent variables:

F_1 = major road AADT
F_2 = minor road AADT
F_{tot} = total entering AADT

The regression models used for intersections that were stop-controlled are as follows:

Rural 4-legged

Total accidents/year = $0.000379*(F_1)^{0.256}*(F_2)^{0.831}$
Injury accidents/year = $0.000118*(F_1)^{0.256}*(F_2)^{0.831}$

Urban 3-legged (major and minor entering AADTs known)

Total accidents/year = $e^{-8.051} * F_{tot}^{1.053} * (F_2 / F_{tot})^{0.559}$
Injury accidents/year = $e^{-11.364} F_{tot}^{1.225} * (F_2 / F_{tot})^{0.466}$

Urban 3-legged (major and minor entering AADTs not known, only total entering AADT)

Total accidents/year = $e^{-4.382} * F_{tot}^{0.516}$
Injury accidents/year = $e^{-8.64} * F_{tot}^{0.809}$

Urban 4-legged (major and minor entering AADTs known)

Total accidents/year =$e^{-9.886} * F_{tot}^{1.202} * (F_2 / F_{tot})^{0.376}$
Injury accidents/year =$e^{-8.613} * F_{tot}^{0.904} * (F_2 / F_{tot})^{0.197}$

Urban 4-legged (major and minor entering AADTs not known, only total entering AADT)

Total accidents/year = $e^{-6.834} * F_{tot}^{0.796}$
Injury accidents/year = $e^{-7.058} * F_{tot}^{0.695}$

The regression models used for intersections that were previously signal controlled are as follows:

Total accidents/year = $e^{-9.818} * F_{tot}^{1.212} * (F_2 / F_{tot})^{0.474}$
Injury accidents/year = $e^{-11.32} * F_{tot}^{1.232} * (F_2 / F_{tot})^{0.412}$

6.2 Results

The composite results for various site groupings are shown in Table 6-1, both in terms of percentage reductions in accidents and the index of effectiveness, θ. The index of effectiveness is shown because this is what is calculated directly in the EB methodology and since this is what is also referred to as an accident modification factor that is now a conventional term in many accident analysis methodologies (e.g., IHSDM) [18].

In interpreting the results, it is important to notice the standard errors for θ. For example for the multilane urban stop condition, the value of $\theta = 0.92$ while the standard error is 0.12. This means that the corresponding reduction of 100*(1-0.92) = 8% with a standard deviation of (100 x 0.12) = 12%. The 8% reduction is not statistically significant at the 5% level it is larger than 1.96 standard deviations.

For completeness, the results of the empirical Bayes calculations for individual sites are shown in Table 6-2. While safety effect estimates for individual conversions might be of interest to local traffic engineers, it should be recognized that the precision, in general, is so low that the results would be unreliable for the conversion of these specific sites.

Table 6-1: Composite Results

	Sites	Data months before and after	Accidents recorded in before and after periods			EB estimate of accidents expected after without roundabouts (and standard error)*			Point estimate of the % reduction in accidents* (and approximate 95% confidence interval)			Index of Effectiveness θ (and standard error)*		
			All	PDO	Injury	All	PDO*	Injury	All	PDO	Injury	All	PDO*	Injury
All Sites	33	1256 1215	611 321	446 289	165 32	605.35 (23.84)	490.47	114.88 (7.86)	47% 39-55	41%	72% 60-96	0.53 (0.04)	0.59	0.28 (0.06)
All SL Urban STOP	12	446 428	133 40	95 35	38 5	130.14 (10.55)	104.90	25.24 (3.23)	69% 59-79	67%	80% 62-98	0.31 (0.05)	0.33	0.20 (0.09)
3-Leg SL Urban STOP	3	110 88	25 5	19 4	6 1	23.14 (4.39)	18.94	4.20 (1.27)	79% 59-99	79%	78% 32-99	0.21 (0.10)	0.21	0.22 (0.23)
4-leg SL Urban STOP	9	336 340	108 35	76 31	32 4	107.00 (9.60)	85.96	21.04 (2.97)	68% 56-80	64%	81% 61-99	0.32 (0.06)	0.36	0.19 (0.10)
SL Rural STOP	9	448 448	218 72	122 54	96 18	203.86 (14.36)	147.84	56.02 (5.86)	65% 55-75	63%	68% 52-84	0.35 (0.05)	0.37	0.32 (0.08)
Multilane Urban STOP	7	224 198	127 118	112 114	15 4	127.93 (11.13)	113.63	14.30 (2.79)	8% 0-32	0%	73% 43-99	0.92 (0.12)	1.00	0.27 (0.15)
Urban Signalized	5	138 141	133 91	117 86	16 5	143.41 (11.26)	124.09	19.32 (3.02)	37% 21-53	31%	75% 51-99	0.63 (0.08)	0.69	0.25 (0.12)
Maryland Only	13	556 556	244 81	139 61	105 20	231.93 (15.03)	167.29	64.64 (6.13)	65% 55-75	64%	69% 55-83	0.35 (0.05)	0.36	0.31 (0.07)
OTHERS	20	772 703	398 240	317 228	60 12	373.42 (18.51)	323.17	50.25 (4.92)	36% 26-46	29%	76% 10-38	0.64 (0.05)	0.71	0.24 (0.07)

* PDO estimates are derived as the difference between "all and "injury" for which the EB procedure was applied using available SPFs and for which variances were obtained and reported in the Table.

Table 6-2: Results for Individual Sites

Group characteristics before conversion/ Jrisdiction	Months before and after	Total before	Injury before	Total after	Injury after	Expected Total After without roundabout	Variance of Expected Total After	Expected Injury After without roundabout	Variance of Expected Injury After
Single Lane, Urban, stop controlled									
Florida - West Boca Raton	31-29	4	1	7	0	8.06	9.16	2.58	1.58
Florida – Bradenton Beach	36-63	5	0	1	0	9.91	12.80	0.00	0.00
Florida – Gainesville	48-60	4	1	11	3	4.79	2.10	1.33	0.27
Maine – Gorham	40-41	20	2	13	2	18.45	14.73	2.43	0.98
South Carolina - Hilton Head	36-36	48	15	9	0	42.84	36.22	8.17	3.70
Vermont - Manchester	66-31	2	0	1	1	1.66	0.54	0.00	0.00
Vermont - Montpelier	29-40	3	1	1	1	4.33	3.40	1.13	0.36
Vermont - Brattleboro	43-34	11	8	0	0	10.57	8.18	3.98	1.43
Oregon - Eugene	60-24	8	3	0	0	1.96	0.37	0.41	0.03
Kansas – Manhattan	36-26	9	4	0	0	4.24	1.49	1.20	0.20
Maryland - Baltimore Co. 1	24-36	7	1	3	1	8.79	7.65	1.69	0.67
Maryland - Queen Anne's Co.	24-24	2	1	1	0	2.49	1.32	0.99	0.24
Entire group (12)	446-428	133	38	40	5	130.14	10.55	25.24	3.23
Single lane, Rural, stop controlled									
Maryland – Howard Co.	56-96	40	10	16	3	51.83	61.05	10.88	8.45
Maryland – Anne Arundel Co.	56-60	34	9	27	9	38.87	39.76	9.86	7.48
Maryland – Washington Co.	56-72	18	6	3	1	29.59	39.79	8.58	7.35
Maryland – Cecil Co.	56-60	20	12	11	1	21.49	19.24	8.35	4.36
Maryland – Carroll Co.	56-64	30	8	9	3	34.65	35.30	7.28	4.42
Maryland - Lisbon North	36-36	16	11	3	0	9.49	4.5	3.29	0.72
Maryland - Federalsburg	36-36	11	9	2	1	8.81	5.17	3.99	1.22
Maryland - Rosemont	36-12	17	9	0	0	3.5	0.58	1.03	0.08
Maryland - North Hartford	60-12	32	22	1	0	5.65	0.89	2.77	0.29
Entire Group (9)	448-448	218	96	72	18	203.86	14.36	56.02	5.86
Multilane, Urban, stop controlled									
Colorado – Avon	22-19	12	0	3	0	19.87	24.22	0.00	0.00
Colorado – Avon	22-19	11	0	17	1	12.21	9.75	0.00	0.00
Colorado – Vail	36-47	16	5	14	2	19.13	19.60	4.60	2.63
Colorado – Vail	36-47	42	5	61	0	50.92	58.05	5.70	4.04
Colorado – Vail	36-21	18	1	8	1	9.79	4.64	1.10	0.30
Colorado – Vail	36-21	23	2	15	0	11.75	5.38	1.29	0.33
Maryland – Baltimore Co. 2	36-24	5	2	0	0	4.25	2.35	1.60	0.51
Entire Group (7)	224-198	127	15	118	4	127.93	123.98	14.30	7.80
Urban Signalized									
Colorado – Avon	22-19	44	4	44	1	49.79	48.67	5.40	3.03
Colorado – Avon	22-19	25	2	13	0	24.22	18.36	2.95	1.14
Colorado – Avon	22-19	48	4	18	0	52.08	49.36	5.31	2.93
Maryland – Annapolis	24-24	12	5	5	1	12.54	8.30	4.33	1.77
Florida - Ft. Walton Beach	21-24	14	2	4	0	16.85	15.50	2.66	1.23
Entire Group (5)	138-141	133	91	16	5	143.41	126.79	19.32	9.13
All Conversions (33)	1256-1215	611	321	165	32	605.35	23.84	114.88	7.86

