National Cooperative Highway Research Program

NCHRP Synthesis 264

Modern Roundabout Practice in the United States

A Synthesis of Highway Practice

Transportation Research Board
National Research Council

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Modern Roundabout Practice in the United States

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Transportation Research Board
National Research Council

Research Sponsored by the American Association of State Highway and Transportation Officials in Cooperation with the Federal Highway Administration

NATIONAL ACADEMY PRESS
Washington, D.C. 1998

Subject Areas
Highway and Facility Design,
Highway Operations, Capacity,
and Traffic Control

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NCHRP SYNTHESIS 264

Project 20-5 FY 1996 (Topic 28-09)
ISSN 0547-5570
ISBN 0-309-06120-2
Library of Congress Catalog Card No. 98-66468

Price $23.00

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Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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Printed in the United States of America

PREFACE

A vast storehouse of information exists on nearly every subject of concern to highway administrators and engineers. Much of this information has resulted from both research and the successful application of solutions to the problems faced by practitioners in their daily work. Because previously there has been no systematic means for compiling such useful information and making it available to the entire community, the American Association of State Highway and Transportation Officials has, through the mechanism of the National Cooperative Highway Research Program, authorized the Transportation Research Board to undertake a continuing project to search out and synthesize useful knowledge from all available sources and to prepare documented reports on current practices in the subject areas of concern.

This synthesis series reports on various practices, making specific recommendations where appropriate but without the detailed directions usually found in handbooks or design manuals. Nonetheless, these documents can serve similar purposes, for each is a compendium of the best knowledge available on those measures found to be the most successful in resolving specific problems. The extent to which these reports are useful will be tempered by the user's knowledge and experience in the particular problem area.

FOREWORD

By Staff
Transportation Research Board

This synthesis presents information on current practices with respect to the planning, design, and operation of modern roundabouts in the United States. It will be of interest to state and local highway design engineers, traffic engineers, maintenance engineers, as well as officials concerned with roadway safety. It will also be useful to design and traffic engineering consultants who may be assisting communities with the implementation of roundabouts.

Administrators, engineers, and researchers are continually faced with highway problems on which much information exists, either in the form of reports or in terms of undocumented experience and practice. Unfortunately, this information often is scattered and unevaluated and, as a consequence, in seeking solutions, full information on what has been learned about a problem frequently is not assembled. Costly research findings may go unused, valuable experience may be overlooked, and full consideration may not be given to available practices for solving or alleviating the problem. In an effort to correct this situation, a continuing NCHRP project, carried out by the Transportation Research Board as the research agency, has the objective of reporting on common highway problems and synthesizing available information. The synthesis reports from this endeavor constitute an NCHRP publication series in which various forms of relevant information are assembled into single, concise documents pertaining to specific highway problems or sets of closely related problems.

The concept of the modern roundabout to move traffic more efficiently through unsignalized intersections has evolved from conventional traffic circles. This report of the Transportation Research Board presents a discussion of modern roundabout applications in the United States, based on a survey of state and local transportation agencies who provided information on 38 individual roundabouts. Case examples of three roundabouts, each representing a different type of roundabout, are described in detail. The synthesis presents information on the design guidelines used in the United States as well as those of other countries. Other major areas of interest with regard to roundabouts include safety issues; traffic capacities and delays; issues related to pedestrians, bicyclists, and the visually impaired; costs; and location criteria to be considered for roundabouts.

To develop this synthesis in a comprehensive manner and to ensure inclusion of significant knowledge, the Board analyzed available information assembled from numerous sources, including a large number of state highway and transportation departments. A topic panel of experts in the subject area was established to guide the research in organizing and evaluating the collected data, and to review the final synthesis report.

This synthesis is an immediately useful document that records the practices that were acceptable within the limitations of the knowledge available at the time of its preparation. As the processes of advancement continue, new knowledge can be expected to be added to that now at hand.

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ACKNOWLEDGMENTS

Georges Jacquemart, P.E., AICP, Principal, Buckhurst Fish and Jacquemart Inc., was responsible for collection of the data and preparation of the report.

Valuable assistance in the preparation of this synthesis was provided by the Topic Panel, consisting of Joseph E. Bared, Ph.D., P.E., Highway Research Engineer, Safety Design Division, Federal Highway Administration; Kenneth G. Courage, Professor, University of Florida, Department of Civil Engineering; Richard A. Cunard, Engineer of Traffic and Operations, Transportation Research Board; Peter I. Doctors, Principal, Ourston & Doctors, Santa Barbara, California; Michael W. Thomas, Supervising Transportation Engineer, California Department of Transportation; Gregory A. Hall, P.E., Town Engineer/Deputy Director, Public Works and Transportation, Town of Vail, Colorado; Robert E. Maki, Ph.D., P.E., Special Assistant to Deputy Director, Highway Operations, Michigan Department of Transportation; Michael Niederhauser, Traffic Engineer, Maryland State Highway Administration; William A. Prosser, Highway Design Engineer, Federal Highway Administration; Tony Redington, Montpelier, Vermont; George W. Schoene, Team Coordinator, Office of Traffic Management and ITS Applications, Federal Highway Administration; and Seppo I. Sillan, Senior Engineer, Federal Highway Administration.

This study was managed by Sally D. Liff, Senior Program Officer, who worked with the consultant, the Topic Panel, and the Project 20-5 Committee in the development and review of the report. Assistance in Topic Panel selection and project scope development was provided by Stephen F. Maher, P.E., Senior Program Officer. Linda S. Mason was responsible for editing and production.

Crawford F. Jencks, Manager, National Cooperative Highway Research Program, assisted the NCHRP 20-5 staff and the Topic Panel.

Information on current practice was provided by many highway and transportation agencies. Their cooperation and assistance are appreciated.

MODERN ROUNDABOUT PRACTICE IN THE UNITED STATES

SUMMARY

Modern roundabouts have become a subject of great interest and attention over the last few years in the United States. This interest is partially based on the great success of roundabouts in Europe and Australia, where intersection design practice has changed substantially as the result of the good performance of roundabouts and their acceptance by the public.

Modern roundabouts follow design principles that are different from those of traffic circles built in the United States in the first half of the century. The old circles often gave priority to entering traffic and were designed with the weaving movement as a prime consideration. The circles became fairly large, with long distances between consecutive entrances and exits and with relatively high speeds. In contrast, the modern roundabout is designed for lower speeds, and its dimensions are determined by the number of branches, required capacity, and by the turning radii of larger vehicles. Deflection of the vehicle path through the roundabout is a critical design element affecting the safety of the roundabout. Entering traffic has to yield to circulating traffic. At low traffic loads, vehicles enter without stopping; at higher loads, entering traffic has to wait for a gap in the circulating stream. To increase roundabout capacity, entries are flared to provide more than one entry lane, and the circulatory roadway is widened.

A survey was conducted of all state departments of transportation in the United States, the Canadian provinces, and 26 U.S. municipalities and counties to gain an understanding of the general perceptions regarding modern roundabouts, and of current use. The main reasons survey respondents gave for building or considering roundabouts are: 1) greater safety, 2) shorter delays, 3) lower costs, and 4) aesthetic and urban design reasons. The survey respondents mentioned the following as the greatest benefits observed after the construction of roundabouts: 1) shorter delays, 2) increased capacity, 3) improved safety, and 4) improved aesthetics. All respondents were unanimous in that they were, overall, satisfied with the roundabout. When asked whether they would build more roundabouts in their jurisdiction, 10 out of 13 said "yes" and three said "maybe." The main reasons for not building roundabouts given by responding states that have none are uncertainty that drivers could adjust, and questions about efficiency and safety.

A few minor problems were mentioned by the respondents: the advantage given to the low-volume street, which sometimes causes undue delays to the major street; the lack of clear right-of-way control for pedestrians; unusual or new maintenance procedures; and high construction costs in some instances. The construction costs reported ranged from $10,000 for an existing intersection that was retrofitted into a small roundabout to $500,000 for a roundabout built on a state highway with construction involving major grading and drainage work. The maintenance of traffic during construction is relatively expensive. Although roundabout interchanges may be expensive to retrofit ($2.8 to $6.4 million), they are often less expensive than alternative interchange capacity improvements.

The public reaction to roundabouts has been positive in general. This is substantiated by the survey respondents, by opinion surveys, and by reporting in the press.

The design guidelines most commonly used by the U.S. respondents are the Australian guide, or derivatives thereof (Maryland DOT Guide, Florida DOT Guide). About a third of

the respondents used British guidelines (or the guidelines developed by Ourston & Doctors). The following are the most widely used roundabout guidelines, worldwide: *AUSTROADS* from Australia, *Geometric Design of Roundabouts* from Great Britain, *CETUR* urban guide from France, *SETRA* rural guide from France, *Swiss Roundabout Guide*, and various guides from Germany. Currently, there are no U.S. guidelines for modern roundabouts, however, the Federal Highway Administration has started a 2-year study to develop guidelines for the United States by the end of 1999.

The survey collected "before-and-after" crash statistics for 11 roundabouts in the United States. For these 11 roundabouts, total crashes decreased by 37 percent, injury crashes decreased by 51 percent, and property-damage-only crashes decreased by 29 percent. For the eight small-to-moderate roundabouts with outside diameters less than 37 m (121 ft), the crash reductions were statistically significant for total crashes (a reduction of 51 percent) and for injury crashes (a reduction of 73 percent). For property-damage-only crashes the trends were also favorable, but not statistically significant. The crash statistics for the three larger roundabouts also showed favorable trends, but were not statistically significant.

Similar, and often higher, safety benefits have been measured in European countries and in Australia. Safety benefits seem to be greatest for single-lane roundabouts in rural conditions. Studies in the Netherlands, in Germany, and in France also show positive safety impacts for pedestrians at roundabouts. For bicycles, the safety impacts are mixed. The study from the Netherlands showed reductions for bicycle accidents across the board, whereas the study from Germany showed increases in crashes for cases in which the bicycle lane was continued through the roundabout, but no significant changes where bicycles were in mixed traffic. Safety benefits in general are related to the reduced speed in the roundabouts and also to the simplification of the conflicts in a roundabout. Another reason for their safety, mentioned by a researcher from Switzerland, is the higher degree of responsibility caused by the slower motion and the need to concentrate and yield, as compared to the driver behavior in signalized intersections.

Delays in U.S. roundabouts are about 75 percent less than under the previous traffic control method. A wide range of methods and formulas exist to estimate capacities and delays. In the United States, a majority of agencies use the Australian method as incorporated in the SIDRA software. About 14 percent use RODEL, a British software application. The draft of the new *Highway Capacity Manual* includes a simplified version of the gap-acceptance method from Australia for single-lane roundabouts. This analytical method estimates the capacity of each roundabout entrance based on gap acceptance for entering traffic. Most other countries use statistically derived empirical formulas expressing the capacity of each approach in relation to the circulating traffic and to geometric parameters of the roundabout.

Some concerns were raised regarding pedestrians at roundabouts, especially with regard to the absence of clear right-of-way control. This perceived problem is related to some degree to the belief by the general public that signalized intersections bring the greatest safety to pedestrians. These concerns tend to disappear after the pedestrians have an opportunity to use the roundabout. Public opinion surveys show that the attitude of users is generally positive after the roundabout installation.

For bicyclists, the preferred arrangement in the case of single-lane and low-speed roundabouts is to stop bicycle lanes before they reach the roundabout and to let bicycles circulate in mixed traffic through the circle. For larger, multi-lane roundabouts, it appears preferable to provide separate bike paths, or to provide for mixed bicycle/pedestrian paths, or reroute bicyclists.

To conclude, roundabouts can have significant benefits in terms of safety, delays, and capacity. Another major new benefit is related to the aesthetic and urban design improvements resulting from the landscaping and sculptural elements in the central island.

Roundabouts can bring a sense of place to an intersection and improve the visual quality for drivers as well as for the non-driving public.

Among the most appropriate applications for roundabouts are locations where there is insufficient space for queue storage or where it would be expensive to provide for the storage space required by a signalized intersection. These locations include interchanges and intersections near tunnels and bridges. Other appropriate locations are intersections with high accident rates, especially accidents related to cross-movements or left-turns. Roundabouts are also appropriate where a change in roadway character occurs or is desired, such as the entrance to a community or where a bypass road connects to an arterial road.

National design guidelines will be helpful in assisting the states and other government agencies to build safe and effective roundabouts. The survey undertaken for this synthesis also found that research is needed to determine the best methods to estimate roundabout capacities in the United States and to assist in the design of roundabouts.

CHAPTER ONE

INTRODUCTION

BACKGROUND

Although the United States was home to the first one-way rotary system in the world (implemented around New York City's Columbus Circle in 1904), traffic circles had fallen out of favor in this country by the 1950s. Older traffic circles, located primarily in the northeastern states, encountered serious operational and safety problems, including the tendency to lock up at higher volumes. The modern roundabout, although following different design principles from those of the old circles, has been notably less popular in the United States than abroad, in part because of this country's experience with the traffic circles and rotaries built in the first half of the 20th century.

Since 1990, however, there has been an emergence of the modern roundabout in some parts of the United States. The strong interest expressed in this type of intersection in recent years is partially due to its success in several countries in Europe and in Australia, where the modern roundabout has changed the practice of intersection design. France, which leads the world with an estimated 15,000 modern roundabouts, has been building them at a rate of about 1,000 per year *(1)*. By comparison, the United States' inventory of such intersections, although growing, remains small. As of mid-1997, there were fewer than 50 modern roundabouts in the United States, in contrast with more than 35,000 in the rest of the world.

The purpose of this synthesis is to report on the use and performance of the modern roundabouts that have been recently built in the United States, to describe the design principles used, and to compare the U.S. experience with the practice in other countries.

DEFINITIONS

"Nonconforming" Traffic Circles

The early traffic circles often incorporated one or several problematic operational or design elements that would not be permitted in a modern roundabout. For example:

- *Entering traffic had right-of-way*—At higher volumes this locks up the circle.
- *Entries were regulated by stop signs or traffic lights*—This reduces fluidity and capacity.
- *Entries were tangential to circle*—This encourages high entering speeds and reduces the safety benefits.
- *Pedestrians crossed onto the central island*—This is unsafe for pedestrians and disruptive for drivers.
- *The through road cut through the circle*—Capacity, fluidity, and safety benefits are lost by the need to signalize the central intersection.
- *Circulating traffic was controlled by a traffic signal or stop sign*—This decreases the fluidity of circulating traffic and can lock up the circle.
- *Parking was permitted in the circle*—This reduces the capacity and safety of the circle by adding friction and conflicts.

Among the more notable nonconforming traffic circles are:

- Dupont Circle in Washington, D.C.—where entries are regulated by a mixture of traffic lights, stop and yield signs, the circle includes a weaving section, and pedestrians walk onto the central island;
- Columbus Circle in New York City—where traffic lights control the entries, the circle is cut by through traffic, and pedestrians walk onto the central island; and
- Place Charles de Gaulle in Paris, formerly known as Place de l'Etoile—where entering traffic has priority, and police officers regulate traffic in the circle.