7.0 Pedestrian Issues

One question that often arises is whether roundabouts are safe for pedestrians. Since no vehicles actually have to stop except for conflicting vehicles or pedestrians, people want to know how they should cross the intersection and whether they will be protected. At the extreme, opponents say that roundabouts are unsafe. It is unclear whether that is true or not. The trends in Europe and Australia tend to suggest that they are safe.

Unfortunately, the survey responses will not support a thorough investigation of this issue. Not enough of the sites have significant pedestrian volumes. However, some anecdotal information has been received. A couple of the roundabouts are near schools and for those locations there are articles and reports that describe how people reacted to the installation of the roundabouts.

Figure 7-1. Lineville Road at Cardinal Lane

7.1 Howard, Wisconsin

Lineville Road and Cardinal Lane in the Village of Howard, Wisconsin is one location where a significant number of pedestrians use the roundabout. In fact, most of the pedestrians are students going to and from school. An aerial photograph of the site can be seen in Figure 7-1. In the foreground is a gas station and convenience store. The pump station can be seen in the foreground. Diagonally across the street is a collection of houses. To the left out of the picture is a football field and outdoor track facility, and to the right are more houses.

The land use near the site is a mixture of residential, commercial, and institutional activities. The principal institutional activity is a nearby school.

In fact, there is a second 3-legged roundabout adjacent to the school property. An aerial photograph of that facility is shown in Figure 7-2. The school can be seen in the upper left-hand corner of the picture. Just out of view to the left is a farm, which illustrates the variation in the land use nearby.

As the November 2001 roundabout study by the Brown Count Planning Commission indicates [19]:

“Prior to 1999, Bay View Middle School and Forest Glen Elementary School in the Village of Howard were bounded to the south by a county highway (Lineville Road) that carried vehicles at very high speeds. Since Lineville Road runs directly in front of the middle school and very close to the elementary school, a 15 mph school zone had been in place for several years. However, the regular posted speed limit was 45 mph, and many motorists traveled closer to this speed when children were present and above it when children were not. For this and other reasons, the Brown County Sheriff's Department designated the highway as a hazardous area to force the school district to bus kids across the road. This situation was expected to worsen when the new high school opened on the campus in 2000 and hundreds of inexperienced drivers were added to the hazardous highway's growing daily traffic load. To address this situation, the Brown County Planning Commission worked in 1998 and 1999 with the county highway department, Howard, and Town of Suamico to plan, design, and build Wisconsin's first modern roundabouts at the east and west ends of the school campus. The roundabouts were believed to be the best method of slowing drivers in the school zone and making the highway safe and accessible for pedestrians and bicyclists of all ages.”

Figure 7-2. Lineville Road and Rockwell Lane

The report then continues:

“[M]any people were convinced that the roundabouts (which were often confused with much larger traffic circles) would create traffic congestion, cause severe crashes, and lead to the injury or death of the children they were designed to protect. But this resistance began to disappear as they were being built and people had the chance to see that the roundabouts were much smaller, efficient, and attractive than they had thought. About three months after the project was completed, the planning commission found that congestion did not exist at the intersections even though the vast majority of vehicles approaching the roundabouts were traveling at or below 20 mph before reaching the crosswalks throughout the entire day. The planning commission also discovered that reportable crashes and injuries suddenly disappeared from the most heavily traveled of the two intersections after the roundabout was built, even though the number of entering vehicles increased significantly after the high school opened in August of 2000.”

In fact, it appears that the roundabout may have produced a significant decrease in accidents:

“Before the roundabouts were built in 1999, the intersection of Lineville Road and Cardinal Lane experienced several reportable crashes and injuries each year. In 1996 alone, this intersection experienced five reportable crashes and eleven injuries, and reportable crashes and injuries continued to occur until the spring of 1999. This situation changed, however, as the roundabouts were being built and motorists were no longer able to run the stop signs at high speeds and meet other vehicles at right angles. According to the Brown County Sheriff's Department's crash records, there have been no reportable crashes or injuries at the Lineville/Cardinal intersection since the roundabout project began in July of 1999….The elimination of crashes and injuries occurred in spite of the introduction of hundreds of inexperienced drivers to Lineville Road following the opening of the new Howard/Suamico High School in August of 2000.”

As the report then notes, students are now allowed to walk to school once the roundabouts were installed whereas before they were bused. Moreover, students are also allowed to use bicycles.

A comment by the principal of the nearby intermediate school summarizes the before-after perceptions:

“’At first, I was a little apprehensive - wondering how they would work to slow traffic,' said Lineville Intermediate Principal Chuck Templer. 'Overall, I'm very pleased with the way they've slowed traffic down. Traffic in general is traveling at a much slower rate in front of our school than it was prior to the roundabouts.'”

A comment by one of the crossing guards is particularly telling:

“’Personally, I love them, and I'll tell you why… You only have to stop one lane of traffic, then go to the middle and wait. The cars can't go much faster than 20 mph through the roundabout, so the crossing aspect here is great…. Overall, [the guard] thinks the roundabouts are easier for crossing guards to get children safely across streets. When asked about the controversy surrounding the issue of roundabouts in the area, [the guard] just shook her head. ‘I think it's just people being afraid of change,' [the guard] said. ‘There've been no close calls, no accidents. I haven't had to report any drivers. It pretty much goes smoothly. If they see a vest, they slow down pretty much.'”

The intermediate school principal agrees:

“’I think the crossing guard does a wonderful job of getting those kids through there,’ [the principal said], adding the motorists generally see the roundabouts coming and slow down.”

The local sheriff noted that:

“The current roundabouts located on Lineville Road are not presenting any safety hazards. They are actually solving two particular problems that we had prior to their installation. Those problems were,

> 1 . Traffic congestion from the school to Lineville Road. At times last year, an officer was tied up with traffic control because vehicles could not enter Lineville Road due to traffic volume. This problem has diminished.
> 2. Speeding on Lineville Road near Bayview Middle School. The roundabouts provide speed control by making it impossible to navigate a vehicle through the roundabout at a high rate of speed. There have been no complaints of school zone speeding on Lineville Road since the roundabout installation.

The above information was gained by talking to the officers currently working during school hours in the village and my observations. I appreciate the village taking an innovative position in installing the roundabouts.”

The person who completed the survey from Wisconsin DOT [20] provides yet another perspective that reinforces the comments above:

“During the year between the Brown County Planning Commission's recommendation for the roundabouts and the project's completion in the fall of 1999, many people were convinced that the roundabouts (which were often confused with much larger traffic circles) would create traffic congestion, cause severe crashes, and lead to the injury or death of the children they were designed to protect…. This resistance began to disappear as the roundabouts were being built and people had the chance to see that the roundabouts were much smaller, efficient, and attractive than they had thought. Even though the Lineville Road roundabouts were viewed by most to be successful from the start, small groups of Howard residents attempted to thwart future roundabout projects in the village. This resistance did not, however, prevent Howard from building a third roundabout in 2000 and the Brown County communities of De Pere and Ledgeview from warmly accepting three roundabouts on a county trunk highway in 2001.”

7.2 Lisbon, Maryland

Figure 7-3. One Approach to the Lisbon Roundabout

Lisbon, Maryland is the site of a semi-rural 4-leg, single lane roundabout. It is at the intersection of Maryland state highways 94 and 144 in Howard County. This is a facility for which pedestrian issues have been significant.

As is evident from Figure 7-3, this is not an urban or suburban environment. There is a field on both sides in the foreground and buildings in the distance up near the roundabout.

In his survey response, Niederhauser [21] makes it clear that the roundabout was installed to mitigate a high accident rate, especially right angle accidents. In the period 1988 and 1993, six years before the roundabout was constructed, there were 19 injury accidents (48 people injured; there were no fatalities) and 23 property damage accidents. This is more than 3 injury accidents per year (and 8 injuries per year).

It is clear that the roundabout had a very beneficial impact on the safety of the intersection. From 1994 to 2001, eight years after installation, there have been only three injury accidents (3 people injured) and 13 property damage accidents. That’s a rate of 0.375 injury accidents per year, one tenth of what it was before, and 0.375 injuries per year, less than 5% of what it was before.

Figure 7-4. Lisbon Roundabout

Apparently, since it was the subject of considerable controversy, the roundabout, shown in Figure 7-4, was first constructed using temporary materials. Niederhauser [21] indicates the local citizens were significantly opposed, saying it would be hugely unsafe, apparently for pedestrians (see the houses and establishments in Figure 21). At public meetings, they said the Maryland State Highway Department was “experimenting with the lives of their children.” Pedestrian activity must have been a major concern. It is a very telling quote because it demonstrates the very negative, visceral reaction that people have to roundabouts when they are unfamiliar with them. In point of fact, and in retrospect, Niederhauser says the roundabout should have been installed permanently right away. The public was so pleased with the change (presumably, including the safety of pedestrian activities) that they asked to have it be installed permanently after just *five weeks* of operation.

7.3 Towson, Maryland

The roundabout in Towson, Maryland is a relatively unusual facility. As shown in Figure 7-5, it is oblong in shape, like an oval, but with two half circles joined by straight sections in-between. It is in a downtown area, at the juncture of three major roadways, and it sees considerable vehicular and pedestrian traffic across the course of a typical day.

Figure 7-5. Towson Roundabout

The roundabout has been the center of considerable controversy since its introduction several years ago. Pedestrian concerns are a major part of that controversy, and the majority of the comments seem to be negative. An article in *The Baltimore Sun* [22] cites Bob Konkol, a retiree who lives close by as saying: "It's impossible to cross… motorists speed up on you when you're trying to cross. This is the story of the year – a travesty." While one person's perception doesn't make the case for a significant problem, the authors of this report are aware that this roundabout has been the source of considerable pedestrian concerns. It has been mentioned as the impetus behind the call from the ADA Board for signals at every roundabout in the US to provide safe accommodation for handicapped pedestrians.

The conclusion one draws from this example is that it is possible to have roundabouts with negative reputations in their accommodation of pedestrians. Whether the facility is truly unsafe or it is perceived to be so will only be learned with time as the accident performance of the facility becomes clear. There are, however, potential lessons to be learned about how to design such facilities, especially in complex urban situations, so that pedestrians perceive that they are being accommodated in a safe and equitable manner.

7.3 Claremont, California

Claremont, California decided to experiment with the introduction of three roundabouts along Indian Hill Boulevard as part of a village redevelopment project [23]. In 1999, the town spent four months studying their performance with a temporary facility at the intersection of Bonita Avenue and Indian Hill Boulevard.

The final conclusion was that the temporary facility should be removed. The public did not like the longer delays for vehicular traffic during the peak hours and they had serious concerns about pedestrian safety.

However, it is useful to look at the public comments as provided to us by the City Engineer in the survey response [23]. While the majority of the people interviewed were opposed to the roundabout, there were a significant number that were supportive, including its accommodation of pedestrians. One respondent said it was much safer for pedestrians than was the intersection that was there previously. A recurring theme, though, among most of these supporters, is a sense that the design could have been better from a pedestrian standpoint, especially curbing and signs for motorists alerting them to the presence of pedestrians. So it seems apparent that there are subtleties to design that are important, especially from a pedestrian perspective.

8.0 RODEL Analysis

RODEL analyses were conducted for eight sites based on the data from the survey responses. The datasets were also used as example problems for a roundabouts design workshop held for the benefit of designers from NYSDOT.

8.1 Understanding the Data Source

Table 8-1 summarizes the data items in the operational database created from the survey responses. A complete copy of the survey instrument is provided in Appendix A.

Table 8-1. Survey Data Request Items for Operations

Operational Data (all approaches and time periods)
After condition
Speed of Vehicles Entering, Traversing and Exiting
Flow Rates of all Roundabout Segments
Before condition
Control Type (e.g. Signal, Stop Sign)
Signal Phasing (if applicable), Including
Protected Lefts (Y/N by approach)
Permitted Lefts (Y/N by approach)
Before and After (by approach)
Traffic Volumes / Turning Counts
Vehicle Composition
Queue Lengths and Delays
Bicycle and Pedestrian Volumes

As of August 2002, when the RODEL workshop was held, only a few responses had enough information to create RODEL datasets. In general, the responses had to have a scaled drawing of the facility and turning counts, at least for the before conditions, to be considered.

In some cases, the responses also included turning counts for the after condition. In two instances delay data were provided for the after condition. In one more, an overall average delay was provided for the after condition. Although the low number of complete datasets limits their value to this research project, the low number is not unexpected given the limited priority most agencies give to formal before-and-after studies.

Before presenting the results of the RODEL analysis, it is useful to refer back to some of the findings from the operational analysis. In Figures 4-5 through 4-8 presented earlier, entering volumes are plotted against the conflicting volumes by approach for single lane and double lane roundabouts. These data points were compared and contrasted with the capacities predicted for "typical" single and double-lane approaches as documented in the FHWA publication "Roundabouts: An Informational Guide"[3].

All four figures clearly illustrate the downward sloping relationship that typically exists between the approach volumes and the conflicting volumes. The figures also show how the approaches are operating at or below the capacity predictions provided by the British empirical capacity model upon which RODEL is based. In the case of the single lane, four-leg facilities shown in Figure 4-6, there are slightly lower approach volumes and slightly larger conflicting volumes compared with the three leg roundabouts shown in Figure 4-5. In the case of the double lane roundabouts shown in Figures 4-7 and 4-8, the capacity curve is higher than for the single lane condition. Note that many of the double lane volumes would exceed the capacity curve of a single lane roundabout.

As all of the figures show, most of the roundabout approaches are operating below the capacities predicted by the FHWA method. This is to be expected given that most U.S. roundabouts are early in their design life. The detriment of this condition is that for purposes of doing capacity research, there is an apparent lack of situations where roundabouts in the U.S. are at or near capacity. As this specific RODEL initiative helps make clear, it is difficult to validate the capacity predictions of any existing models for U.S. conditions because the number of sites that have approaches at capacity is very limited.

8.2 Developing the Input Data

For purposes of the RODEL workshop, eight RODEL datasets were created. Table 8-2 gives a list of the selected sites, as well as a summary of their characteristics. The sites have a wide

Table 8-2. Rodel Analysis Sites

State	City	Site	Setting	Approaches	Lanes	Diameter (m)	Creation Date	Previous Fac	Est/Act ADT
OR	Eugene	Barger Dr/Green Hill Rd	Suburban	3	1	38	1999	owsc	13920
MD	Baltimore	MD139(CharlesSt.)@Bellona Ave	Urban	4	2	32	1999	twsc	21610
NY	Kingston	I-587/Rt 28/I-87/Washington Ave	Rural	4	2	70	2001	circle	32440
WA	Monroe	SR 522 EB Ramps/164th St SE/Tester Rd	Suburban	5	2	67	2002	twsc	23660
CA	Long Beach	Pac Coast Hgwy/Hgwy 19/Los Coyotes	Urban	4	3	143	1993	circle	47050
VT	Brattleboro	RT 9/RT 5	Suburban	4	2	53	1999	signal	25085
MD	Stevensville	MD 18@Castle Marina Rd (Castle Marina)	Suburban	4	1	34	1999	twsc	11400
WA	Bainbridge Island	High School Rd & Madison Ave.	Suburban	4	1	32	2001	awsc	18000

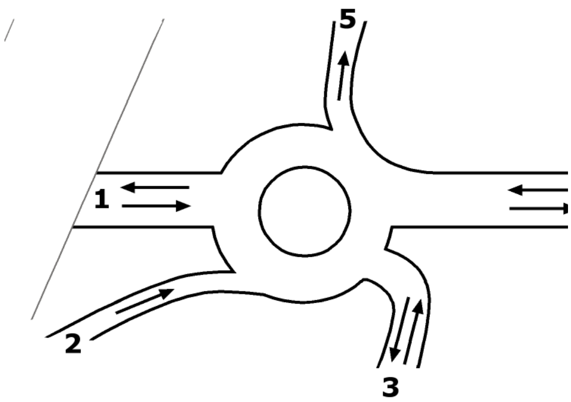
spread of conditions. There is one 3-leg, single-lane facility; two 4-leg, single-lane facilities; three 4-leg, 2-lane sites; one 5-leg, 2-lane site; and one 4-leg, 3-lane site. The ADT values range from 11,400 veh/day to 47,050 veh/day and the inscribed diameters vary from 32 to 143 meters.