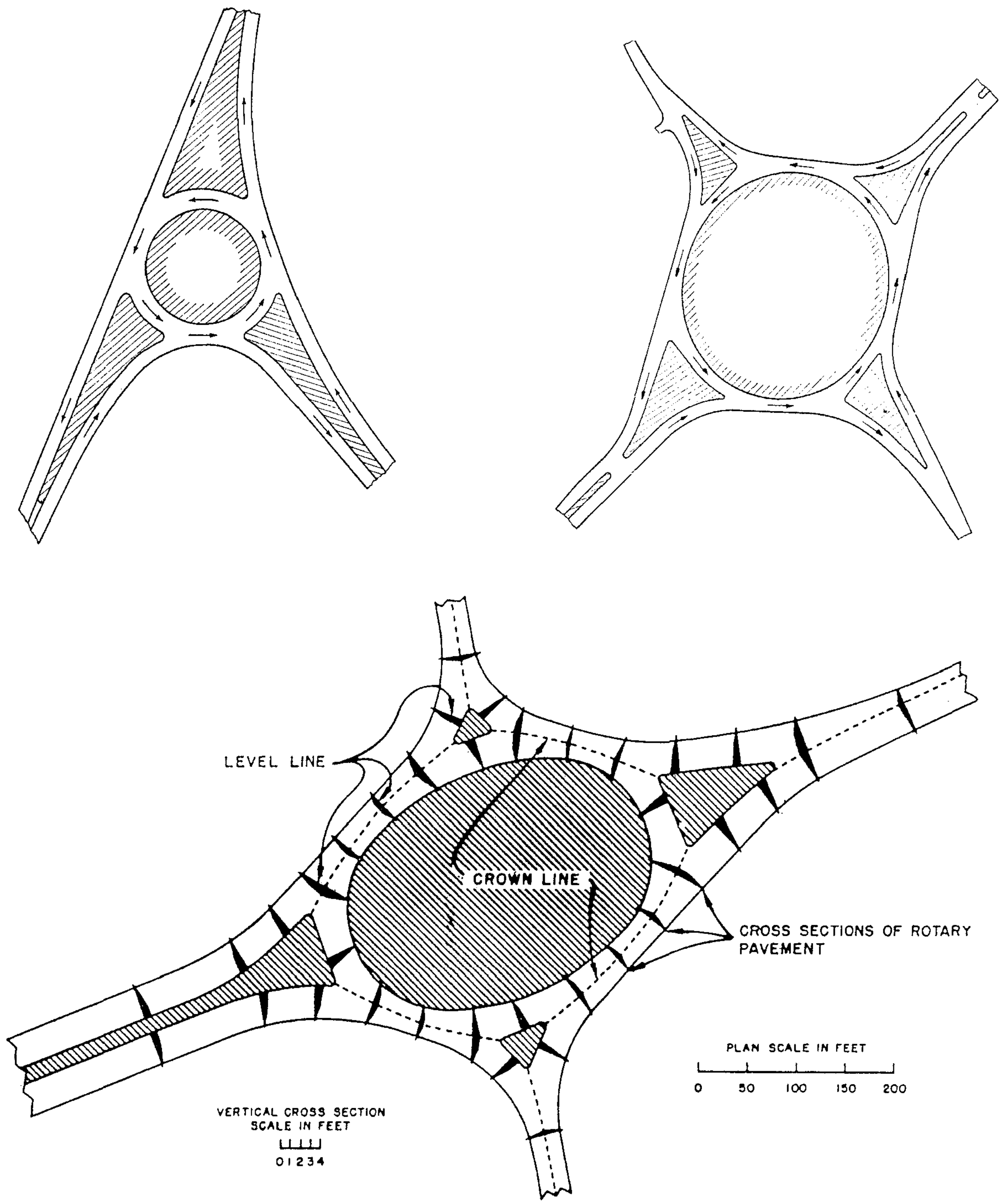
Figure 1 shows examples of old rotary designs. Generally, the design objective was to maintain fluidity for the major traffic movements and to maximize the weaving distances *(2)*.

Definition of Modern Roundabouts

The term *modern roundabout* is used in the United States to differentiate it from the nonconforming traffic circles or rotaries that have been in use for many years, primarily in the Northeast. Modern roundabouts are defined by two basic operational and design principles (illustrated in Figure 2):

1. Yield-at-Entry: Also known as off-side priority or yield-to-left rule, yield-at-entry requires that vehicles in the circulatory roadway have the right-of-way and all entering vehicles on the approaches have to wait for a gap in the circulating flow. To maintain fluidity and high capacity, the entry control is a YIELD sign. As opposed to nonconforming traffic circles, modern roundabouts are not designed for weaving movements, thus allowing smaller diameters. Even for multi-lane roundabouts weaving movements are not considered a design or capacity criterion.
2. Deflection for Entering Traffic: No tangential entries are permitted, and no traffic stream gets a straight movement through the intersection. Entering traffic points toward the central island, which deflects vehicles to the right, thus causing low entry speeds.

To provide for increased capacity, the modern roundabout often incorporates flares at the entry by adding lanes before the yield line, and has a wider circulatory roadway (see Figure 3).

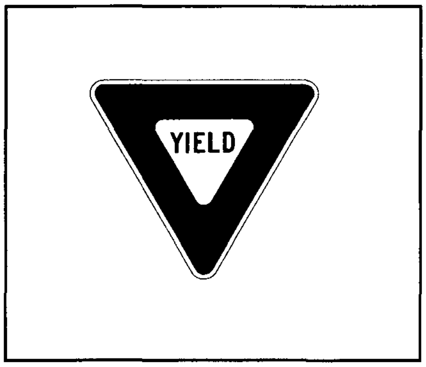


ROTARY PAVEMENT CROSS SLOPES AND CROWN LINE

FIGURE 1 Examples of old rotary designs *(2)*.

Modern roundabouts range in size from mini-roundabouts (with outside diameters as small as 15 m [50 ft]), to compact roundabouts with outside diameters between 30 and 35 m (98 to 115 ft), to large, often multilane, roundabouts (up to 150 m [492 ft] in diameter) with more than four entries and two-bridge grade-separated roundabouts, located over or under freeways. The greater speeds permitted by the larger roundabouts (with outside diameters greater than 75 m [246 ft]) reduce the safety benefits to some degree.

Mini-roundabouts and traffic calming circles are typically retrofitted within existing intersections. Mini-roundabouts have one-way circulation around a flush or slightly raised central island less than 4 m (13 ft) in diameter. They may also have flared entries to provide higher capacity. Because of their flush, drivable central island, mini-roundabouts can be installed in the smallest of intersections. Whatever space is available for truck turns before conversion of an intersection to a mini-roundabout remains available after conversion. The



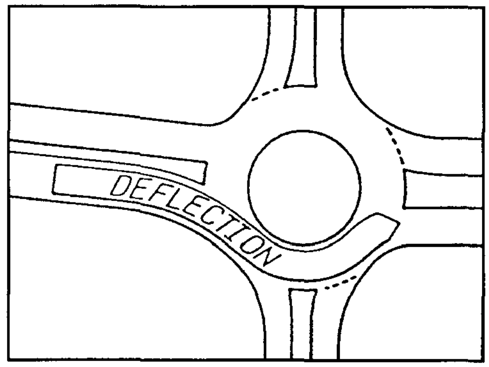


FIGURE 2 Yield-at-entry and deflection of entering traffic.

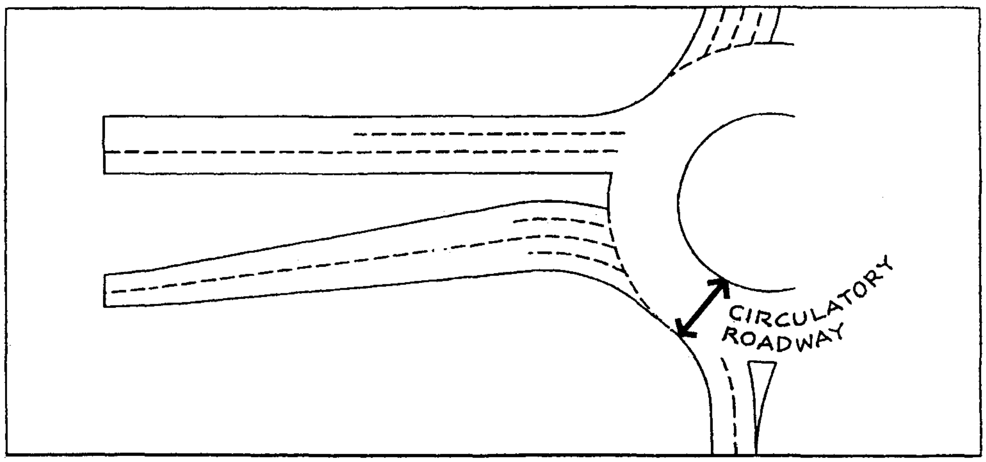


FIGURE 3 Flare-at-entry.

traversable central islands of mini-roundabouts do not force deflection of through traffic. Mini-roundabouts thus are generally more appropriate for areas where approach speeds are limited to approximately 50 kmph (30 mph) *(3)*.

Mini-roundabouts are a type of modern roundabout. Some of them, with two-lane entries, are used as medium-capacity intersections of arterial roads. To date none have been built in the United States, but they are used in other countries.

By contrast, traffic calming circles, sometimes referred to as "Seattle circles," have raised central islands to impose the deflection on through traffic. However, Seattle circles are not considered roundabouts because they permit left-turning vehicles, in particular buses and trucks, to turn in front of the central island. Figure 4 shows a Seattle-type traffic calming circle *(4)*.

This synthesis addresses "normal" roundabouts, roundabouts with raised central islands larger than 4 m (13 feet). Mini-roundabouts and traffic calming circles are not the subject of this report.

FIGURE 4 Seattle-type traffic calming circle *(4)*.

Basic Geometric Elements of Modern Roundabouts

Figure 5 shows the following typical geometric elements of a roundabout:

- Approach width—The one-way width of the roadway approaching the roundabout. British engineers define this as the approach half-width.
- Departure width—The one-way width of the roadway departing from the roundabout.

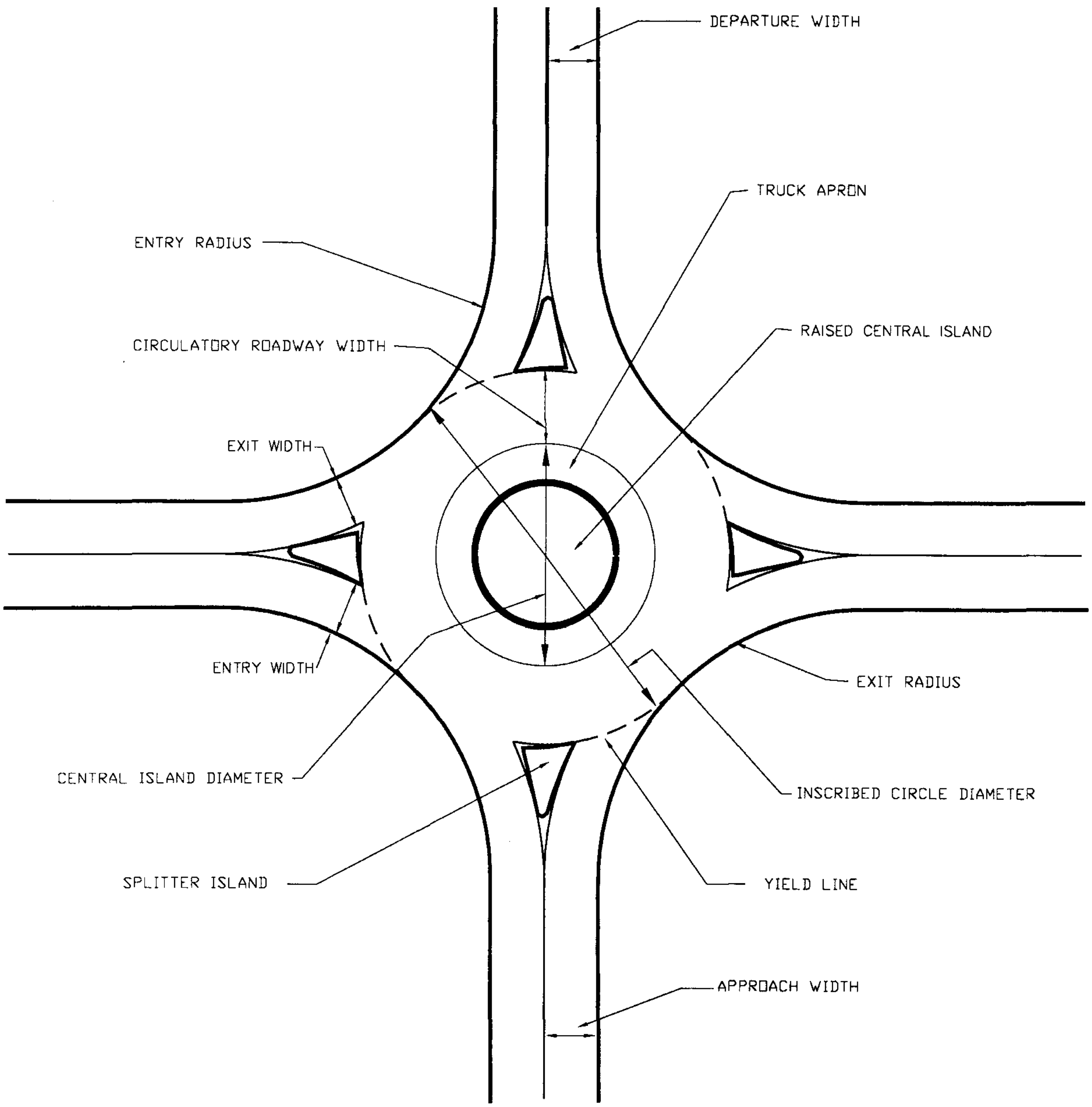


FIGURE 5 Geometric elements of a roundabout.

- Central island—The circular central island around which traffic circulates. This island can be raised or flush (for mini-roundabouts), or it can have a raised central island with a mountable or drivable apron surrounding it. The truck apron is generally included in the central island diameter.
- Circulatory roadway—The roadway around the central island on which circulating vehicles travel in a counterclockwise direction.
- Entry width—This width is measured perpendicularly from the right curb line of the entry to the intersection of the left edge line and the yield line.
- Exit width—This width is measured perpendicularly from the right curb line of the exit to the intersection of the left edge line and the inscribed circle.
- Entry radius—Measured as the minimum radius of curvature of the right-side curb at entry.
- Exit radius—The minimum radius of curvature of the right-side curb at exit.
- Inscribed circle diameter—The circle that can be inscribed within the outer curb line of the circulatory roadway.
- Splitter island—The raised island sometimes called separator island, placed within a leg of a roundabout, separating entering and exiting traffic. It is designed to deflect entering traffic and as a safety zone for pedestrian crossings. As the approach speeds increase, the splitter islands become longer.
- Truck apron—The portion of the central island that is drivable, and is specifically provided to accommodate the path of the rear left wheels of larger vehicles. The truck apron is generally constructed with a different material to discourage passenger cars from driving over it.
- Yield line—A broken line marked across the entry roadway where it meets the outer edge of the circulatory

roadway and where entering vehicles wait, if necessary, for an acceptable gap to enter the circulating flow.

The typical, single-lane roundabout shown in Figure 5 does not incorporate any features for pedestrians or for bicyclists. These design features are addressed in chapter 8. Other geometric elements, not shown in Figure 5, need to be taken into consideration for the design of roundabouts, for example, cross-slope of the circulatory roadway, grades at the approaches, and sight distance requirements. Other design elements, such as the entry angle, the design of flares, and the length of the splitter island along the inscribed circle, can affect the capacity and safety of the roundabout.

SYNTHESIS CONTENT AND FORMAT

This introduction has presented a brief overview of modern roundabouts and explained the differences between modern roundabouts and nonconforming traffic circles. Chapter 2 describes the history of the modern roundabout, placing it in the context of the evolution of traffic circles in the United States. Chapter 3 outlines the results of the survey of various state departments of transportation and various municipalities concerning their experience with roundabouts. In chapters 4 through 7, the main conclusions of the survey are described, and comparisons are made between roundabout design, safety, and capacity methodologies in the United States and those of other countries. Issues relating to pedestrians, bicycles, and visually impaired users are discussed in chapter 8. Chapter 9 describes appropriate and inappropriate locations for modern roundabouts based on the literature review and the survey results. Three examples of different roundabout applications in the United States are included. In chapter 10, conclusions are presented regarding the development of this type of intersection in the United States.

CHAPTER TWO

HISTORY AND EVOLUTION OF ROUNDABOUTS

THE OLD TRAFFIC CIRCLES

The history of the modern roundabout, and in particular its evolution from the old traffic circles and rotaries built in the first half of the 20th century, explains to a large degree its current status in the United States, and particularly the negative perception of roundabouts held by many traffic engineers and the general public.

The idea of a one-way rotary system was first proposed in 1903 for Columbus Circle in New York City by William Phelps Eno, "the father of traffic control" *(5)*. Other circular places existed prior to 1903; however, they were built primarily as architectural features and permitted two-way circulation around a central island. One-way circulation was implemented around Columbus Circle in November 1904. (Figure 6 shows a photograph of Columbus Circle in New York City, circa 1915.) Eno was a strong advocate of one-way streets and gyratory systems. The traffic circles that he recommended often had relatively small central islands, sometimes consisting only of an iron disc, 1.50 m (5 ft) or less in diameter, with electric lights or reflectors fitted on the side.

In 1906, Eugène Hénard, the Architect for the City of Paris, proposed a gyratory traffic scheme (one-way circulation around a central island) for some major intersections in Paris (see Figure 7). In 1907 the Place de l'Etoile became the first French gyratory, followed by several others built in 1910. Eno also submitted several gyratory intersection designs to the authorities in Paris. A lively debate arose as to who was the inventor of the gyratory: Hénard or Eno. It appears that each arrived at the concept of the gyratory traffic movement independently. One important difference between their designs was the size of the central island of the roundabout: Hénard felt that it should be a minimum of 8 m (26 ft) in diameter, in contrast to Eno's smaller iron disk *(5)*.

No consistent right-of-way rules were adopted in those years. In New York City, for example, the north-south and south-north traffic had priority over east-west and west-east traffic. Practices differed in other places in the United States. Some U.S. courts decided that the "first-in" rule would be the most practical. In general, the right-of-way rule was not too critical in the early days because traffic volumes were fairly low. Wisconsin, in 1913, was the first state to adopt the yield-to-right rule, meaning entering vehicles had the right-of-way. The yield sign, however, was unknown in the United States until the early 1950s.

In 1929, Eno pointed out the main drawback of the yield-to-right rule (i.e., that traffic locks up at higher volumes) and recommended changing to the yield-to-left rule. He was not, however, able to convince the traffic engineering community to implement such a change. From the early 1920s onward, in conjunction with a rapidly developing automobile technology, the design philosophy instead evolved to allow higher speeds through the intersection, and to create larger circles with longer weaving distances and the yield-to-right rule to prevent rear-end collisions at the entrance. The longer storage distance between successive entries and exits reduced the locking problem.

As traffic volumes increased, however, more and more traffic circles locked up. At the Ellisburg traffic circle in New Jersey, traffic would lock up at hourly volumes ranging from 4,400 to 5,600 vehicles, and traffic often remained at a standstill until the police intervened. This circle has an elliptical shape with outside diameters of 130 m and 99 m (436 ft and 325 ft). Reluctant to reverse the right-of-way rule, the highway department installed a $270,000 computerized signal system yielding an hourly capacity of 4,400 vehicles *(5)*. Other traffic circles, such as the Hawthorne Circle in Westchester County, New York, were replaced with grade-separated interchanges.

In the 1950s, traffic circles fell out of favor in the United States largely because of the locking problem. In many cases they were replaced with signalized intersections, or signals were simply added to the circle. Between 1950 and 1977, eight jurisdictions passed laws to reverse the right-of-way rules that gave priority to the vehicles in the circle. But signals generally were not removed from traffic circles.

In France, the large sizes of the circles, the desire to maintain relatively high speeds, and the priority to the right became major impediments to safety and high capacity. The original gyratory at the Place Charles de Gaulle (formerly the Place de l'Etoile) became the symbol of traffic congestion in Paris.

THE BEGINNINGS OF THE "MODERN ROUNDABOUT"

Progress in roundabout design began early in Great Britain, where one-way streets and gyratory systems had existed since the mid-1920s, partially as the result of the consulting work by Eno. It was also in Great Britain where the term "roundabout" was officially adopted in 1926 to replace the term "gyratory." In the 1950s, British traffic engineers started questioning the American practice of large circles, arguing that long weaving sections, combined with the higher speeds made possible with the larger radii, were detrimental to high capacities. The American view that weaving volumes in excess of 1,500 hourly vehicles were impractical was challenged in Great Britain, although British traffic engineers continued analyzing roundabout capacity in terms of weaving capacity *(7)*.

In Great Britain there are no priority rules at uncontrolled intersections. The requirement to exercise due care has been mentioned as one of the reasons for the high degree of courtesy

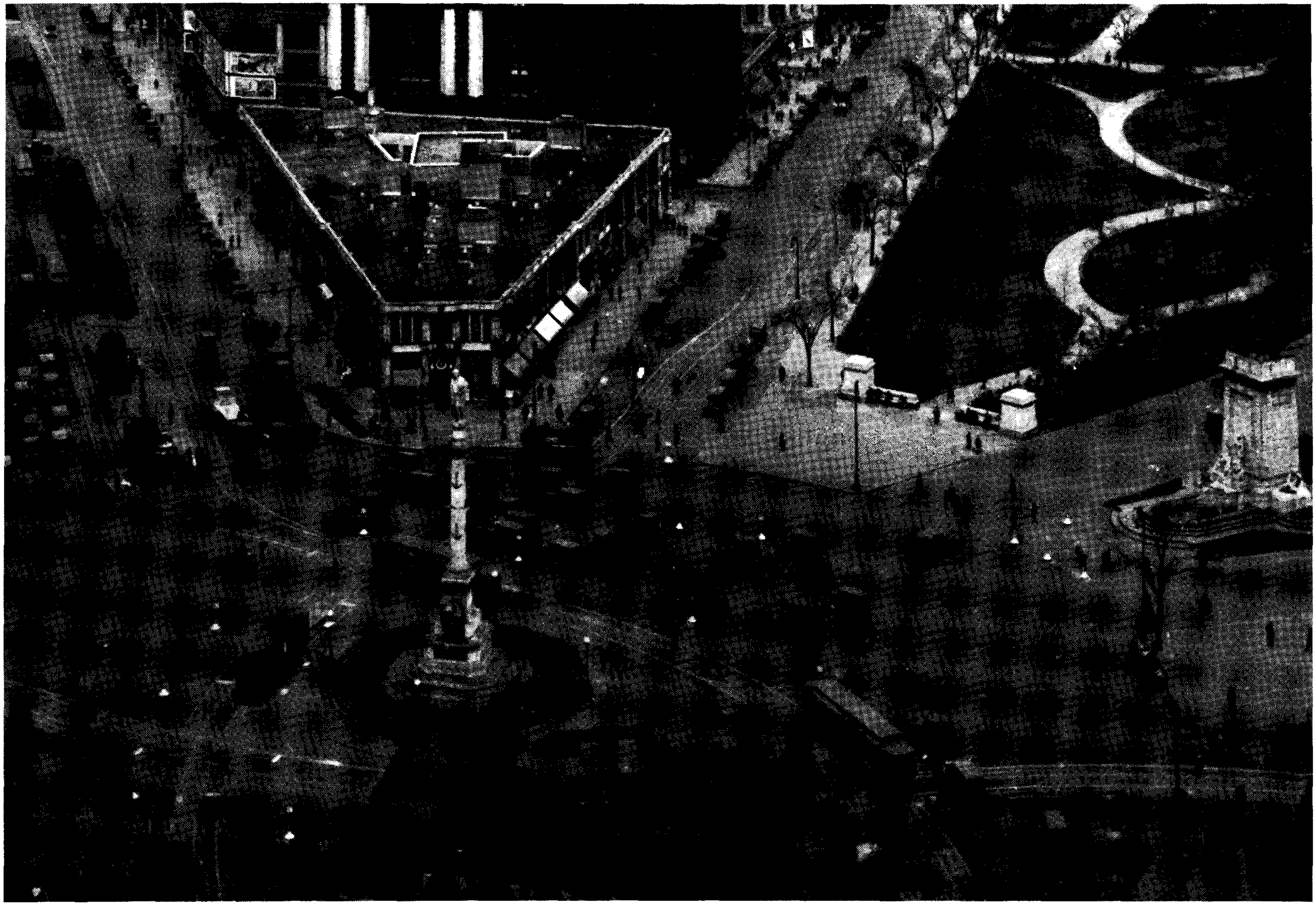


FIGURE 6 View of Columbus Circle, circa 1915 *(Courtesy of the New York City Department of Planning).*

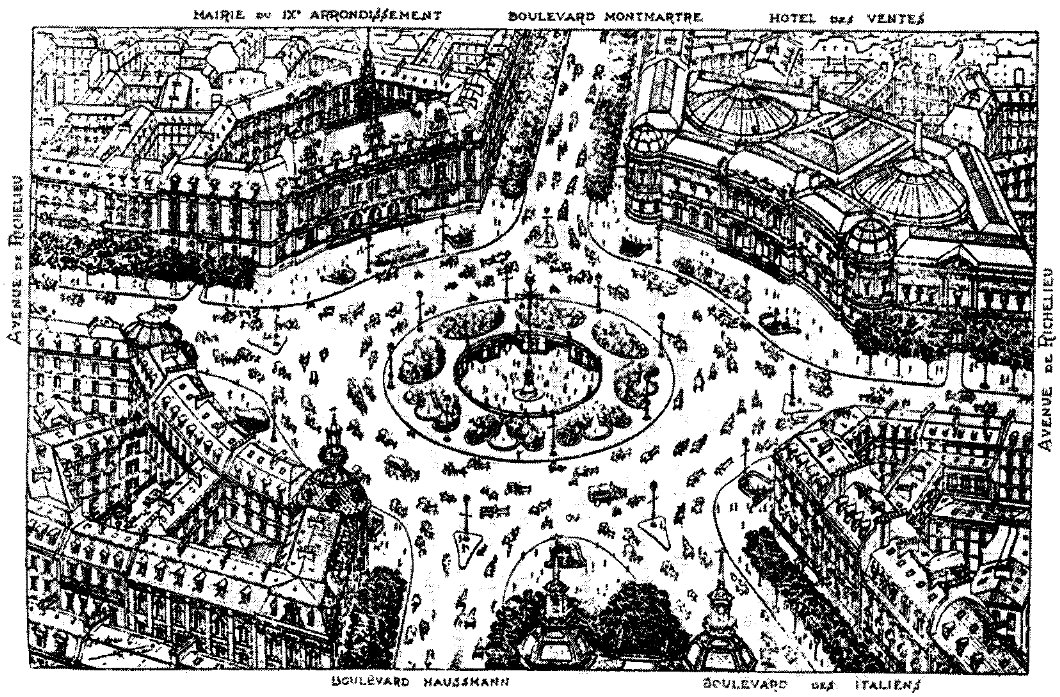


FIGURE 7 View of giratory intersection of the "Grands Boulevards" in Paris *(6)*.

on British roads. As more roundabouts became congested, some municipalities installed signs at the entrances to roundabouts asking drivers to give way to the vehicles in the roundabout. Tests and research by the Road Research Laboratory (now the Transport Research Laboratory) found that the "priority-to-the-circle" rule (also known as "off-side" priority) increased capacity by 10 percent and reduced delays by 40 percent in comparison to the other options—no control, police control, or signal control. Injury accidents decreased by 40 percent *(7)*.

The off-side priority rule was officially adopted for roundabouts in Great Britain in 1966. From then on, roundabout design changed from larger circles with emphasis on merging and weaving to smaller roundabouts where the driver's task was to accept a gap in the circulating flow. Capacities of large roundabouts were increased by 10 to 50 percent by reducing the size of the central island, bringing the yield line closer to the center of the circle, and widening the entries to the roundabout. In some cases the roundabout capacity was increased to the degree that the capacity of the links between the intersections became the limiting factor for the network capacity. The first design guidelines for off-side priority roundabouts were issued in 1971 by the British Ministry of Transport, followed by revised guidelines in 1975, 1984, and 1993 *(7)*.

Roundabouts were "exported" to Australia and some communities in France in the 1970s, and then to a larger number of countries in the 1980s. In 1984, the French government adopted the off-side priority rule for roundabouts on national highways, meaning that entering traffic had to yield to traffic in the circle, even if the entering road was a national highway. This represented a major shift in French driving laws where "priority-to-the-right" had always been a basic rule.

As of mid-1997, there are about 15,000 modern roundabouts in France *(1)*. Other European countries have also adopted this form of intersection as a standard design solution. In addition to their popularity in Great Britain and France, roundabouts are very common in Germany, Switzerland, the Benelux countries, the Nordic countries, Spain, and Portugal. Outside of Europe the modern roundabout is a standard feature in Australia, and it is becoming more common in New Zealand, South Africa, and Israel.

WHY HAVE ROUNDABOUTS BEEN SO SUCCESSFUL IN EUROPE?

Capacity and Fluidity

The high capacity and fluidity achieved by the modern roundabout are two main reasons for its success. Especially in Great Britain, where the design criteria put major emphasis on the capacity of the roundabout, the resulting throughput is substantial. It is not uncommon in Great Britain to have roundabouts carrying more than 6,000 vehicles per hour *(7)*.

Safety

The substantial reduction in injury accidents has been the primary reason for the great success of modern roundabouts in France and in Germany. A 1996 article in the French daily *Le Monde* attributes the overall reduction in injuries and fatalities on French highways at least to some degree to the introduction of roundabouts *(8)*. A promotional brochure on the roundabout by the German automobile club ADAC also mentions the improved safety of the design as a major advantage *(9)*.

Shorter Delays and Reduced Environmental Impacts

The fact that drivers do not have to wait as long at roundabouts as at signalized intersections makes the roundabout friendlier to both the driver and to the environment. The reduced amount of paved areas, as well as the reduction in noise and air pollutant emissions, are also cited in the European literature as advantages for roundabouts *(10–12)*. Field measurements in Sweden showed reductions in pollutant emissions and fuel consumption in the range of 21 to 29 percent *(13)*.

(Before)

(After)

FIGURE 8 Before and after views of intersection in Brühl, Germany *(11)*.

Aesthetics and Urban Design

The capability of the modern roundabout to improve the visual quality of the transportation infrastructure is a major reason why it has gained widespread support from urban planners, politicians, and residents. The Swiss Roundabout Guide describes the roundabout as an opportunity and tool to harmonize the circulation requirements with the urban and environmental design objectives *(10, page F1)*. The European guides *(10–12)* emphasize the monumental aspect, the simple form, and the architectural integration into the environment as positive elements. Figure 8 shows "before-and-after" views of an intersection in Germany. Figures 9, 10, and 11 show examples of roundabouts in France and Luxembourg with particular aesthetic treatments.

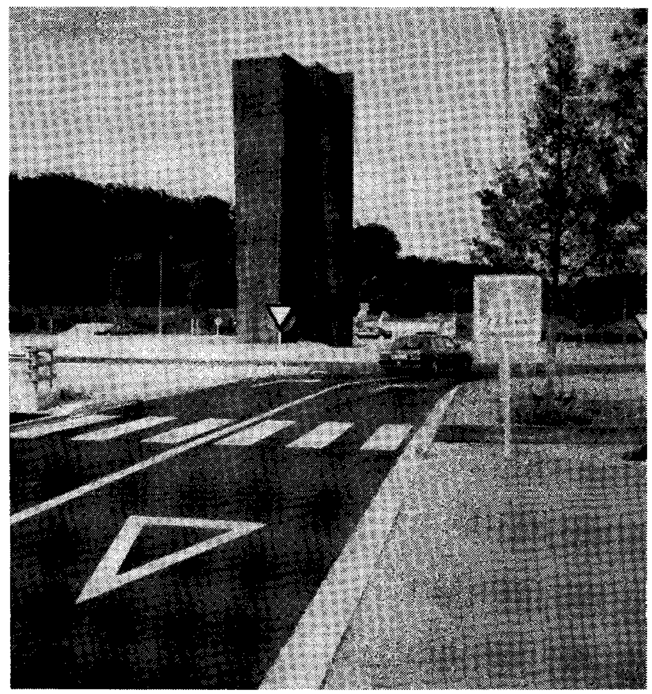


FIGURE 9 Roundabout Kirchberg, Luxembourg.