A brief description of each of these sites is as follows:

- *Green Hill / Barger, Eugene, OR*: This is a three-leg single lane roundabout with a 38-meter diameter. Each of the approaches has an entry width of 6m and an approach half width of approximately 3.3m. Truck traffic percentages are in the range of two to seven percent.

- *Charles Street, Baltimore, MD*: This is a four-leg double lane roundabout with a 30-32 meter diameter. Three of the approaches have an entry width of 4.2m and an approach half width of 3.7m. The entry width and approach half width of the East approach are 7m and 6.8m respectively.

- *Thruway Interchange, Kingston, NY*: This is a four-leg double lane roundabout with a 70 meter diameter. Each of the approaches has an entry width of 7.8m. The approach half width of the south and west approaches is 7.2m, while the north and east is 3.6m. Truck traffic percentages are in the range of two to five percent for each leg.



- *Tester Road, Monroe, WA*: This is a five-leg double lane roundabout with four approaches. The diameter is 70 meters. The west and east approaches have an entry width of 7.7m and an approach half width of 7.4m. The southwest on ramp also has an entry width of 7.7m, but an approach half width of 3.7m and the south approach has an entry width of 4.9m and an approach half width of 3.7m. Note there are high truck percentages on the south and east approaches (17 and 10 percent).

- *Pacific Coast Highway, Long Beach, CA*: This is a four-leg roundabout with three circulating lanes. The diameter is 143 meters. Three of the approaches have an entry width of 11m and an approach half width of 7.3m. The entry width and approach half width of the south approach are 15m and 7.3m respectively.

- *Castle Marina, Stevensville, MD*: This is a four-leg single lane roundabout with a 34 meter diameter. The additional geometric conditions were not provided; therefore the RODEL default values were used. The entry width was 6m and the approach half widths were 3.7m.

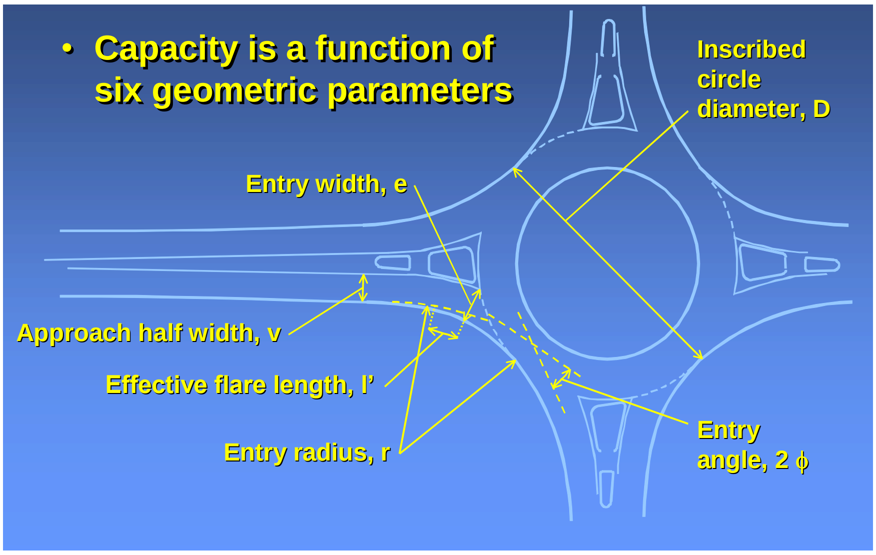
- *Routes 5&9, Brattleboro, VT*: This is a 4-leg double lane roundabout with a 53 meter diameter. Three of the approaches have an entry width of 8.5m, while the South approach is 12.3m. The approach half width is 6.8m for all approaches. Also note the truck traffic percentages are in the range of eight to twelve percent for each leg.

- *High School Road and Madison Avenue, Bainbridge Island, WA*: This is a four-leg single lane roundabout with a 32 meter diameter. Each of the approaches has an entry width of 5m and an approach half width of approximately 3.4m. (The source of the photo is Lorenz Eber/City of Bainbridge Island)

For purposes of the RODEL analysis, an input dataset was created for each these sites. The geometric inputs were derived directly from the scaled drawings, by members of the research team from Kittelson & Associates, Inc. who regularly design such facilities. (The research team specifically decided not to use survey responses in which the respondent had provided this information, without a set of drawings, so that there would not be issues of different interpretations of how to derive the input values, for example, the entry radius.) The peak hour intersecting volumes were derived from the survey responses.

For each of these sites, six geometric inputs were obtained. These are the inscribed circle diameter, entry radius, entry angle, effective flare length, entry width, and approach half width. Figure 8-1 provides an illustrative definition of these parameters. Exact definitions of these variables can be found, among other places, in the RODEL Users Manual [5].

Figure 8-1. Geometric Inputs for TRL Capacity Model



One more important thing to specify in a RODEL input dataset is the temporal profile of the flows (i.e., the temporal trends in vehicular flow rates) across the peak hour. See Figure 8-2. This is RODEL's way of specifying what in the U.S. is normally regarded as being the peak hour factor. One diagram, taken from the RODEL users manual illustrates this point. In the figure, the values T_0, T_1, T_2, T_3, and T_4 specify the points in time when changes in the flow rate occur; for example, when the before period starts, when the peak hour begins, when the peak flow is reached, when the peak period ends, and when the after period ends. A is the average flow rate across the peak period, R_1 is the flow rate that exists before the peak period begins, R_2 is the maximum flow rate reached during the peak period, and R_3 is the flow rate that exists after the peak period ends. These values were not available for any of the sites. Assumptions had to be made, based on converting the peak hour factors, which were provided. It was important to make those assumptions and think about the implications of the RODEL defaults so that comparisons could

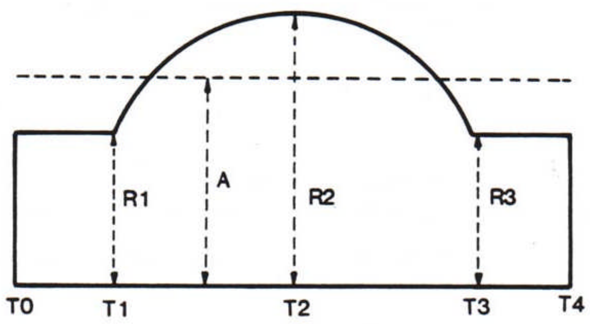


Figure 8-2. Parameters to Specify Flow Profile in

be made between the RODEL results and the predictions of the British Empirical Method itself and other models such as the FHWA design guide.

As one might expect, each of these variables has an effect on the capacity of a given approach. Figure 8-3 has an example of the manner in which the geometric input parameters typically affect the capacity values predicted by RODEL. It is clear that some of these variables have more influence than do others. For example, the entry width, *e*, the approach half-width, *v*, and the effective flare length, *l'*, have a substantial impact on the approach capacity while the inscribed diameter, *D*, has relatively little impact. Still other variables, like the entry radius *r*, have a major impact over a narrow range of values and then their influence ceases. These trends can be verified by conducting experiments in which each of the parameters is varied over a range that is typical of what might arise in design. The research team did this in preparation for conducting the analysis.