ROUNDABOUTS IN THE UNITED STATES

A few pioneers started to advocate use of the new roundabouts in the United States almost 20 years ago. An article by Ken Todd describing the roundabout evolution in Great Britain appeared in the *Institute of Transportation Engineers Journal* in July 1979 *(14)*. About 10 years ago a few engineers on the East Coast and the West Coast started designing the first modern roundabouts in the United States. In March 1990, the first two U.S. roundabouts, designed by Leif Ourston & Associates, were built in Summerlin, Nevada. The Gainesville, Florida roundabout built in 1992, with design assistance from M. Wallwork, was the first in the United States to replace a traffic signal. The I-70/Vail Road interchange, completed in October 1995, is the first retrofitted two-roundabout interchange in the United States. Designed by Leif Ourston & Associates in association with Alpine Engineering Inc., it is a diamond interchange with a roundabout at each of the two intersections formed by the on- and off-ramps. In 1997, the Town of Avon, Colorado built a string of five roundabouts

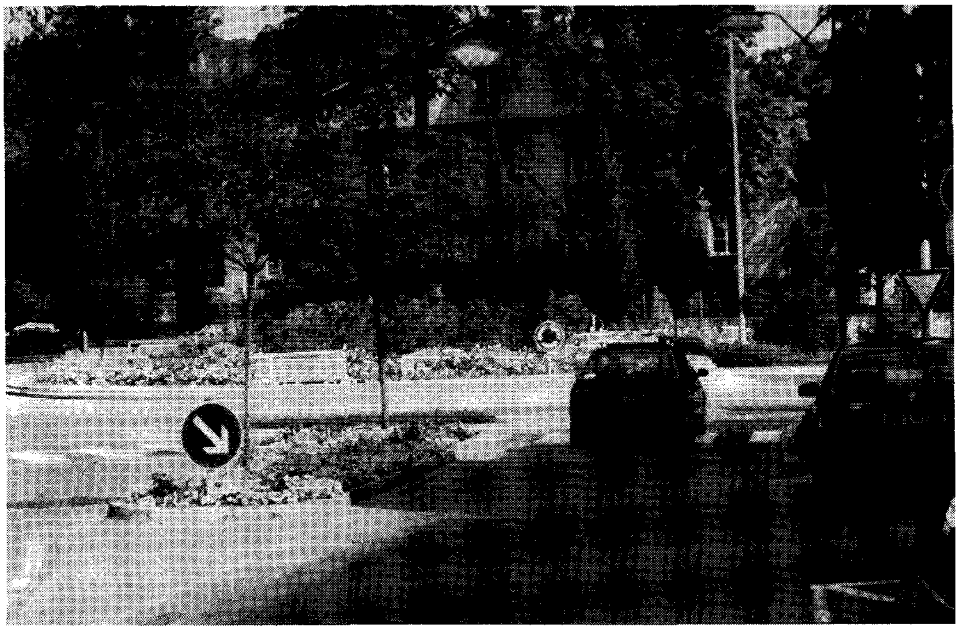


FIGURE 10 Roundabout Walferdange, Luxembourg.

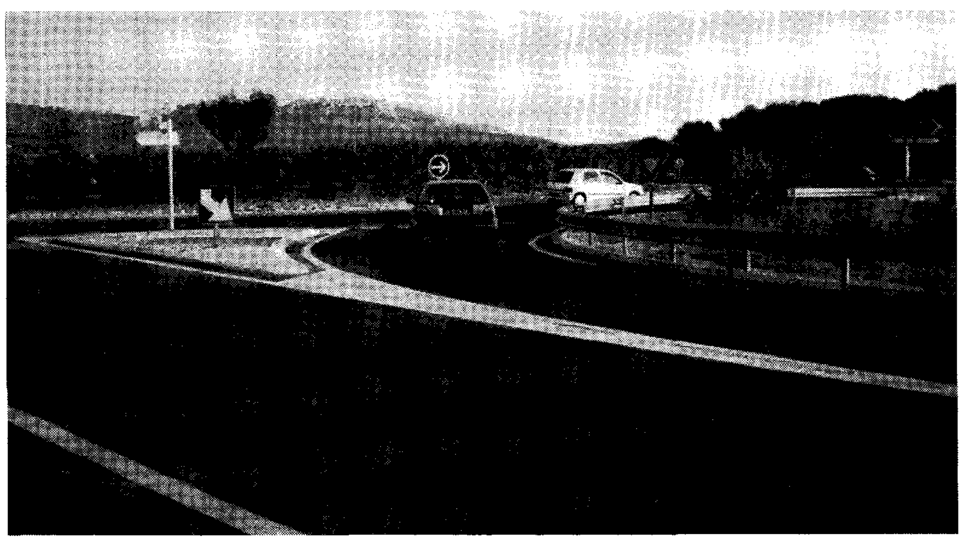


FIGURE 11 Roundabout in Le Beausset in Vars Department, France.

along Avon Road with a common cultural and landscaping theme. Designed by Ourston & Doctors, two of these roundabouts replaced stop-controlled intersections and three replaced traffic signals.

Table 1 lists 38 modern roundabouts, with their key characteristics, in operation in the United States as of October 1997. An attempt is made to list all existing roundabouts, including some for which no survey responses were returned. Table 2 in chapter 3 lists only those roundabouts, both existing and in the design stage, for which survey responses were obtained.

Appendix A includes layouts of a few typical roundabouts that have been built in recent years. In addition, chapter 9 describes three roundabout cases in more detail: Lisbon, Maryland; Long Beach, California; and Vail Road/I-70 in Vail, Colorado.

Of the 38 roundabouts listed in Table 1, not all rigorously satisfy all the design criteria for modern roundabouts. In a few examples, because of physical constraints or design objectives, the deflection of one or more approaches may be less than desirable, or the inscribed circle diameter may be greater than desirable. However, each of these roundabouts still satisfies the *general* design objectives of a modern roundabout. In addition, there are older traffic circles or rotaries that meet most of the design criteria of modern roundabouts. Some of these are larger than would be built today, but they have off-side priority and deflection for entering vehicles.

TABLE 1

MODERN ROUNDABOUTS IN OPERATION IN THE UNITED STATES AS OF OCTOBER 1997

State	City/Town	Intersection	No. of Legs	Inscribed Diameter (m)	Previous Traffic Control	Peak Hour Total Approach Volume	Date of Completion
California	Long Beach	Rte 1/19/Los Coyotes	4	143	Free Merge	4,700 (1994)	June 1993
	Santa Barbara	Five Points/Rte 144/ Alameda	5	26	All-Way Stop	1,500 (1994)	November 1992
Colorado	Vail	I-70/Vail Road N	5	37	One-Way Stop	1,900 (1995)	October 1995
		I-70/Vail Road S	6	61	One-Way Stop	3,400 (1995)	October 1995
	Vail	I-70/Chamonix N	6	46	Two-Way Stop	2,300 (1996)	1997
		I-70/Chamonix S	6	46	Two-Way Stop	2,000 (1996)	1997
	Avon	I-70/Avon Road N	4	46	Two-Way Stop	1,400 (1996)	1997
		I-70/Avon Road S	4	46	Two-Way Stop	2,100 (1996)	1997
		Avon Rd/Beaver Creek	4	46	Signal	3,000 (1996)	1997
		Avon Rd/Benchmark Rd.	4	44	Signal	2,200 (1996)	1997
		Avon Rd/US Rte 6	4	44	Signal	2,500 (1996)	1997
	Nederland	Highway 72/Rte 119	5	30	Two-Way Stop	1,100 (1996)	June 1995
Florida	Ft Walton Beach	Hollywood/Doolittle	3	31	One-Way Stop	1,200 (1993)	May 1994
	Bradenton Beach	SR 789/Bridge St	4	20	Two-Way Stop	850 (1995)	August 1994
	Tallahassee	Killarney/Shamrock	3	42/28	One-Way Stop	1,800 (1994)	August 1994
	Palm Beach Co.	Boca Raton/Cain Blvd	4	31	Two-Way Stop	650 (1995)	November 1994
	Gainesville	SE 7th St/SE 4th Ave	4	23	Signal	550 (1994)	April 1992
	Naples	7th Ave N/7th St	4	21	Two-Way Stop	600 (1996)	April 1995
	Naples	7th Ave N/3rd St	4	18	Two-Way Stop	600 (1996)	April 1995
	Tampa	North Blvd/ Country Club	4	21	Signal	1,500 (1996)	June 1996
Maryland	Gaithersburg	Longdraft/Kentlands	4	41			November 1993
	Lisbon	MD-144/MD-94	4	31	Two-Way Stop	630 (1995)	April 1993
	Cearfoss	MD-63/MD-58/MD-494	4	37	Two-Way Stop	800 (1995)	December 1995
	Leeds	MD-213/Elk Mills	4	34	Two-Way Stop	800 (1994)	August 1995
	Lothian	MD-422/MD-2/MD-408	4	37	Two-Way Stop	1,400 (1995)	October 1995
	Taneytown	MD-140/MD-832	4	46	Two-Way Stop	1,300 (1996)	August 1996
Mississippi	Jackson	MS475/Airport Rd./Old Brandon	4	37	Four-Way Stop	2,300	October 1997
Nevada	Las Vegas	South Roundabout	4	91	New	1,000	March 1990
		North Roundabout	4	61	New	1,000	March 1990
		Banbury Cross	4	61			December 1994
		Hualapai	4	82			March 1995
		Lake South/Crystal Way	4	25	Two-Way Stop	400	August 1994
		Michael/Harmony	3		One-Way Stop	300	August 1993
South Carolina	Hilton Head	Main/Whooping Crane	4	34	Signal	1,800	February 1996
Texas	Addison	Addison Circle	4	61			1997
	Olmos Park	Olmos/El Prado	5	32	Signal	1,700	July 1996
Vermont	Montpelier	Main/Spring	3	34	One-Way Stop	1,000	August 1995
	Manchester	Rte 7A/Grand Union	4	34	Two-Way Stop		October 1997

CHAPTER THREE

USE OF ROUNDABOUTS IN THE UNITED STATES: SURVEY RESULTS

SURVEY METHODOLOGY

In the spring of 1997, a survey was undertaken to learn about the status of roundabouts in North America, and the experience and perceptions of local and state transportation agencies concerning their use. A survey questionnaire was mailed to each state department of transportation in the United States, to each province in Canada, and to 26 U.S. municipalities and counties known to have roundabouts. The survey questionnaire was structured to obtain information about each jurisdiction's practices regarding roundabouts in general, and about those roundabouts that were in place, under construction, or in the design stage. Those states and provinces that had no roundabouts (either completed or planned) were asked why this type of intersection had not been built or designed in their jurisdiction. Appendix B is a copy of the survey questionnaire.

A total of 44 state departments of transportation in the United States responded to the survey. Nine of these states reported roundabouts in operation, under construction, or in design: California, Colorado, Kansas, Maine, Maryland, Massachusetts, Mississippi, New Jersey, and Vermont. There are also roundabouts in other states, as shown in Table 1. These were not reported on the survey, either because they are not on state highways or because the state did not respond to the survey.

Information was thus received on 31 roundabout cases, representing a total of 38 individual roundabouts. Three of the cases involved two-roundabout interchanges and one case involved a string of five roundabouts. Of the 38 individual roundabouts reported on, 28 were operating, one was under construction, and the remaining nine were in the design stage. The 28 existing roundabouts in the survey represent more than two-thirds of the roundabouts known to exist in the United States. Six survey responses were received from the Canadian provinces; however, none of them indicated that they have modern roundabouts.

Table 2 lists the responses received from jurisdictions providing information on individual roundabouts. (Note that Table 2

TABLE 2

SURVEY RESPONSES FROM JURISDICTIONS WITH ROUNDABOUTS

Cases	Existing (Oct. 1997)	Under Construction	In Design	Prior Traffic Control	Special Note
Los Alamitos Circle, Long Beach, Calif.	X			Old Traffic Circle	Traffic Circle Conversion
Five Points, Santa Barbara, Calif.	X			Five-Way Stop	
I-70/Vail Rd., Vail, Colo.	X			TWSC/FWSC	Two-Roundabout Interchange
I-70/Chamonix Rd., Vail, Colo.	X			TWSC/FWSC	Two-Roundabout Interchange
Avon Road, Vail, Colo.	X			Various	Sequence of 5 Rdbts. incl. Interchange
Rte 72/119, Nederland, Colo.	X			TWSC	
Rte 202/4/237, Gorham, Maine		X		TWSC	
Rte. 94/144, Lisbon, Md.	X			TWSC	
Rte 140/832, Taneytown, Md.	X			TWSC	
Rte 63/58, Cearfoss, Md.	X			TWSC	
Rte 2/408/422, Lothian, Md.	X			TWSC	
Rte 213/Leeds/Elk Mill, Leeds, Md.	X			TWSC	
Ft. Wash. Rd., Pr. Georges Cty., Md.	X			One-Way Stop	Converted from 3 to 4 legs
Tollgate Rd., Harford Co., Md.	X				New Intersection
Baneker Rd., Howard Co., Md.	X				
Trotter Rd., Howard Co., Md.	X			One-Way Stop	T-intersection
I-70/Rice Rd., Interchange, Kansas			X		New Interchange
Rte. 67A, Bennington, Vt.			X	TWSC	
Rte. 9/5, Brattleboro, Vt.			X	Signal	
Rte. 2/117/I-89, Richmond, Vt.			X	TWSC	One-Roundabout Interchange
Rte. 7A, G. Union, Manchester, Vt.	X			TWSC	
Rte. 7A, Equinox, Manchester, Vt.			X	TWSC	
Rte. 108, Stow, Vt.			X	TWSC	Smugglers Notch Scenic Highway
Main/Spring St., Montpelier, Vt.	X			One-Way Stop	T-intersection
Brielle Circle, Wall, N.J.			X	Old Traffic Circle	Traffic Circle Conversion
Red Lion Circle, Southampton, N.J.			X	Old Traffic Circle	Traffic Circle Conversion
Rte. 475/Old Brandon Rd., Miss.	X			FWSC	
SE4/7 St, Gainesville, Fla.	X			Signal	
N. Blvd., Tampa, Fla.	X			Signal	
Whopping Crane, Hilton Head, S.C.	X			Signal	
McCullough/Olmos Dr., Olmos Park, Tex.	X			Signal	Temporary Roundabout/Permanent 98

is different from Table 1 in that it lists only those roundabouts for which some survey information was obtained.) Most of the roundabouts surveyed had been converted from two-way stop-controlled (TWSC) intersections. Five of the 31 cases were previously signalized intersections, and 3 cases were old traffic circles being converted to modern roundabouts.

GENERAL CHARACTERISTICS OF U.S. ROUNDABOUTS

Environment, Roadway Type, and Traffic Characteristics

Table 3 summarizes the general characteristics of the roundabouts reported on in the survey. The table shows that modern roundabouts in the United States are built in all types of environments: urban, suburban, and rural. The major road is always an arterial or a collector; the minor road is an arterial or a collector in 70 percent of the cases.

TABLE 3
GENERAL CHARACTERISTICS OF U.S. ROUNDABOUTS

		Percent of Respondents
General environment	Suburban areas	39
	Urban areas	22
	Urban fringe areas	21
	Rural areas	18
Classification of major road	Arterials	58
	Collectors	42
Classification of minor road	Arterials	30
	Collectors	40
	Local streets	30
Number of approaches	Three	12
	Four	61
	Five	18
	Six	9
Daily traffic on major road	> 20,000 vehicles	20
	10,000–20,000 vehicles	42
	< 10,000 vehicles	38
Total peak hour traffic	> 2,500 vehicles	26
	1,000–2,500 vehicles	52
	<1,000 vehicles	22

Two-thirds of the cases described involved intersections of roadways of the same functional classification, i.e., an arterial with an arterial, or a collector with a collector. One-quarter of the cases are intersections of roads that have one level difference in classification, i.e., an arterial with a collector, or a collector with a local street. Two roundabouts are located at the junction of an arterial with a local street. Almost three-quarters of the roundabouts have three or four approaches, with the balance having five or six approaches.

Modern roundabouts can be found on high-volume highways (20 percent are on roadways with daily traffic volumes in excess of 20,000 vehicles). About 26 percent carry total entering peak-hour flows in excess of 2,500 vehicles.

The highest volume roundabouts are: the Los Alamitos roundabout in Long Beach, California, with a total of 4,700 vehicles entering during the peak hour, and the I-70/Vail Road interchange roundabout in Vail, Colorado, with 3,400 vehicles (and design hour volumes of 5,500) for the southern roundabout and 1,900 vehicles for the northern roundabout. The Brattleboro, Vermont roundabout is being designed for a peak load of 4,300 vehicles.

Over half (56 percent) of the roundabout cases have no or very few pedestrians, 22 percent have between 20 and 60 pedestrians during the peak hour, and the remaining 22 percent have more than 60 pedestrians per hour. The Montpelier, Vermont roundabout, located adjacent to a senior housing project and close to a middle school, carries in excess of 260 pedestrians during a 12-hour period *(15)*.

Geometric Elements

Inscribed Circle Diameter

One of the key geometric criteria of the modern roundabout is the inscribed circle diameter (see chapter 1 for definitions of geometric elements). The majority (80 percent) of the 31 roundabout cases reported have inscribed circle diameters in the range of 30 to 61 m (98 to 200 ft). Note that not all the survey responses included information on geometric or operational characteristics. Table 4 shows the breakdown of the reported inscribed circle diameters. There were no cases in the ranges of 37 to 45 m (121 to 148 ft) and 61 to 125 m (200 to 410 ft). The three cases with large diameters were old circles that have been, or are in the process of being converted to modern roundabouts.

Circulatory Roadway Width

Table 4 also shows a breakdown of the cases according to the width of the circulatory roadway. It can be seen that 36 percent of the reported cases have circulating widths that are equivalent to at least two lanes.

TABLE 4
GEOMETRIC CHARACTERISTICS OF U.S. ROUNDABOUTS

	No. of Cases	Percent of Total Cases
Inscribed Circle Diameter		
< 30 m (98 ft)	3	10
30 to 32.9 m (98 to 108 ft)	11	35
33 to 37 m (109 to 121 ft)	6	19
45 to 61 m (148 to 200 ft)	8	26
125 to 145 m (410 to 476 ft)	3	10
Circulatory Roadway Width		
4.5 to 5.5 m (15 to 18 ft)	12	43
6.0 to 7.0 m (20 to 23 ft)	6	21
7.3 to 9.1 m (24 to 30 ft)	7	25
10.7 to 11.0 m (35 to 36 ft)	3	11

Central Island

Approximately two-thirds of the reported cases have central islands that are greater than 9 m (30 ft) in diameter. Aprons allowing trucks and buses to circulate around the central island are generally included in the roundabouts with inscribed diameters that are less than 37 m (121 ft), and occasionally in larger roundabouts as well.

Entry Widths

Based on the widths of the largest entries, 59 percent of the reported cases are single-lane roundabouts, 30 percent are two-lane roundabouts, and 11 percent are three or more lanes wide. The Los Alamitos roundabout that was converted from an old traffic circle has three entries with three lanes each and one entry with four lanes. The south roundabout at the I-70/Vail Road interchange in Vail, Colorado originally had a four-lane entry. This entry was subsequently narrowed to three lanes.

In 40 percent of the reported cases, additional right-of-way had to be acquired, whereas for the balance of the cases no land acquisition was necessary.

Signing, Markings, and Lighting

There was some divergence in the types of signs at the entrances to the roundabouts: although each case included the standard YIELD sign (R1-2 designation in the *Manual on Uniform Traffic Control Devices* [MUTCD]), these were often supplemented with an additional plate. This addition is sometimes the international roundabout symbol (three arrows in a circular form) or a plate supplementing the YIELD sign with specific yield instructions: e.g., "TO TRAFFIC ON LEFT," "TO TRAFFIC IN ROUNDABOUT," or "TO TRAFFIC IN CIRCLE." None of the these additional signs is included in the MUTCD.

In addition to the YIELD sign at the roundabout entries, about 90 percent of the cases include advance Yield Ahead signs (W3-2a), and 7 percent use the written message "YIELD AHEAD." Sixteen percent of the cases report signs that do not conform to the MUTCD, and 24 percent of the cases include supplemental plates to the advanced warning signs: typically speed limit signs, a sign indicating "YIELD AT ROUNDABOUT," or the roundabout symbol sign. In one case, advance flashing signals were installed on each approach, and occasionally rumble strips were installed to alert drivers to the need to slow down.

About one-fifth of the cases supplemented the yield line at the roundabout entrance with the legend "YIELD" or "YIELD AHEAD" marked on the pavement. Except for one case, there are no lane markings in multi-lane roundabouts. The exception is a roundabout in Hilton Head, South Carolina, where authorities believed that the large number of senior drivers would be more comfortable with lane markings in the circle.

All the cases have some type of one-way sign (R6-1 or R6-2), or a one-way arrow (W1-6), in the central island. Often these signs are supplemented with chevron signs. In the case of the Santa Barbara Five Points roundabout, the signs were originally mounted on flex posts, but the flex posts were eventually replaced by break-away tube posts.

All existing roundabouts have nighttime lighting.

Splitter Islands, Pedestrian Crossings, Curbs, and Slope

In almost all cases, the roundabouts are constructed with raised splitter islands. Only the Baneker Road Roundabout in Howard County, Maryland has painted splitter islands. Pedestrian crosswalks are marked in two-thirds of the cases, generally about 6 m (20 ft) back from the yield line. In one-third of the cases there are no crosswalks. In 76 percent of the cases outer curbs are provided. Three-quarters of the roundabouts are sloped toward the outside of the inscribed circle, whereas one-quarter of the roundabouts have crowned circulatory roadways.

REASONS FOR BUILDING ROUNDABOUTS

The survey participants were asked to identify the major reasons that led their agency to install a roundabout. Table 5 summarizes the responses to this question. Respondents were allowed to give more than one response.

TABLE 5

MAJOR REASONS FOR BUILDING ROUNDABOUTS

Major Reason	Number of Responses	Percent of Responses
Greater safety	16	22
Shorter delays	12	16
Lower costs	10	14
Aesthetic/urban design	10	14
Lower speeds/traffic calming	7	10
Higher capacity	6	8
Geometric complications	6	8
Request from local jurisdiction	4	5
Request from local official	2	3
Total	93	100

It should be noted that the reasons given are always specific to the individual cases and are in response to the conditions before the installation of the roundabout. For instance, the roundabout installation may have been prompted by physical constraints at a location, by a high accident rate, by the capacity limitation of a four-way or two-way stop intersection, or by the high cost of an alternative improvement.

MAJOR BENEFITS OF ROUNDABOUTS

The survey respondents were asked to rate the general impacts of the roundabouts in comparison to the previous

TABLE 6

GENERAL IMPACTS OF ROUNDABOUTS

Evaluation Criteria	Cumulative Points	Number of Responses "Improved"	"Worse"	"Same"
Vehicle delay	11.0	11	0	0
Capacity	8.0	8	0	1
Safety	8.0	8	0	3
Aesthetics	5.5	5.5	0	3
Desired vehicle speeds	4.5	5.5	1	3
Noise	4.0	4	0	4
Pedestrian movements	0.5	1	0.5	7
Bicycle movements	0	0.5	0.5	7
Maintenance	-2.0	2	4	4

"pre-roundabout" traffic control situation, relative to nine operational criteria. Three choices were possible for each criterion: "improved," "worse," or "same." The responses were tabulated by giving a value of +1 to each "improved" response, -1 to each "worse" response, and 0 to each "same" response. Two responses marked "not sure" were also rated 0. Table 6 shows the responses to this question, with the evaluation criteria listed in descending order of positive ranking. Those evaluation criteria with the highest cumulative points reflect the greatest overall benefits as perceived by the respondents.

Only participants with roundabouts in operation were able to respond to this question. Some of the respondents did not rate every criterion, presumably because they did not know the impact or they were not sure. When two persons responded for the same roundabout, their responses were averaged, explaining the half-point rankings.

All respondents agreed that the first four criteria (vehicle delay, capacity, safety, and aesthetics) had improved as the result of the roundabout installation, or had stayed the same. Nobody rated these as "worse." The first three of these criteria (delay, capacity, and safety) had the highest point ratings, with 73 percent to 100 percent of respondents indicating improvement in these areas of all responses. For the aesthetics criterion, 5.5 responses indicated improvement with roundabouts, and 3 responses indicated that aesthetics remained the same. For the next four criteria (desired vehicle speeds, noise, pedestrian movements, and bicycle movements), there was an occasional "worse" rating, some "improved" ratings, and some ratings as the "same." For the criterion of maintenance, four respondents rated it as "worse," two as "improved," and four as the "same."

The reasons given for the "worse" ratings regarding maintenance included:

- Landscaping or other maintenance for the central island, mentioned by two respondents.
- Additional snow removal time, noted by the cities of Vail, Colorado, and Montpelier, Vermont.
- Occasional sign replacement, mentioned by one respondent.
- The need to do maintenance work during the night because of the circulation restrictions imposed by the vertical curbs of the splitter islands in single-lane roundabouts, mentioned by one respondent.

No details on before-and-after maintenance costs were provided by any of the respondents, although two respondents mentioned that overall maintenance costs for roundabouts were less than for signalized intersections.

All of the respondents indicated that, overall, they were satisfied with the roundabouts. When asked whether more roundabouts will be built in their jurisdiction, 11 out of 14 responded "yes," and three responded "maybe."

To conclude, there seems to be general agreement among the respondents that the major benefits of roundabouts are reduced delays, increased capacity, increased safety, and improved aesthetics.

PROBLEMS ENCOUNTERED

The problems and disadvantages mentioned by the survey respondents included the following:

- In the case of unequal approach volumes, the roundabout gives an advantage to the low-volume approach, causing delays to the high-volume approach. This is a result of the roundabout's equal opportunity approach treatment. One respondent also mentioned that roundabouts give an advantage to more aggressive drivers.
- The lack of clear (i.e., signalized) right-of-way control for pedestrians was occasionally cited as a concern. This has also been mentioned by a representative of visually impaired persons, who noted as a disadvantage the absence of audible messages indicating to pedestrians their right-of-way status.
- Maintenance was sometimes mentioned as an issue. Special procedures have to be established for snow plowing and removal, and for the maintenance of the central island. For the two-roundabout interchange in Vail, Colorado, snow removal takes a motor grader 2 hours per snow storm. In single-lane roundabouts any maintenance or other activity in the circulatory roadway or any of the approaches may become a hindrance to traffic flow. The raised splitter islands (with vertical curbs) limit circulation flexibility during construction and in cases of accidents in single-lane roundabouts. One respondent mentioned the need to undertake maintenance activities during the night because of this circulation hindrance. The need for increased sign maintenance was mentioned by one respondent,

although he added that overall maintenance costs are less than for signalized intersections.

- Construction can become complicated and costly, because of the need to grade a larger surface and because of maintenance of traffic during construction.
- In one case, tire damages were reported from vehicles hitting the outside vertical curb.
- One respondent also mentioned larger vehicles occasionally running over the central island.
- Locating driveways near roundabout entrances, especially the multi-lane entrances, and achieving the necessary deflection for smaller roundabouts or certain three-way roundabouts, were mentioned as design challenges.

Some of the suggestions addressing the above problems were: the use of mountable or sloped curbs on the splitter islands or the outer circle to enable vehicles to drive over the curb; the use of sloped curbs to avoid tire damage; the design of a standard central island curb and apron that discourage large and errant vehicles, and the development of uniform signage for the roundabout approaches and entrances.

COSTS OF ROUNDABOUTS

A wide range of construction costs was reported for roundabouts. For those roundabouts that are not part of a freeway interchange or that involve a conversion from an old traffic circle, the range of total costs (including construction, maintenance of traffic, design, and engineering) is between $10,000 and $500,000, with an average total cost of $250,000 (average cost of 14 roundabouts). At the low end, $10,000 reflects the cost of a roundabout that was installed by the municipality's own personnel within an existing intersection, where the only work involved the construction of the central island and the splitter islands. No adjustment was made to the outer curbs or to the drainage. At the high end are roundabouts built by state agencies on state highways, generally involving substantial amounts of grading and drainage, as well as relatively long splitter islands and lots of curbs. These state-built roundabouts cost in the range of $350,000 to $500,000 each.

Maryland DOT reported average maintenance of traffic costs for the four latest roundabouts of $133,000 (with a range of $111,000 to $149,000), representing 29 percent of the total costs. This high proportion of maintenance of traffic costs is due to the new roundabout being built at existing intersections with relatively high traffic volumes. The following shows a percentage breakdown of the costs for different roundabout construction elements, taken from cost elements for the four latest roundabouts bid for construction in Maryland:

	Percentage
Maintenance of traffic	29
Grading	11
Drainage	5
Paving	30
Shoulders	7
Landscaping	6
Signage and lighting	12

The cost elements that varied the most were the drainage costs, with a range of 1 percent to 14 percent of total costs. Not enough cost data were available to break out costs by the size of the roundabouts.

Maryland DOT is currently reviewing ways to reduce roundabout costs. Because of the novelty of this type of intersection, past design decisions had a tendency to err on the side of caution and greater expense. The following are some of the cost reduction measures being considered:

- *Maintenance of traffic*—Detouring all traffic or several legs of traffic would reduce costs. This would also reduce construction time.
- *Paving*—Instead of adding resurfacing beyond the limits of the project, the department could limit the resurfacing to that which is actually needed for the roundabout.
- *Landscaping*—Scaling back the landscaping to simple and low-maintenance designs.
- *Signing and lighting*—Reducing the size of signs so they may be mounted on wooden posts, and installing the signs on existing poles, if possible.
- *Curbing*—Review the need for a curb on the outside circle.
- *Volume contracting*—Considering setting up areawide contractors to bid on larger quantities.

The conversion of the old Los Alamitos traffic circle in Long Beach, California to a roundabout cost $238,000 for construction and $162,000 for design studies, and engineering. The conversion of the I-70/Vail Road interchange in Vail, Colorado to a roundabout interchange cost a total of $2.8 million. This figure includes construction of both roundabouts, the reconstruction of the freeway ramp termini and other roadways, drainage work, landscaping ($500,000), maintenance of traffic, and design and engineering costs ($375,000). (See chapter 9 for a presentation of this case.) The estimated total cost of the interchange reconfiguration of I-70/Chamonix Road in Vail, Colorado is $6.4 million.

PUBLIC ACCEPTANCE OF ROUNDABOUTS

The survey respondents were asked what the public attitude was toward roundabouts before the construction and after the construction. Table 7 summarizes the responses.

In all but one case, the public attitude toward roundabouts improved after construction. Whereas before the construction of the roundabout, 68 percent of the responses were negative or very negative toward the roundabout, there were no negative feelings after the construction. After construction, 73 percent of the respondents indicated a positive or very positive attitude.

The City of Santa Barbara, California summarized the public comments made during a 6-month period after the roundabout installation. Of the 36 comments, 26 (or 72 percent) were in favor, and 10 (or 28 percent) were against, the roundabout. The negative comments mostly concerned right-of-way violations and the lack of pedestrian crossings. The Five Points roundabout in Santa Barbara has a marked pedestrian crossing on only one of its five legs.

TABLE 7

PUBLIC ATTITUDE TOWARD ROUNDABOUT BEFORE AND AFTER CONSTRUCTION

	Percent	
Attitude	Before Construction	After Construction
Very negative	23	0
Negative	45	0
Neutral	18	27
Positive	14	41
Very positive	0	32

A survey of residents and workers near the Montpelier, Vermont roundabout indicated that 56 percent of the respondents had a favorable opinion of the roundabout, 29 percent had a neutral opinion, and 15 percent had an unfavorable opinion. Of the 106 respondents, 93 percent had driven through the roundabout, 82 percent had walked through the roundabout, and 18 percent had bicycled through the roundabout. No differences in opinion were discerned among the drivers, pedestrians, and bicyclists.

The survey respondents were also asked whether they undertook any special public education or information efforts. Thirty percent indicated that they held special public meetings, 30 percent responded that they published informational brochures, 9 percent announced the change on local TV or produced a video, and the remaining 30 percent did not do anything. Examples of public information leaflets are included in Appendix C of this synthesis.