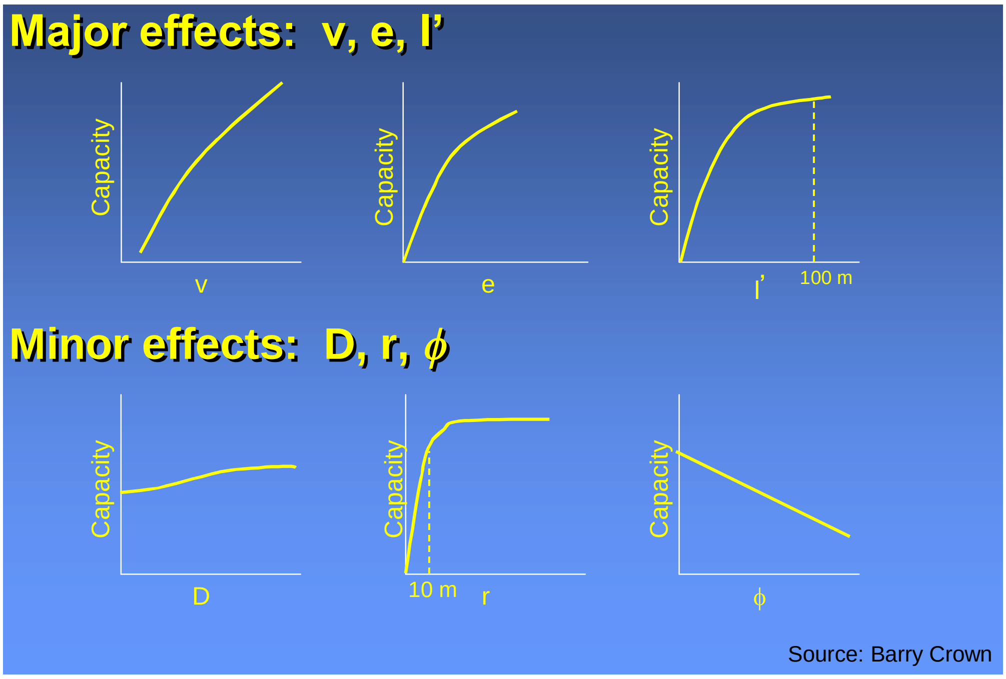


Figure 8-3. Relative Sensitivities of Geometric Variables in TRL Capacity Model

Table 8-3 presents the input information used in the creation of eight RODEL datasets. The first three fields identify the site and the island diameter. The 4th identifies a specific approach, the 5th through 10th identify geometric parameters provided in the survey response or extracted from the CAD drawings provided for each site. The 11th and 12th fields identify the percentage of trucks

Table 8-3. Rodel Inputs for Eight Case Study Sites

			GEOMETRY								PEAK PERIOD – VOLUMES					PEAK PERIOD – FLOW RATIO			
#	Site	Approach	e	l'	v	r	ϕ	D	% trucks	Circ. Wdth	1st Exit	2nd Exit	3rd Exit	4th Exit	U-Turn	PHF	R1	R2	R3
1	Green Hill Rdbt, OR	South	6	82.5	3.3	22	17	38	5	6	145	390	n/a	n/a	n/a	0.88	0.71	1.145	0.71
	Island Diameter = 26m	East	6	26	3.6	14	17	38	2	6	190	212	n/a	n/a	n/a				
		North	6	82	3.3	22	17	38	7	6	270	185	n/a	n/a	n/a				
											PM Peak								
2	Charles Street Rdbt, MD	*South	4.2	25	3.7	16	25	30	2	6	0	13	246	n/a	n/a	0.93	0.84	1.080	0.84
	Island Diameter = 16m	*East	7	25	6.8	28	19	32	2	8	2	199	681	n/a	n/a				
		*North	4.2	25	3.7	10	24	30	0	8	16	24	3	n/a	n/a				
		*West	4.2	25	3.7	15	23	32	0	8	53	30	0	n/a	n/a				
											PM Peak								
3	Kingston Rdbt, NY	*South	7.8	25	7.2	35	16	70	5	10	264	542	395	n/a	n/a	0.90	0.76	1.119	0.76
	Island Diameter = 50m	East	7.8	45	3.6	60.6	20	70	2	10	0	538	357	n/a	n/a				
		North	7.8	25	7.2	60.6	6	70	5	10	0	308	177	n/a	n/a				
		*West	7.8	35	3.6	60	24	70	5	10	0	218	395	n/a	n/a				
											PM Peak								
4	Tester Rd Rdbt, WA	South	4.9	30	3.7	42	30	71	17	10	123	22	93	0	n/a	0.80	0.47	1.267	0.47
	Island Diameter = 51m	East	7.7	49	7.4	57	26	71	10	10	17	260	0	193	n/a				
		North (off R)	n/a	n/a	n/a	n/a	n/a	71	n/a	n/a	0	0	0	0	n/a				
		West	7.7	27	7.4	25	22	71	5	10	0	185	221	6	n/a				
		SWest (on R)	7.7	46	3.7	22	22	71	6	10	69	130	0	84	n/a				
											AM Peak								
5	Long Beach Rdbt, CA	South	15	20	7.3	61	17	147	n/a	15	255	249	550	n/a	n/a	1.00	1.00	1.000	1.00
	Island Diameter = 121m	East	11	25	7.3	46	22	143	n/a	11	50	236	291	n/a	n/a				
		North	11	15	7.3	46	10	143	n/a	11	343	508	50	n/a	n/a				
		West	11	10	7.3	38	12	143	n/a	11	189	442	465	n/a	n/a				
											PM Peak								
6	Castle Marina Rdbt MD	South	6	10	3.7	20	30	34	2	6	146	10	41	n/a	n/a	0.94	0.86	1.068	0.86
		East	6	10	3.7	20	30	34	3	6	271	183	125	n/a	n/a				
	Island Diameter = 24m	North	6	10	3.7	20	30	34	2	6	33	49	27	n/a	n/a				
	No geometry provided - used default values	West	6	10	3.7	20	30	34	2	6	200	18	37	n/a	n/a				
											PM Peak								
7	Brattleboro Rdbt, VT	South	12.3	25	6.8	37.5	29	54	5	12	70	220	145	n/a	n/a	0.90	0.76	1.119	0.76
		East	8.5	10	6.8	30	34	50	5	8	400	495	405	n/a	n/a				
	Island Diameter = 34m	North	8.5	10	6.8	30	34	54	5	8	200	285	195	n/a	n/a				
	Vol. shown are 2000 - used a 6% adj. in analysis	West	8.5	10	6.8	30	34	50	5	8	305	285	200	n/a	n/a				
											PM Peak								
8	Bainbridge Rdbt, WA	South	5	13.1	3.4	16	25	32	2	6	356	87	90	n/a	n/a	0.90	0.76	1.119	0.76
	Island Diameter = 20m	East	5	5.8	3.4	16	22	32	2	6	101	247	130	n/a	n/a				
		North	5	13.1	3.4	22	22	32	2	6	82	202	111	n/a	n/a				
		West	5	13.1	3.4	22	22	32	2	6	87	269	35	n/a	n/a				
											PM Peak								

*No flare length evident in Diagram - assume 25m

and the circulating width while the next five fields identify the flow volumes. The final four fields identify the peak hour factor and the three ratios (R_1, R_2, and R_3) used by RODEL to describe the flow profile across the peak hour. (Note, these are not the radii experienced by vehicles passing through the roundabout making various turning movements, which are also designated by variables R_1, R_2, and R_3). These flow ratios were developed using the method described in the RODEL User Manual [2] (see the previous Figure 4).

8.3 RODEL Outputs

The results of the RODEL outputs for the eight sites are shown in Table 8-4. As can be seen from the volume/capacity or delay results, all of these roundabouts are operating below their approach capacities with low values for both delays and queues.