REASONS WHY AGENCIES HAVE NOT BUILT ROUNDABOUTS

Of the state transportation agencies responding to the survey, thirty-five (80 percent) indicated that they had not built any roundabouts and were not in the process of implementing any. The reasons given by these respondents for not building any roundabouts were:

	Percentage
Not sure drivers will get used to them	*37.1*
Not sure they work efficiently	*34.3*
Not sure they are safe	*17.1*
Not part of AASHTO guide	*14.3*
Concerned about liability	*14.3*

The Canadian respondents gave similar reasons, except that the absence of American Association and State Highway and Transportation Officials (AASHTO) guidelines and liability concerns were not mentioned.

A few noteworthy specific reasons were given for not building roundabouts:

- Cannot give priority to major route,
- Difficulty of providing adequate guide signing,
- Uncertain about appropriate applications,
- Politicians and public want traffic lights,
- Concerned with modeling operational efficiency,
- Additional right-of-way needed for construction, and
- Awaiting more widespread use of roundabouts.

Asked whether the agency was considering the construction of roundabouts, the responses were 30 percent yes, 17 percent maybe, and 53 percent no. Several respondents mentioned that they would like to obtain more operational and safety performance results of the existing roundabouts, that they are studying locations for possible roundabouts, or that they look forward to obtaining guidelines from the Federal Highway Administration (FHWA).

CHAPTER FOUR

DESIGN GUIDELINES USED IN THE UNITED STATES

INTRODUCTION

Roundabout design has been addressed in U.S. professional publications over the last few years *(16)*. However, no standard nationwide design guide is currently available. Practitioners are using design guides that have been developed by a state department of transportation, a consulting firm, or a foreign government agency or research institute. Appendix D lists the sources for various design guides and analysis programs that are available.

Planned *Roundabout Design Guide*

The Federal Highway Administration (FHWA) has started the process of developing federal design guidelines for roundabouts. The expected publication date of the FHWA *Roundabout Design Guide* is the fall of 1999. The objective of the project is to encourage a uniform roundabout practice throughout the United States, encompassing roundabout geometry, operation, and capacity/delay analysis. FHWA will also include a public outreach program to notify planners and engineers of the availability of the guide.

Planned MUTCD Additions

The MUTCD will be upgraded to include the signing and striping of roundabouts. For the first time it will add the yield line. Presently, yield lines in the United States are not standard.

CURRENT ROUNDABOUT GUIDES

Roundabout Design Guidelines by Maryland DOT

Roundabout Design Guidelines, issued by the Maryland DOT in 1995 *(17),* was the first such guide to be published in the United States. It closely follows the Australian design guide published in 1993 *(18).* In the section on "Use of Roundabouts," the Maryland DOT manual suggests appropriate and inappropriate sites for roundabouts. To analyze the performance of roundabouts, Maryland DOT recommends the use of the SIDRA software developed by the Australian transport research organization, Australian Road Research Board (ARRB) Transport Research Ltd. Simple graphs are included to obtain a general estimate of roundabout capacity when a high degree of accuracy is not required. In addition to the geometric design recommendations, the guide includes recommendations for landscape design, signing and pavement marking, lighting, pedestrian and bicycle circulation, and work zone traffic control. Single-lane and multi-lane roundabouts are addressed, along with typical signing examples for a roundabout on a state route and a roundabout on a local road. A unique feature in the Maryland guide is the additional plate under the YIELD sign (R1-2) stating "TO TRAFFIC ON LEFT" or "TO TRAFFIC IN CIRCLE."

Roundabout Design Guidelines by Ourston & Doctors

Published in September 1995, Ourston & Doctors' *Roundabout Design Guidelines (19)* is based on the British standards for roundabouts, and more specifically on the British design manual TD 16/93, *Geometric Design of Roundabouts (20)*. This guide was originally prepared at the request of the California Department of Transportation (Caltrans). However, Caltrans decided to not to publish it. Ourston & Doctors' guide includes a section describing the different types of roundabouts and a section on the appropriate locations for roundabouts. The chapter on safety addresses entry speed and measures to reduce accidents, including bicycle and truck accidents. Specific design requirements for bicyclists and pedestrians are also mentioned. Detailed geometric design features are described for mini-roundabouts, as well as for normal roundabouts having entries up to four lanes wide. The Ourston & Doctors guidelines do not include any analyses of capacity and delays, but refer the reader to two British software packages (ARCADY and RODEL). The guide does not address signage.

Florida Roundabout Guide by Florida DOT

Published in 1996 by the Florida DOT, the *Florida Roundabout Guide (21)* includes criteria to aid in the selection of locations appropriate for roundabouts and proposes a formal justification process for the most appropriate form of traffic control. The Florida DOT guide presents the Australian method for the capacity calculation and recommends the use of SIDRA software. It includes a comparative analysis of SIDRA and RODEL, showing graphically the influence of geometric variables, such as inscribed circle diameter, entry width, entry angle, and entry radius for each of the software packages. The guide, which concentrates primarily on single-lane roundabouts, includes recommendations for geometric design, signing, marking, and lighting.

SURVEY RESPONSES ON ROUNDABOUT GUIDELINES

As part of the survey for this synthesis, each of the state and other agencies that had built, or was in the process of building, a roundabout was asked the source of the guidelines used to design the roundabout. Table 8 summarizes the responses.

TABLE 8
DESIGN GUIDELINES USED IN THE UNITED STATES

Guidelines Utilized	Number of Responses	Percent of Responses
Maryland DOT	7	26
Florida DOT	3	11
Australian	8	30
British	3	11
Ourston & Doctors	6	22
Total	27	100

It can be seen that the Australian guidelines (i.e., the combination of Maryland, Florida, and AUSTROADS guides) were followed in two-thirds of the cases. For one-third of the cases, the British methods were used. However, one-quarter of the respondents checked *both* the Australian and British methods as sources for design and analysis. The roundabouts with the highest traffic volumes (Los Alamitos and I-70/Vail Road) have been analyzed and designed with the use of the British methods.

In two-thirds of the cases the guidelines used were adapted for local or state conditions. One-third of the designs—all of which were "Australian type" roundabouts—followed the guidelines rigorously. Similarly, about two-thirds of the respondents indicated that they plan to revise the guidelines being used. Some of the proposed changes include signing, mountable splitter islands and curbs, design of the central island curb and apron, and sight lines. One respondent mentioned the need to evaluate the capacity software programs in use in the United States, indicating contradictory results between SIDRA and RODEL.

A few agencies mentioned that they undertook statutory modifications to allow roundabouts. One state added a paragraph on roundabouts in the drivers manual.

CHAPTER FIVE

DESIGN GUIDELINES OF OTHER COUNTRIES

AUSTRALIAN GUIDELINES

Part 6 of the AUSTROADS *Guide to Traffic Engineering Practice (18)* covers roundabouts. This 1993 document follows a major revision of the 1986 publication *Roundabouts—A Design Guide,* issued by the National Association of Australian State Road Authority. Part 6 includes a total of 84 pages with numerous photos and calculation examples. Chapters in the guide that are important to this discussion include:

- Use of Roundabouts, with sections on appropriate and inappropriate sites for roundabouts.
- Performance of Roundabouts, including a section on "Means of Improving the Performance of Roundabouts."
- Geometric Design of Roundabouts, with sections on arterial and local roads. The distinction between local and arterial roads is made because of the different operational objectives of these two types of roads, and because of cost and space constraints for local road roundabouts. The geometric requirements of multi-lane roundabouts are addressed.
- Pedestrian and Cyclist Considerations, including design recommendations for these modes.
- Lanemarking and Signing, including a discussion on lane markings for multi-lane roundabouts, and designs for regulatory signs at the entrances. Typical signing and marking schemes are presented for an urban arterial roundabout, a rural roundabout and a local street roundabout.
- Lighting, including schemes for various types of roundabouts.
- Landscaping and Road Furniture.
- Trial Installations.
- Case Studies.

The Australian capacity method is based on the "gap acceptance techniques," which are described in chapter 7 of this synthesis.

BRITISH DESIGN GUIDELINES

The British Design Manual, *Geometric Design of Roundabouts,* also known as TD 16/93 *(20),* provides guidance and standards for the geometric design of roundabouts with regard to traffic operation and safety. It addresses six types of roundabouts:

1. *Normal roundabout,* with a raised central island with a minimum diameter of 4 m (13 ft), typically with flared approaches to allow multiple vehicle entry.
2. *Mini-roundabout,* having one-way circulation around a flush or slightly raised central island less than 4 m (13 ft) in diameter and with or without flared approaches.
3. *Double roundabout,* a single intersection with two normal or mini-roundabouts, either contiguous, or connected with a short central link.
4. *Grade-separated roundabout,* with at least one entry passing through an underpass or overpass. This could be a two-bridge roundabout or a grade-separated interchange with two roundabouts and one underpass or overpass.
5. *Ring junction,* two-way circulation around a large island, with three branch mini-roundabouts at the intersection of each approach.
6. *Signalized roundabout,* with traffic signals installed on one or more approaches. Traffic signals under part-time or continuous operation are seen as a means to meter entering traffic on one or more branches to prevent overloading of the roundabout.

The following outlines key chapters of the British guide:

- Siting of Roundabouts, explaining favorable and unfavorable factors to be taken into account for installing roundabouts.
- Safety, explaining the overall safety of roundabouts and measures that have been effective in reducing accidents at roundabouts.
- Bicycle and Pedestrian Requirements, with design suggestions for these modes, as well as accommodations for equestrians.
- Landscaping.
- Geometric Design Features, with particular attention to the design of the entries: i.e., the entry width, the entry angle, the design of the entry flare, entry radius, and entry path curvature. A section on sight distances and visibility requirements is also included. Regarding pavement slopes for the entries, exits, and circulatory roadway, the British guide suggests a slope of two percent for drainage purposes and mentions that superelevation is not required for the circulatory roadway. Superelevation is suggested on the approaches and exits to assist drivers in negotiating the associated curves. One or two crown lines are recommended for circulatory roadways of larger roundabouts, implying drainage systems on both sides of the circulatory roadway. Adverse slopes (i.e., toward the outside of the circle) are acceptable provided approach speeds are low.

The British guide proposes an empirical formula to calculate entry capacity and suggests ARCADY as the software program to calculate capacities. The ratio of flow to capacity (RFC) is mentioned as a key indicator of the likely performance.

FRENCH DESIGN GUIDES

In 1988, France produced two design guides for roundabouts, one for urban conditions by the Centre d'Etudes des

Transports Urbains (CETUR, now known as CERTU), and one for rural conditions by the Service d'Etudes Techniques des Routes et Autoroutes (SETRA). Both of these guides are currently in the process of being updated.

CETUR Guide for Urban Conditions

This guide *(12)* includes the following chapters:

- General description of roundabouts,
- Capacity calculation,
- Geometry,
- Pedestrian amenities,
- Bicycle amenities,
- Landscaping, and
- Signing.

The guide shows examples of urban roundabout installations with landscaping features. Among the recommended geometric criteria are the deflection of traffic passing through the roundabout and the sloping of the circular roadway toward the outside. The outward slope of the roadway serves to increase the visibility of the central island, to facilitate the connection to the other roadways, and to simplify the drainage. The guide includes an empirical formula for entry capacity as a function of impeding traffic in a linear form. The updated version of this guide is expected to be issued in 1998.

SETRA Guide for Rural Conditions

The 1988 SETRA guide *(22)* has been updated by a provisional 31-page 1996 version *(23)*, which includes the following sections:

- Terminology,
- Safety,
- Capacity,
- General Design Principles,
- Geometry of Roundabout Elements,
- Additional Amenities, and
- Signage.

The section on capacity includes general guidelines specifying the threshold levels when a more detailed capacity analysis with a computer program is recommended. Minimum visibility and deflection criteria are recommended. The SETRA guide also recommends that the circulatory roadway be sloped to the outside. The same simplified linear formula used in the 1988 guide is included, but reference is also made to Girabase, a roundabout software program that includes more variables. The official version of the SETRA guide is expected to be issued in 1998.

SWISS ROUNDABOUT GUIDE

The Swiss guide, *Guide Suisse des Giratoires (10)*, was developed in 1991 by the Transportation and Planning Institute of the Federal Polytechnic School of Lausanne, Switzerland with funding from the Swiss Highway Safety Fund. It puts major emphasis on the integration of the roundabout into the urban space or general environment. The guide is divided into three parts: Part A describes the general characteristics and design aspects, Part B describes the feasibility, study, and design processes, and Part C includes sections on capacity, software, and mini-roundabouts. Besides multi-lane roundabouts, the Swiss guide also addresses double roundabouts and includes pictures of existing double roundabouts.

GERMAN GUIDELINES

In Germany, three documents are currently used as guidelines: two focus on urban conditions *(11, 24)*, and a third, published by the federal government *(25)*, addresses rural conditions. Moreover, a first draft of the German Highway Capacity Manual *(26)* has been prepared, containing a chapter on roundabouts. The German Highway Capacity Manual is scheduled to be officially published in 2000.

The most commonly used guideline is the brochure for "small" roundabouts prepared by the State of Nordrhein-Westfalen in 1993 *(11)*. This guide addresses roundabouts for developed areas with maximum inscribed diameters of 35 m (115 ft) inside urban areas and 45 m (148 ft) outside urban areas. It includes 32 pages with photographs of existing roundabouts in Germany. Examples of intersections before and after roundabouts are shown (see Figure 8 in chapter 2 of this report). Following a definition of the roundabout, the guide presents traffic criteria and urban design criteria for the installation of roundabouts, with operational and design recommendations, including recommendations for accommodating pedestrians and bicycles. A simple graph for a verification of capacity is included. This guide addresses only single-lane roundabouts.

The federal government guide for national highways in rural conditions *(25)* follows a similar outline as the guide for Nordrhein-Westfalen. It only addresses single-lane designs and recommends that multi-lane roundabouts be approved by the federal department of transportation. It includes 24 pages with graphs but no pictures. Appendix D includes addresses where these guidelines can be obtained.

CHAPTER SIX

SAFETY OF ROUNDABOUTS

SAFETY OF ROUNDABOUTS IN THE UNITED STATES

The 1997 survey produced before-and-after accident statistics for 11 roundabouts. Generally, crash frequencies were obtained for several years before the roundabout was built, and for a shorter time period after installation. Average annual crash frequencies were calculated for each roundabout, broken down by total crashes, injury crashes, and property damage only (PDO) crashes. Fatalities are included in the injury statistics (there was one fatal accident before roundabout construction and zero accidents after). Table 9 summarizes the results for the 11 roundabouts, broken down into larger roundabouts with three-lane entries, and smaller roundabouts with one-or two-lane entries and inscribed circle diameters of 37 m. (121 ft) or less. The three larger roundabouts include the Long Beach roundabout, converted from a nonconforming traffic circle, and the two-roundabout interchange in Vail, Colorado. The eight smaller roundabouts include those in Santa Barbara, California; Lisbon, Cearfoss, Lothian, and Leeds, Maryland; Tampa, Florida; Montpelier, Vermont; and Hilton Head, South Carolina.

For the small to moderate roundabouts, reductions in crashes are significant at the 95 percent and 90 percent confidence levels for total crashes (a reduction of 51 percent) and for injury crashes (a reduction of 73 percent), respectively. The statistical tests did not show any significant differences with any reasonable confidence levels for PDO crashes at the small to moderate roundabouts, nor for any of the crashes of the larger roundabouts. There appear to be favorable safety trends for larger roundabouts; however, more crash statistics need to be collected for these roundabouts.

On an individual basis, each roundabout experienced a reduction in injury crashes, ranging from 20 to 100 percent. Two of the 11 roundabouts experienced increases in PDO crashes. In Vail, Colorado, one of the two-roundabout interchanges experienced an increase in PDO crashes from 15 to 18 per year. This increase was more than offset by the reduction in PDO crashes at the other interchange roundabout from 6 to 1 per year. In Leeds, Maryland, PDO crashes increased from 1.5 per year to 5.3 per year, while the injury crashes decreased from 2.2 to 0.0 per year. PDO crashes at the Leeds roundabout were all single-car crashes, mostly related to vehicles entering the roundabout too fast.

The number of pedestrian/bicycle crashes decreased from a total annual frequency of 2.3 to 0.6, statistically not a reliable number.

The safety improvements identified in this survey are in line with those presented in a recent paper comparing before-and-after crash statistics at six roundabouts in the United States *(27)*. This research paper concluded that "in all but one case, the reduction in accidents for roundabout sites was in the range of 60 to 70 percent." Statistical tests "indicated a significant difference in the reduction of frequency and mean of accidents at 95 and 99 percent confidence levels." Similar conclusions were drawn in a 1995 article in the journal *Public Roads (28)*. The improvements in safety shown here parallel those found in other countries.

A calculation of costs at the five Maryland roundabouts showed that the average cost per crash decreased from $120,000 before the roundabout to $84,000 after the roundabout, a reduction of 30 percent in crash severity *(29)*.

SAFETY OF ROUNDABOUTS OUTSIDE THE UNITED STATES

The Netherlands

At the end of 1992 a before-and-after study was conducted in the Netherlands of 181 roundabouts that were previously intersections *(30)*. These were generally smaller, single-lane roundabouts with typical outside diameters of 30 m that replaced mostly stop-controlled or yield-controlled intersections.

TABLE 9

AVERAGE ANNUAL CRASH FREQUENCIES BEFORE AND AFTER ROUNDABOUT CONSTRUCTION IN THE UNITED STATES

		Average Annual Crashes								
		Before Roundabout			After Roundabout			Percent Change		
Type of Roundabout	Number	Total	Injury	PDO	Total	Injury	PDO	Total	Injury	PDO
Small/Moderate	8	4.8	2.0**	2.4	2.4*	0.5**	1.6	-51	-73	-32
Large	3	21.5	5.8	15.7	15.3	4.0	11.3	-29	-31	-10
Total	11	9.3	3.0	6.0	5.9	1.5	4.2	-37	-51	-29

Notes:
* Significant difference at 95% confidence level.
** Significant difference at 90% confidence level.
PDO Property-Damage-Only Crashes.
For the small/moderate roundabouts and for the Total row, the sum of the injury and PDO crashes is less than the total crashes, because one respondent gave only total crash statistics.

Table 10 summarizes the numbers of average crashes per year and shows that the reduction in total crashes and injuries experienced in the Netherlands is very similar to the safety experience of smaller roundabouts in the United States.

TABLE 10

AVERAGE ANNUAL CRASH FREQUENCIES BEFORE AND AFTER ROUNDABOUT CONSTRUCTION IN THE NETHERLANDS *(30)*

	Before Roundabout	After Roundabout	Percent Change
Total crashes	4.9	2.4	-51
Injuries	1.3	0.37	-72
Moped/Bicycle Injuries	0.55	0.31	-44

Notes: Based on 181 intersections with an average of 5.3 study years before roundabout and 2.0 study years after roundabout. The first seven months after construction were excluded from the analysis.

The more severe injury crashes (resulting in hospital admissions) experienced the most impressive reduction at roundabouts, down 81 percent from the comparable statistics at the prior intersections. By transportation mode, the reduction in casualties (fatalities and injuries) was as follows:

	Percentage
Passenger cars	*95*
Moped	*63*
Bicycles	*30*
Pedestrians	*89*

In some cases, the greatest gains in safety were realized in the first year and a half after roundabout installation. These safety benefits had a tendency to "wear off" to some degree, but the rates did not go back up to the level before roundabouts.

Australia

A before-and-after study conducted in 1981 of 73 roundabouts in Victoria, Australia showed a reduction of 74 percent in the casualty accident rate *(31)*. This reduction was more pronounced for lower volume roundabouts, but remained significant for all categories. There were no fatalities during the 3 years following the roundabout installation. The property damage accidents decreased by 32 percent and the accident rates involving pedestrians decreased 68 percent, although, because of the low numbers of pedestrian accidents, this reduction was not statistically significant.

A paper presented at the 15th Australian Road Research Board Conference by R. T. Tudge in August 1990, "Accidents at Roundabouts in New South Wales," *(32)* analyzed before-and-after accident data at 230 roundabout sites and at 60 control (non-roundabout) sites (see Table 11). A significant overall reduction in crashes was observed, while the control sites experienced significant increases in accident rates per year during the same time period.

Tudge drew the following conclusions from his safety and cost analysis *(32)*:

1. Roundabouts are cost effective overall.
2. The optimum cost-effective size of a roundabout is between 10 and 20 meters internal diameter (diameter of central island).
3. The higher the existing accident rate, the greater the reduction in accidents and the more cost-effective the construction of a roundabout.
4. Some roundabouts tend to increase accidents, especially at those intersections with no recorded accidents before roundabout construction.
5. Roundabouts specifically designed to reduce accident problems are more successful in that respect than those constructed for other purposes, such as speed control or capacity restraint.
6. Local street roundabouts generally have higher present value/cost ratios than main road roundabouts. This is primarily due to the cost of main road roundabouts.
7. Further work is required to determine what specific features of roundabout design mitigate accidents.

TABLE 11

AVERAGE ANNUAL CRASH FREQUENCIES BEFORE AND AFTER ROUNDABOUT CONSTRUCTION IN AUSTRALIA *(32)*

	Before Roundabout	After Roundabout	Percent Change
Total crashes	3.910	2.289	-41
Fatal crashes	0.024	0.009	-63
Injury crashes	1.045	0.571	-45
PDO crash injuries	2.841	1.709	-40

Notes: Based on 230 intersections in New South Wales, Australia

Germany

A study of 34 modern roundabouts in Germany by Prof. Dr. Ing. Werner Brilon dated April 9, 1996 analyzes the before and after accident conditions by location and by accident type *(33)*. Most of these roundabouts were single-lane roundabouts with inscribed diameters of about 30 m. Two of the roundabouts had previously been signalized.

In this study, the total number of accidents decreased by 40 percent as the result of the roundabout implementation. This reduction was highest for the more severe accidents. The safety benefits were greatest for the roundabouts located outside urbanized areas, where total accident costs decreased by 84 percent. The number of fatalities and severe injuries outside urbanized areas decreased from 18 to 2, the number of light injuries from 25 to 3, and the number of accidents with heavy property damage decreased from 24 to 3. In urbanized areas the total accident cost reduction was 36 percent.

The number of pedestrian accidents decreased from 8 to 2. For bicyclists the results were mixed, depending on the bicycle arrangement. Bicycle lanes at the outer edge of the circulating roadway were found to lead to more accidents (increase from 1 to 8 accidents). No significant safety impacts were found when bicycles mixed with regular traffic or with the pedestrian path, or when bike paths were built outside the circulating roadway.

The study concluded that 30 m (98 ft) seemed to be the ideal inscribed diameter for a single-lane roundabout. Smaller diameters result in larger circulatory roadways, which reduces the deflection. The circle, as opposed to the ellipse, is the ideal form. Truck aprons with a rougher pavement are recommended such that the circulatory roadway remains 4 to 4.5 m (13 to 15 ft) wide. The circulating roadway should slope toward the outside of the circle to increase the visibility of the circle to the approaching traffic and to slow down the circulating traffic. Lighting was considered important, with the preferred installation along the outside, directing light toward the inside.

Regarding the safety of pedestrians, the study concluded that splitter islands are important and that they should be between 1.6 and 2.5 m (5 to 8 ft) wide, with the crossings located 4 to 5 m (13 to 16 ft) back from the circulating roadway. The splitter islands also increase the visibility of the roundabouts. Zebra-striped crossings were recommended only when there are more than 100 pedestrians crossing during the peak hour.

Great Britain

One of the most significant safety studies undertaken in Great Britain is "Accidents at 4-arm roundabouts" by G. Maycock and R.D. Hall *(34)*. This 1984 report gives the findings of a study of personal injury crashes at a sample of 84 4-arm roundabouts on main roads in Great Britain. The objectives of the study were to provide some insights into the character of roundabout accidents, and to derive relationships between accident frequencies, traffic flows, and geometric design, to be used in design and appraisal. The following are some of the main conclusions of the study:

- The average crash frequency (averaged over all roundabouts in the sample) was 3.31 personal injury accidents per year, 16 percent of which were classed as fatal or serious. The average accident rate per 100 million vehicles passing through the roundabout was 27.5.
- A disaggregation of crashes by road user showed that bicyclists are involved in 13 to 16 percent of all accidents, and motorcyclists in 30 to 40 percent. The accident involvement rates (per 100 million of road-user class) of two-wheeler riders were about 10 to 15 times those of car occupants. Pedestrian crashes represented about 4 to 6 percent of all crashes at this sample of roundabouts.
- An analysis of crashes by arm using a generalized linear modeling methodology was successful in relating the crash frequencies (accidents per year per arm) of the four crash types (entering-circulating crashes, approaching crashes, single-vehicle crashes, and "other" crashes), to traffic flow and roundabout geometry. Pedestrian accidents were related to vehicular and pedestrian flows only. The significant geometric variables for the various crash types are listed in Table 12.
- The prediction model suggests that for safety, roundabouts with heavily flared entries should have as much entry path deflection as possible.

TABLE 12

FLOW FUNCTIONS AND GEOMETRIC VARIABLES USED TO PREDICT INJURY CRASH TYPES (By G. Maycock and R.D. Hall) *(34)*

Crash Type	Flow Function	Geometric Variable
Entering-circulating	Entering flow	Entry curvature Entry width Approach width correction
	Circulating flow	Ratio of inscribed diameter to central island diameter Proportion of motorcycles Angle between arms
Approaching	Entering flow	Entry curvature Entry width
Single-vehicle	Entering flow	Entry curvature Approach width Approach curvature
"Other"	Entering × circulating flow	Proportion of motorcycles
Pedestrian	(Entering + Exiting vehicular flow) × pedestrian crossing flow	

France

A study of 83 roundabouts in France was conducted in 1986 by the Centre D'Etudes Techniques de L'Equipement de l'Ouest *(35)*. The study concluded that the transformation of a traditional intersection into a roundabout resulted in significant safety benefits, and that the standardization of priority rules in 1984 improved safety results. The report further found that roundabouts with smaller diameters have fewer crashes than larger roundabouts or those with oval circles, and that the slope toward the outside of the circle is preferable to the inside slope, because it improves the visibility of the roundabout. Table 13 summarizes the main results of this study.

It should be noted that the crash frequencies in Table 13 exclude property-damage-only crashes and do not take into consideration the traffic volumes entering each roundabout. If one assumes that larger roundabouts carry higher traffic volumes than smaller ones, the statistics would be less favorable for the smaller roundabouts, as compared with the larger roundabouts.

The authors relate the better safety behavior of the outside slope to the improved visibility of the central island. The fact that no vehicles lost control on the circular roadways of the outside sloping roundabouts is surprising. It may be that the "wrong" slope reinforces the message to slow down.

A paper entitled "Roundabouts and Road Safety, State of the Art in France" by F. Alphand, U. Noelle, and B. Guichet analyzed the safety record at 522 roundabouts up to the year 1988 *(36)*. In the year 1988, 90 percent of these roundabouts had no injury accidents at all. The average injury crash rates per roundabout for that year were:

Injury crashes per roundabout	*0.15*
Fatalities per roundabout	*0.01*
Injuries per roundabout	*0.20*

About one-quarter of the injuries were classified as serious and three-quarters as light. Note that the average daily traffic for these roundabouts was about 12,500 vehicles.

The study found that, although the number of crashes involving bicycles was lower for roundabouts than for signalized intersections, the reduction was less than for the other modes of travel. About half of the bicycle and moped crashes were due to a refusal of priority of the entering vehicle vis-à-vis the circulating bicycle, and a large proportion of these crashes occurred at two-lane entries.

Switzerland

Two early roundabouts that were built in 1977 and 1980 with inscribed diameters of 30 and 32 m showed reductions of 75 percent in total accidents and 90 percent in the number of injuries after the conversion to a modern roundabout. These measurements were taken over a period of 4 to 8 years following the conversion.

A research project undertaken in 1988 by a consulting firm in Switzerland concentrated primarily on safety for bicycles and pedestrians on roundabouts in urbanized areas *(37)*. This study included interviews with 250 bicyclists and small motorcycle (moped) users, as well as video observations. Of the total respondents, 93 percent preferred the roundabout to the previous stop controlled intersection; 81 percent of the bicyclists/moped users enjoyed bicycling through the roundabout; and 74 percent of the bicyclists indicated that they felt safe in the roundabout, with only 26 percent feeling not safe. The video showed that 53 percent of the bicycles/mopeds stayed on the right side of the circulating roadway, 20 percent drove in the middle of the lane, 21 percent on the left side of the lane, and 6 percent shifted. All of the bicycles/mopeds on the left side of the lane made a half circle or three-quarters circle around the central island.

The study concluded that roundabouts are very effective in reducing crashes at dangerous intersections. For all intersections that are converted to roundabouts, the severity of crashes decreases. Entering traffic should be oriented toward the inner circle and good visibility should be provided at entry and for the circulating roadway. For main roads or national highways, advance directional signs with the roundabout symbol should supplement the roundabout yield sign at the entry. Other special warning signs (such as roundabout ahead or priority to the left) are not recommended *(37)*.

The study also found that bicyclists should be encouraged to circulate in mixed traffic through the roundabout and the roundabout designed to reduce speed as much as possible. Bicycle lanes should be discontinued at least 10 m before the roundabout. For entering vehicles, visibility to the left should be maximized so that the bicycles in the circle are visible. This study did not observe any special problems for bicycles with multi-lane entries *(37)*.

For pedestrians, the consultants observed shorter delays to cross the road than at signalized intersections. The recommended

TABLE 13

CRASH STATISTICS FOR EIGHTY-THREE ROUNDABOUTS IN FRANCE *(35)*

Before and After Crash Frequencies

	Before Roundabout	After Roundabout	Percent Change
Injury accidents per year	1.42	0.31	-78
Fatalities per year	0.16	0.02	-88
Injuries per year	2.78	0.49	-82

Crash Frequencies and Size of Inscribed Diameter

Size of Inscribed Diameters	Number of Roundabouts	Crashes per Roundabouts
< 30 m	13	0.69
30–50 m	11	1.54
50–70 m	26	1.58
70–90 m	16	1.81
> 90 m	8	3.80
Oval	9	4.40

Crash Frequencies and Slope of Circulatory Roadway

	Slope to the Inside (42 roundabouts)	Slope to the Outside (21 roundabouts)
Total crashes per year per roundabout	0.50	0.28
Accidents due to loss of control at entry	0.12	0.06
Accidents due to loss of control on ring	0.09	0.00
Accidents due to refusal of priority at entry	0.14	0.09

distance between the pedestrian crossing and the inscribed circle is 5 m (16 ft). Greater distances do not seem to increase pedestrian safety. Splitter islands with safety zones for pedestrians are recommended for crossings of more than 300 vehicles per hour.

Two-lane approaches seem appropriate in cases where there are two important traffic streams driving in different directions *(37)*.

Other Safety Studies

Studies in other countries have also indicated similar safety findings. A study by the Ministry of Transport in New Zealand entitled "The Safety Implications of Some Control Changes at Urban Intersections" *(38)*, concluded that "Roundabouts appear generally to offer greater safety benefits than signals." A 1987 study by the Norwegian Institute of Technology entitled "Accident Rates on Road Sections and Junctions in Norway" *(39)* summarized the accident rates as follows:

	Per Year
Ordinary four-way junctions	*0.24*
Signalized junctions	*0.16*
Roundabouts	*0.04*

REASONS FOR GREATER SAFETY

The improved safety of roundabouts can be related to a series of design, operational, and human factors, some of which are interrelated.