Table 8-4. Rodel Output Summary for Eight Case Study Sites

			RODEL						
#	Site	Approach	Flow (veh)	Capacity (veh)	V/C	Avg. Delay (min)	Avg. Delay (sec)	Max. Queue (veh)	Max. Queue (meters)
1	Green Hill Rdbt, OR	South	535	1610	0.33	0.05	3.0	1	7.6
		East	402	1397	0.29	0.05	3.0	0	0.0
		North	455	1568	0.29	0.05	3.0	0	0.0
2	Charles Street Rdbt, MD	*South	259	1227	0.21	0.05	3.0	0	0.0
		*East	882	1985	0.44	0.05	3.0	1	7.6
		*North	43	594	0.07	0.1	6.0	0	0.0
		*West	83	862	0.10	0.07	4.2	0	0.0
3	Kingston Rdbt, NY	*South	1201	1881	0.64	0.09	5.4	3	22.9
		East	895	1343	0.67	0.14	8.4	3	22.9
		North	485	1642	0.30	0.05	3.0	1	7.6
		*West	613	1532	0.40	0.06	3.6	1	7.6
4	Tester Rd Rdbt, WA	South	238	1113	0.21	0.07	4.2	0	0.0
		East	470	2095	0.22	0.03	1.8	0	0.0
		North (off R)	-	-	-	-	-	-	-
		West	412	2177	0.19	0.03	1.8	0	0.0
		SWest (on R)	283	1664	0.17	0.04	2.4	0	0.0
5	Long Beach Rdbt, CA	South	1054	2829	0.37	0.03	1.8	1	7.6
		East	577	2308	0.25	0.03	1.8	0	0.0
		North	901	2401	0.38	0.03	1.8	1	7.6
		West	1096	2417	0.45	0.04	2.4	1	7.6
6	Castle Marina Rdbt MD	South	197	1442	0.14	0.04	2.4	0	0.0
		East	579	1424	0.41	0.06	3.6	1	7.6
		North	109	1276	0.09	0.05	3.0	0	0.0
		West	255	1368	0.19	0.05	3.0	0	0.0
7	Brattleboro Rdbt, VT	South	435	2388	0.18	0.03	1.8	0	0.0
		East	1300	1867	0.70	0.11	6.6	3	22.9
		North	680	1536	0.44	0.07	4.2	1	7.6
		West	790	1630	0.48	0.07	4.2	1	7.6
8	Bainbridge Rdbt, WA	South	533	1113	0.48	0.1	6.0	1	7.6
		East	478	1159	0.41	0.08	4.8	1	7.6
		North	395	1111	0.36	0.08	4.8	1	7.6
		West	391	1126	0.35	0.07	4.2	1	7.6

* no flare length evident in diagram – assume 25m

Several trends are observable in Table 8-4. Focusing first on the capacities, notice that for the multilane roundabouts (Charles St., Kingston, Tester Rd., Long Beach, and Brattleboro) the expected capacities are much higher than for the single lane roundabouts (Green Hill, Castle Marina, and Bainbridge).

Although the roundabouts are operating well below capacity and have insignificant delays and queues, it is useful to look at the upper bounds of these values. Of all the datasets, the maximum delay (7.2 seconds) and the maximum queue length (30.5 meters) occur on the east approach of the roundabout in Brattleboro, VT. In this instance the main reason is the large approach volume (1378vph) in combination with a relatively high conflicting volume (565vph).

It appears that field estimates of delay exist for two sites: the Kingston and Long Beach facilities. In the case of the Kingston site, the AM average delays per vehicle are reported to be in the range of 17.2 to 18.1 seconds in the AM peak and 15.9-24.6 seconds in the PM peak. These values are clearly higher than the values predicted by RODEL. Our presumption is that the delay data were collected on a day that had heavy traffic, heavier than the values employed in the analysis dataset. This remains to be verified through additional analysis. In the case of the Long Beach roundabout, the delays in the after condition range from 1.3 to 14.4 seconds per vehicle in the AM peak (in order of size: 1.3, 1.4, 5.5, and 14.4 seconds per vehicle) and 2.2 to 7.4 seconds per vehicle in the PM peak (in order of size: 2.2, 3.2, 4.8, and 7.4 seconds per vehicle). These values are again higher than those predicted by RODEL.

9.0 Conclusions and Recommendations

This project has examined the operational and safety performance trends of roundabouts. Included in the report is an examination of:

- General characteristics and trends in the size and configuration of roundabouts in the US including the construction dates, inscribed diameters, number of lanes, number of legs, intersecting volumes AADT values, prior control treatment, and geographic location
- Operational performance trends, especially the percentage of left turns in the intersecting volumes, capacities and their contrast with the combinations of conflicting and entering flow, and delays
- General safety trends, including changes in the number of total accidents and injury accidents per year and an assessment of the quality of the geometric design found for the roundabouts identified in the sites in the overall database
- Findings from an analysis of accident data based on a safety model that estimates the accident frequencies for roundabouts that replace a specific control treatment in a given setting
- Evidence of the manner in which roundabouts affect the accommodation of pedestrians
- Results of RODEL analyses

From a general perspective, the conclusions drawn are these:

- The states with 30 or more roundabouts are Colorado, Maryland, Washington, and Florida. Another five have between 15 and 30: Florida, Kansas, Utah, Nevada, Oregon, and California.
- More than 90% of the roundabouts (at least in the project database) were built since 1995.
- Sixteen of the 288 sites in the database are rural, 158 are suburban, and 106 are urban. The others are either urban or suburban but it is not clear which.
- Two thirds of the roundabouts are single lane. The rest are multilane.
- Half of the roundabouts had two-way stop control as the predecessor mode of operation (allowing for both one-way and two-way stop control). Another quarter of them are new intersections with no previous history. The others had all-way stop control or a signal.
- The AADT values range from 12,000 for a 3-leg, single lane facility to 47,000 for a four-leg, multilane facility.
- Inscribed diameters are 15-143 meters with the most common values being 25-35 meters followed by 45-55 meters and 15-25 meters. Size tends to increase with the number of lanes.
- The left turns at roundabouts seem to be a much larger percentage of the total flows than is common for other types of intersections, especially ones that are signalized. The percentage averages 30% and ranges up to 60%. Moreover, it is common for one of the left turns to be "huge", up to 60% of the total flows.
- The scatter plots of conflicting volume against entering volume suggest that the British capacity model may be able to predict capacities for roundabouts in the US.
- The combinations of conflicting and entering volumes for the multi-lane sites range up to

and beyond values observed for the single lane sites. Hence, there is an indication that the traffic engineers needed to install multi-lane facilities for capacity reasons.

- Average delays per entering vehicle for the roundabout are less than half those of the prior control option, seemingly regardless of what it was. Moreover, where traffic engineers have provided estimates of the delays in the after condition (probably from a model), those estimates are often higher than the field data would support.
- Of the 35 sites with accident data, 28 of them have seen a reduction in the total number of accidents per year.
- The decrease in injury accidents is similarly significant. While the sample size is small, 29 of the 35 sites saw a decrease in injury accidents. In 15 of them, there were no injury accidents in the after period while there had been such accidents in the before period. These trends cannot be generalized with high confidence, but it is likely that larger sample sizes are likely to show similar trends.
- The reasonableness of these trends seems to be corroborated by the "accident-proneness" analysis conducted by the study team for 288 sites. About 60% require all entering vehicles to slow down, which is the desired behavior. The others allow vehicles on one or more of the approaches to pass through without slowing down and a few allow right turn moves without speed decreases.
- Point estimates of the percentage reduction in injury accidents that ought to be possible with the introduction of a roundabout hover around 70-80% regardless of what the prior control situation was and regardless of locale. The reduction range from 81% for four-leg, two-way stop controlled urban intersections to 68% for single lane rural stop controlled intersections.
- At the two sites where pedestrians were significant, the anecdotal evidence tends to suggest that the accommodation of pedestrians was better after the roundabout was introduced that it was before.

Of course, more data about more roundabouts would further enhance these findings and lead to other insights. Hopefully, the NCHRP 3-65 project [12] will yield those new results.

REFERENCES

[1]. Kittelson Associates, Inc., Roundabouts Database, found at http://roundabouts.kittelson.com/ under "Inventory Database" link, 2003.

[2]. Persaud, B. N., P. E. Garder, and D. Lord. Roundabout Safety in the United States (final project report to the Insurance Institute for Highway Safety), Ryerson Polytechnic University, Department of Civil Engineering, Toronto, Ontario, 1999.

[3]. Robinson, B.W., L. Rodegerdts, W. Scarborough, W. Kittelson, R. Troutbeck, W. Brilon, L. Bondzio, K. Courage, M. Kyte, J. Mason, A. Flannery, E. Myers, J. Bunker, and G. Jacquemart, Roundabouts: An Informational Guide, Report No. FHWA-RD-00-067, prepared for the Federal Highway Administration, Washington, DC, June 2000.

[4]. Flannery, A., Design, Safety and Operational Quality of Roundabouts, Doctoral Dissertation, Penn State University, December, 1998.

[5]. Crowne, B., Rodel Software, Ltd. and Staffordshire County Council. RODEL 1: Interactive Roundabout Design. Prepared for NYSDOT, May 16, 2000.

[6]. Akcelik, R. and M. Besley, Sidra 5 User Guide, ARRB Transport Research Ltd, 1998.

[7]. Australian Road Research Laboratory, Guide to Traffic Engineering Practice Roundabouts, Part 6: Roundabouts, AUSTROADS, 1993.

[8]. Maryland Department of Transportation, Roundabout Design Guidelines, 1995.

[9]. Florida Department of Transportation, Florida Roundabout Guide, 1996.

[10]. Oregon Department of Transportation, Modern Roundabouts for Oregon, 1998.

[11]. List, G. Training and Technical Assistance for the Signal Timing Optimization Program, Final Report prepared for the New York State Energy Office, 1991.

[12]. National Cooperative Highway Research Program, Applying Roundabouts in the United States, Project 3-65, 2001.

[13]. Kimber, R.M., The Traffic Capacity of Roundabouts. Transportation and Road Research Laboratory Report LR 942, Great Britain, 1980.

[14]. Eisenman, S., and G. List, Site Selection Thoughts, technical memorandum, NCHRP 3-65, February 4, 2003.

[15]. Hauer E., Observational Before-After Studies in Road Safety, Pergamon Press, 1997.

[16]. Federal Highway Administration (FHWA), SafetyAnalyst Software Tools, (www.safetyanalyst.org), 2003.

[17] Persaud B.N., R. Retting, P. Garder and D. Lord, "Safety Effect of Roundabout Conversions in the U.S.: Empirical Bayes Observational Before-After Study", Transportation Research Record 1757, pp. 1-8, 2001.

[18] Federal Highway Administration, Interactive Highway Safety Design Model (IHSDM), Turner-Fairbanks Research Laboratory, http://www.tfhrc.gov/safety/ihsdm/ihsdm.htm, 2003.

[19]. Brown County Planning Commission, Lineville Road Roundabout Study, November 2001.

[20]. Runge, C. (Wisconsin DOT), Survey Response, Project C-01-47, Operational and Safety Performance of Modern Roundabouts and Other Intersection Types, November 2002.

[21]. Niederhauser, M. (Maryland DOT), Survey Response, Project C-01-47, Operational and Safety Performance of Modern Roundabouts and Other Intersection Types, July 2002.

[22] *The Baltimore Sun*, "Pedestrians must be on toes in Towson roundabout," July 6, 1998.

[23]. Bradshaw, C. (City of Claremont, CA), Survey Response, Project C-01-47, Operational and Safety Performance of Modern Roundabouts and Other Intersection Types, November 2002.

APPENDIX A
Survey Instrument

Roundabout ___________________ Location ___________________

Page 1: Instructions
NYSDOT Project C-01-47
Operational and Safety Performance of Modern Roundabouts and Other Intersection Types

We value your expertise. By completing this survey, you will be helping NYSDOT better understand the operational and safety performance of roundabouts. You will also be helping provide data for NCHRP 3-65, the national study focused on roundabouts, since the researchers involved in this effort are part of that larger study team.

Survey Content:

There are four main parts to the survey: Implementation Experience, Geometric, Operational Performance and Safety.

How to Fill out the Survey:

In addition to completing the survey forms we are requesting that you forward any other information which you believe may be helpful in understanding roundabout performance and implementation issues. Such additional information could include: Design Reports and files, CADD files in AutoCAD or MicroStation format, safety data and analysis, brochures, pictures, and newspaper articles (both favorable and unfavorable). Please indicate file names and software used in all electronic submissions.

Submission

We prefer electronic responses to the survey, however, hard copies are acceptable.
Please e-mail your electronic survey responses to listg@rpi.edu.
Hard copy materials (e.g., survey, reports, traffic data) should be sent to:

Prof. George F. List
Dept. of Civil and Environmental Enginering
4052 Jonsson Engineering Center
Rensselaer Polytechnic Institute
110 Eighth Street
Troy, NY 12180

Additional Information

If you have data for other circulatory intersections (e.g., rotaries and traffic circles) we would appreciate receiving that information. We would like to compare the operational and safety characteristics of rotaries and traffic circles with similar information observed at roundabouts.

Pages 3 - 8 are laid out for up to a four leg roundabout. Please contact us if you have a roundabout with five or more legs.

If you have any questions or if you know people we should contact for information about roundabouts, please e-mail listg@rpi.edu

Your Name: ______________________________
Address: ______________________________
____
e-mail: ______________________________
Telephone: ______________________________

Roundabout ________________ Location ________________

Page 2: Pre- and Post-construction General Information (page 1 of 2)
NYSDOT Project C-01-47

Answer the survey questions below, and send reports (e.g., hard copy or electronic files on floppies, zip-disks, or CD's. Please indicate the following for these items:

File name: ____________ File type: __________ Description: ________________
File name: ____________ File type: __________ Description: ________________

Intersecting Roadways: ____________________ and ____________________
City: ____________________ County: ____________________
State: ____________________

1) Setting: ____ Urban ____ Suburban ____ Rural ____ Other (____________)

2) Land use (e.g., commercial): ________________________________

3) Project dates:
Construction started (date): ____________
Construction complete (date): ____________

4) Goal of the installation: ____ Safety ____ Traffic calming ____ Reduced delays ____ Other (______)

5) Public awareness campaign (Y/N)? ____ Explain: ____________________

6) Public approval: Pre-construction High ______ Moderate _______ Low _______
Post-construction High ______ Moderate _______ Low _______

7) Design software employed (e.g. RODEL, SIDRA, etc.): ____________________

8) Design guide(s) employed (e.g. FHWA): ____________________

9) Design philosophy used: ____ Gap Acceptance Theory ____ British Empirical Model

10) Site-specific problems and solutions (use additional sheets if needed):

Site Specific Problem	Solution

11) Please send any brochures, digital pictures or planning reports that are available for the roundabout.

Roundabout ________________ Location ________________

Page 3: Pre- and Post-construction General Information (page 2 of 2)
NYSDOT Project C-01-47

Answer the survey questions below, and send any reports, (hard copy or electronic files on floppies, zip-disks, or CD's. Include the following for electronic files.

File name: ____________ File type: __________ Description: ________________
File name: ____________ File type: __________ Description: ________________

1) What did you learn and/or what would you do differently to implement a roundabout project. (use additional sheets if needed)?

Lessons learned	Explanation

2) What were the public perceptions about roundabouts? (Please send copies of news articles if possible)

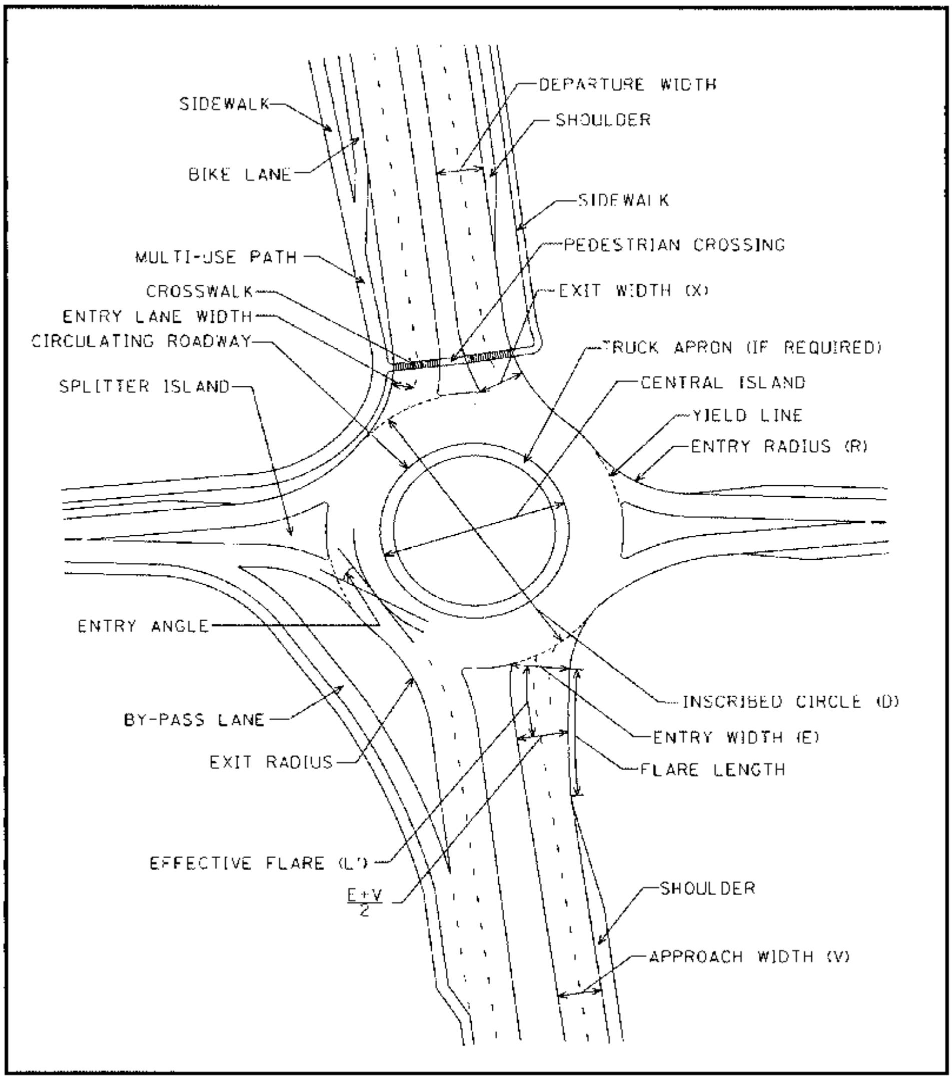
Pre-construction perceptions	Post-construction perceptions and trends

Roundabout ____________________ Location ____________________

Page 4: Roundabout Terms
NYSDOT Project C-01-47

Please use this page as a reference when filling out the data requested on page 5 and creating the sketch requested on page 7.

Figure 1 Roundabout illustration



June 2000

Roundabout ________________ Location ____________________

Page 5: Geometric Data Survey
NYSDOT Project C-01-47

PRE-CONSTRUCTION

Type of Control[1] ________
If signalized ________
Timing (e.g., full actuated) ________
Average cycle length ________
Pedestrian treatment[2] ________
Overhead lighting (Y/N) ________

Approach Leg

For each approach:	1	2	3	4
Lane width (average):				
Shoulder width:				
Stopbar setback:				
Grade				

1. Examples are: none, two-way stop controlled, all-way stop controlled, and signalized.
2. Crosswalks, ped-heads, ped buttons, other.

POST-CONSTRUCTION

Please use the previous page as a reference when filling out the data requested below.

Facility cost: ______
Number of legs: ______
Inscribed circle diameter: ______
Number of lanes on circulating roadway: ______
Circulating roadway width: ______
Striping on circulating roadway (Y/N) ______
Apron type: (e.g., raised, painted) ______
Overhead lighting (Y/N) ______
Pedestrian crosswalk[3] ______

Approach Leg

For each approach:	1	2	3	4
Number of lanes:				
Flare length:				
Entry width:				
Entry radius:				
Shoulder width:				
Crosswalk to entry point:				
Deflection Angle (degrees):				
Sight distance:				
Grade				
Orientation[4]				

3. Number of car lengths back from circulating roadway
4. Clockwise angle from the previous approach

Roundabout ____________ Location ____________

Page 6: Geometric Data: Pre-Construction Plans/Sketch
NYSDOT Project C-01-47

Please provide CADD file plans, (i.e., general plans and pavement marking plans), if available, on floppies, zip disks, or CD's. If electronic files are not available, please send hard copy plans. Please also include a hand drawn sketch below. Be sure that approaches are numbered to correspond with Data Survey on page 3 for all drawings and sketches (hard copy or electronic). If approaches are not numbered, please indicate manually below. Please indicate file names and software used in all electronic submissions.

CAD file names:

Pre-construction: ____________

File type: ____________

Hard copy plans: ____________

Place sketch here; use additional sheets if necessary. Be sure to designate the entry roadways 1, 2, 3, and 4 and the basic configuration.

Roundabout ________________ Location ________________

Page 7: Geometric Data: Post-Construction Sketch
NYSDOT Project C-01-47

Please provide CADD file plans, (i.e., general plans and pavement marking plans), if available, on floppies, zip disks, or CD's. If electronic files are not available, please send hard copy plans. Please also include a hand drawn sketch below. Be sure that approaches are numbered to correspond with Data Survey on page 3 for all drawings and sketches (hard copy or electronic). If approaches are not numbered, please indicate manually below. Please indicate file names and software used in all electronic submissions.

CAD file names:

Post-construction: ________________

File type: ________________

Hard copy plans: ________________

Place sketch here; use additional sheets if necessary. Be sure to designate the entry roadways 1, 2, 3, and 4 and the basic configuration.

Roundabout ____________ Location ____________

Page 8: Operational Performance Data Survey
NYSDOT Project C-01-47

In addition to completing the survey below, please provide any available electronic files or hard copy plans containing operational performance data. Please indicate the following for electronic submissions.

Pre-construction File name(s): ____________
File Type: ____________

Post-construction file name(s): ____________
File Type: ____________
Traffic analysis software used: ____________

PRE-CONSTRUCTION

Approach roadways as designated on page 6.

	1			2			3			4			Source[1]
AM Peak	L	T	R	L	T	R	L	T	R	L	T	R	
Turning Movement Counts[2]													
Delay (sec/veh) or LOS[3]													
Queue Length[3]													
Peak Hour Factor													
Percent HV (trucks, buses, RV)													
Pedestrians/hr													
PM Peak	L	T	R	L	T	R	L	T	R	L	T	R	
Turning Movement Counts[2]													
Delay (sec/veh) or LOS[3]													
Queue Length[3]													
Peak Hour Factor													
Percent HV (trucks, buses, RV)													
Pedestrians/hr													
Approach AADT													
Approach free flow speed													

POST-CONSTRUCTION

Approach roadways as designated on page 7.

	1			2			3			4			Source[1]
AM Peak	2	3	4	1	3	4	1	2	4	1	2	3	
Design Year Volumes[4]													
Turning Movement Counts[4]													
Delay (sec/veh) or LOS[3]													
Queue Length[3]													
Peak Hour Factor													
Percent HV (trucks, buses, RV)													
Pedestrians/hr													
PM Peak	2	3	4	1	3	4	1	2	4	1	2	3	
Design Year Volumes[4]													
Turning Movement Counts[4]													
Delay (sec/veh) or LOS[3]													
Queue Length[3]													
Peak Hour Factor													
Percent HV (trucks, buses, RV)													
Pedestrians/hr													
Approach AADT													
Approach free flow speed													

1. Indicate as appropriate: field measured (f), estimated (e), posted speed limit (p)
2. Count U-turns as left turns.
3. Provide movement specific values if possible, otherwise provide approach specific values
4. The top headings show the origin; the lower, the destination (flow from 1 to 2, 1 to 3, etc.).

Roundabout ____________ Location ____________

Page 9: Safety Data Survey
NYSDOT Project C-01-47

Ideally, we would like to base our safety analysis on the actual police accident reports. Please send those reports or tell us how to obtain them either in electronic form or hard copy. If convenient, please also provide the information requested below. Note that we have asked for AADT values on page 8 and construction dates on page 2.

Person to contact for the accident reports:

Name: ____________ Organization: ____________
e-mail: ____________ Telephone: ____________

PRE-CONSTRUCTION

	Number of Accidents by Year				
Year (e.g. 1998)	____	____	____	____	____
Fatal accidents	____	____	____	____	____
Injury accidents	____	____	____	____	____
Property damage accidents[1]	____	____	____	____	____
By Collision Types:					
Rear end accidents	____	____	____	____	____
Head-on accidents	____	____	____	____	____
Right angle accidents	____	____	____	____	____
Right turning accidents	____	____	____	____	____
Left turning accidents	____	____	____	____	____
Accidents involving pedestrians	____	____	____	____	____
Accidents involving cyclists	____	____	____	____	____
Other	____	____	____	____	____

Describe any changes in reporting practices/requirements during these years:

Describe any high accident problems and mitigating actions

POST-CONSTRUCTION (most representative 5-year sequence)

	Number of Accidents by Year				
Year (e.g. 2000)	____	____	____	____	____
Fatal accidents	____	____	____	____	____
Injury accidents	____	____	____	____	____
Property damage accidents[1]	____	____	____	____	____
By Collision Types (from the FHWA roundabout design guide):					
Failure to yield at entry	____	____	____	____	____
Single-vehicle run off circulatory roadway	____	____	____	____	____
Single vehicle loss of control at entry	____	____	____	____	____
Rear-end at entry	____	____	____	____	____
Circulating/exiting	____	____	____	____	____
Accidents involving pedestrians	____	____	____	____	____
Accidents involving cyclists	____	____	____	____	____
Other	____	____	____	____	____

Describe any changes in reporting practices/requirements during these years:

Describe any high accident problems and mitigating actions

1. Indicate how property damage accidents are reported (i.e. tow-away, property damage cost)