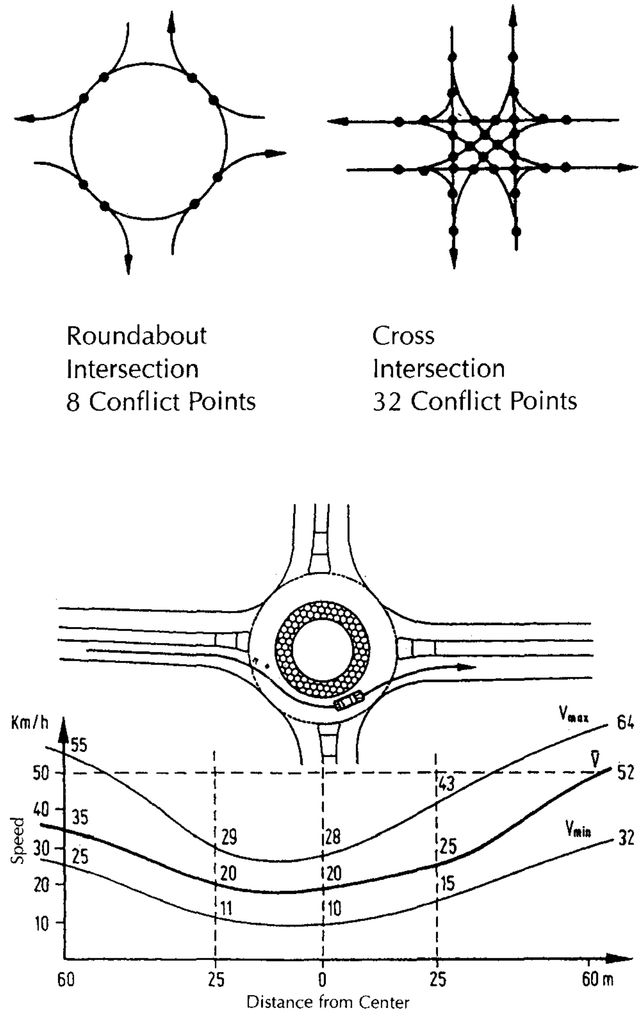
Design Elements

The *entry deflection* forces all vehicles to slow down, thus reducing the probability of a crash and the severity of a crash. Werner Brilon relates the reduction in crashes to the off set of the vehicle path from the straight line (*33*). The fact that *all* vehicles travel at slow speeds, with little difference between cars and bicycles, makes the operation more congenial and safe. Pedestrian crossings are at locations where vehicles travel at slow speeds.

The *physical guidance* and *limitation of traffic*, and the *separation of the various movements* by the splitter islands and the central island reduce the number of conflict points. Whereas a typical four-way intersection has a total of 32 possible conflict points, a four-branch roundabout has only eight possible conflict points (see Figure 12).

Operational Reasons

One-way operation, yield-at-entry, and the *reduced number of conflict points* make the decision process for drivers easier. The entering driver, after looking out for pedestrians, only has to look to the left for an acceptable gap to enter into the flow. Weaving only occurs in multiple-lane roundabouts, where it is simplified by the low speeds.



Vehicle Speed in Roundabouts
(German roundabout with 26 m inscribed diameter.)

FIGURE 12 Safety aspects of roundabouts *(11)*.

Human Elements

Reduced delays at roundabouts compared to signalized intersections decrease the *level of frustration and aggressiveness* of drivers, making them safer drivers. In addition, slower speeds make drivers *more congenial and aware* of their environment. The driver notices other road users more readily, especially the more vulnerable users.

Having to yield to the traffic in the circle and having to slow down induces greater driver courtesy and a *higher level of responsibility,* as opposed to driving at higher speeds through a signalized intersection or an uncontrolled intersection. A driver getting a green light feels more empowered to drive aggressively than somebody facing a YIELD sign and a yield line *(10)*.

CHAPTER SEVEN

CAPACITIES AND DELAYS

DELAYS AT U.S. ROUNDABOUTS

For eight of the U.S. roundabouts, vehicle delays were measured (or calculated, in two cases) before and after roundabout construction. Seven of the eight intersections were two-way or multi-way stop-controlled intersections before conversion to the roundabouts. One was previously signalized. Table 14 shows the average peak-hour delays per vehicle for the eight intersections. The delays indicated are total delays, i.e., they include the stopped delay and move-up time in the queue.

TABLE 14

BEFORE AND AFTER DELAYS AT U.S. ROUNDABOUTS

	Roundabouts		Percent	Number of
Peak Hour	Before	After	Change	Roundabouts
AM Peak Hour	13.7 sec	3.1 sec	-78	6
PM Peak Hour	14.5 sec	3.5 sec	-76	8

At only one of the eight intersections did delays increase following roundabout construction: from 0.6 sec per vehicle to 1.1 sec per vehicle during the morning peak hour, and from 0.7 sec to 1.3 sec during the afternoon peak hour. This increase was due to the fact that before the roundabout was built, a large number of vehicles were free flowing. For the other seven roundabouts, delays decreased substantially.

CAPACITY METHODS AND SOFTWARE USED IN THE UNITED STATES

There are two primary capacity methods and software programs used in the United States: the Australian method with the SIDRA software and the British method with either the RODEL or the ARCADY software. Twenty survey respondents provided information on the type of software they were using to analyze the roundabout:

Software	*Percent Used*
SIDRA	*46*
No software used	*28*
RODEL	*14*
Australian Manual	*6*
TRAFNETSIM	*6*

SIDRA, developed by the ARRB Transport Research Limited (Australia), appears to be the most commonly used in the United States. This is in line with the fact that two-thirds of the survey respondents mentioned that they followed, or at least consulted, the Australian guidelines for roundabout design.

The two capacity methods are very different in their approaches. The Australian method estimates entry capacity based on gap acceptance characteristics observed and measured at roundabouts operating below capacity. Critical gaps and follow-up times are related to the geometric parameters of the roundabouts. The British method estimates entry capacity based on empirically derived regression equations relating capacity directly to geometric parameters. The regression equations were validated by field measurements of capacity. This latter method is similar to the methods used in most other European countries *(40)*.

HIGHWAY CAPACITY MANUAL

The 1997 draft update of the *Highway Capacity Manual* (HCM) includes a procedure for analyzing roundabouts *(41)*. This section gives a general overview and definition of roundabouts and explains the key parameters for determining capacity. The HCM subcommittee developing the calculation procedures for roundabouts recognized the advantages of empirical models relying on field data to develop relationships between geometric design characteristics and roundabout performance. However, given the lack of any empirical roundabout data in the United States (since no existing roundabouts are currently operating at capacity), the HCM opts for an analytic method, i.e., the gap acceptance approach, to calculate roundabout capacity. This approach is similar to the one used by the HCM for two-way stop-controlled intersections. It assumes that drivers need a minimum gap in the circulating stream to enter the intersection. This minimum gap is called the "critical gap." As the available gaps increase in time, more than one driver can enter. Subsequent drivers enter with headways equal to the "follow-up time."

The capacity formula calculates the capacity of each approach as a function of the circulating flow, the critical gap, and the follow-up time. The draft HCM gives lower-range and upper-range numbers for the critical gaps and the follow-up times to be used in the United States:

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

These are then translated into a simple graph expressing approach capacity as a function of circulating flow, with an upper bound value and a lower bound value. The effect of geometric characteristics on capacity is not included in the model.

The given methodology applies to single-lane roundabouts only. The HCM draft states that there is insufficient experience in the United States with multi-lane roundabouts to support an analysis procedure for such roundabouts. It also states that a doubling of the entry width does not produce a doubling of the entry capacity. No specific software programs are recommended.

One U.S. research team collected operational data on existing roundabouts *(42)*. Using video recording equipment, this team made 489 gap observations and 472 follow-up time measurements at four roundabouts (three in Florida and one in Maryland). Table 15 summarizes the measurements for the four roundabouts.

The operational performance criteria from this research project seem to indicate higher capacities than suggested by the HCM draft. The HCM subcommittee opted for more conservative capacity assumptions.

TABLE 15

GAP AND FOLLOW-UP TIME MEASUREMENTS IN THE UNITED STATES *(42)*

	Critical Gap (sec)	Follow-up Time (sec)
Average value	3.94	2.48
Standard deviation	0.41	0.24
Lowest value	3.45	2.25
Highest value	4.44	2.82

PERFORMANCE ANALYSIS METHODS USED IN OTHER COUNTRIES

Australia

Gap Acceptance Method

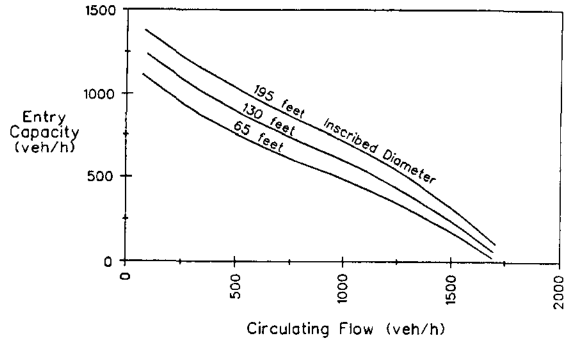
Australia uses the gap acceptance approach extensively. Described in the Australian roundabout design guide (AUSTROADS 1993) *(18)*, this method for analyzing the capacity and performance of roundabouts is based on ARRB Special Report 45 (SR 45) published in 1989 *(43)* and improved since then. The Australian method distinguishes for multiple-lane entries between the *dominant stream* and the *sub-dominant stream*. The dominant stream is the one with the greatest entry flow. Follow-up times are calculated first for each lane as a function of the inscribed diameter, the number of entering lanes and circulating lanes, and of the circulating flow. Critical acceptance gaps (i.e., the minimum gap acceptable for entry) are dependent on the follow-up time, the circulating flow, the number of circulating lanes, and the average entry lane width. The number of useful gaps (long enough for a vehicle to enter) depends on the proportion of vehicles that are bunched and the proportion of non-bunched vehicles.

Based on the above parameters, the Australian capacity formula calculates the entry capacity C for each approach. The degree of saturation x is calculated as

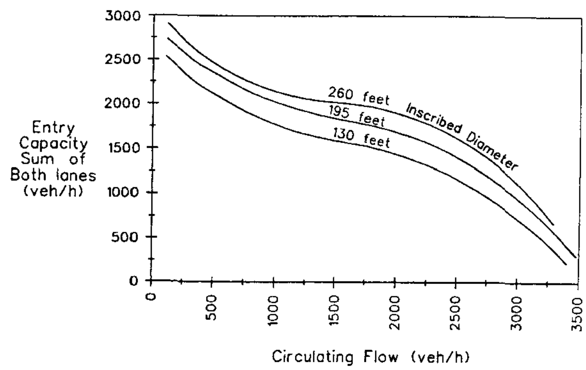
$$x = Q_e / C$$

where Q_e is the entry flow.

Figure 13 shows simple graphs that can be used to obtain an estimate of roundabout capacity, when a high degree of accuracy is not required.



Entry capacity for a single lane roundabout with a 13-foot-wide entry lane and one circulating lane.



Entry capacity for a roundabout with two, 13-foot-wide entry lanes and two circulating lanes.

FIGURE 13 Entry capacities for single-lane and two-lane roundabouts *(17, 18)*.

The degree of saturation during the design period should be less than 0.8 to 0.9 according to the Australian guide for satisfactory operation, although this may not always be attainable. A separate formula calculates the queuing delay (total delay as per HCM definition). The geometric delay (i.e. the delay experienced by a vehicle going through the roundabout in the absence of any other traffic) is added to obtain the overall delay.

A 1997 paper by Troutbeck *(44)* observed that circulating stream vehicles were sometimes forced to slow down slightly to accommodate entering vehicles, a phenomenon called "gap-forcing behavior." Troutbeck studied the effect of gap-forcing behavior and concluded that the headways in the circulating stream could be slightly increased as the result of merging traffic entering, particularly under saturated conditions. Troutbeck then proposes a gap-acceptance model with "limited priority" to account for the gap-forcing behavior. The limited priority entry was found to have a significant impact on entry capacity of two-lane roundabouts, bringing the entry capacity of such roundabouts very close to the straight-line relationship empirically established in Great Britain *(45)*. See Figure 14.

SIDRA Software

SIDRA Version 5.02 includes research results obtained by ARRB since 1993 and differs from the "official" 1993

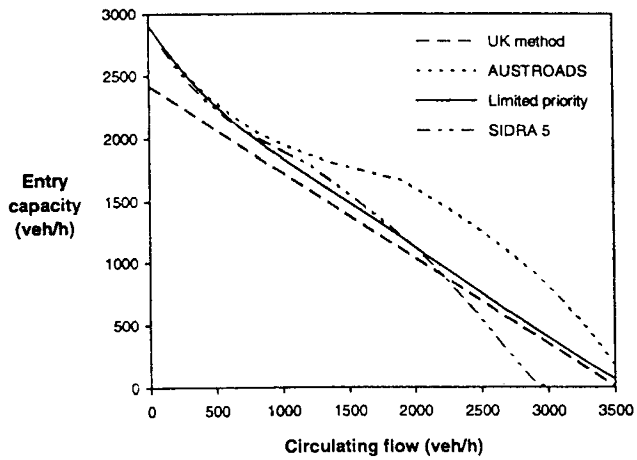


FIGURE 14 Entry capacity for a two-lane roundabout with a 60-m inscribed diameter and a 4-m entry lane width *(44)*.

AUSTROADS methodology in that it takes into consideration the effects of the origin-destination pattern within the roundabout and the queuing characteristics of the approach flows.

SIDRA estimates critical gaps and follow-up headways as a function of roundabout geometry, as well as the circulating and entry flow rate characteristics. However, the user can also specify known critical gap and follow-up headways to take into consideration local conditions. SIDRA includes an option describing the roundabout performance using accepted U.S. definitions, such as for delays and levels of service *(46,47)*.

Great Britain

Capacity Formula

The capacity formula used in Great Britain is a statistically derived empirical formula based on a large number of measurements of capacity at saturated roundabouts. It was developed by the Transport Research Laboratory (TRL) and has the following form:

$$C = k(F - f_c Q_c)$$

where k, F, and f_c are constants derived from the geometry of the roundabout, and Q_c is the circulating flow (Kimber's Equation, LR 942) *(45)*.

In addition to the geometric parameters used in most other capacity methods (inscribed diameter, entry width, circulating width, as shown in Figure 5), the British method incorporates the following geometric variables, shown in Figure 15:

- *The Approach Half-Width, v*, is measured from the right curbline, along a normal to it, to the centerline or left edgeline at a point upstream of the flare.
- *Average Effective Flare Length, l′*, is shown in Figure 8. The right edge of pavement would follow the line GFD if there were no flare. GFD is the upstream half-width v away from the centerline (or, in the case of a raised median, from the median curb). BA is the normal to the curb along which the entry width e is measured, and its length is e. The length of BD is $(e-v)$, and the length of BC is $(e-v)/2$. The average effective flare is CF, a curve $(e-v)/2$ away from the right curb. The length of CF is l', the average effective flare length.
- *Sharpness of Flare, S*, is defined by the relationship $S = 1.6(e-v)/l'$. It is a measure of the rate at which extra width is developed in the entry flare. Large values of S correspond to short, severe flares, and small values of S correspond to long, gradual flares.
- *Entry Angle, ∅*, represents the conflict angle between entering and circulating streams of traffic.
- *Entry Radius, r*, is measured as the minimum radius of curvature of the right curb at entry. For some designs, the arc of minimum radius may extend into the following exit, but this is not important if half or more of the arc length is within the entry region.
- *Vane Island* is a painted island that divides lanes entering a roundabout. A vane island provides entry deflection for the right lanes when the central island is too small to provide this deflection.

The approach used for the British regression equation is based on one of the largest sets of data points collected on roundabout capacities. It provides estimates of the effects of different geometric parameters of British roundabouts. Statistical tests have been performed to confirm the suitability of the parameters.

Figure 16, extracted from the RODEL software manual *(48)* shows the relationships between the entry capacity and geometric characteristics.

Performance analysis methods are also given for mini-roundabouts *(49)*, with efficiency factors (K) given for single mini-roundabouts and for double mini-roundabouts, with three, four, and five arms. Total design flows for all approaches are recommended to be less than 2,500 vehicles for three-arm roundabouts and less than 2,000 vehicles for four-arm roundabouts.

ARCADY Software

The computer program ARCADY (Assessment of Roundabout CApacity and DelaY) is the program originally developed by the Transport Research Laboratory to calculate capacities according to the British formula (LR 942) *(40)*. In addition to predicting capacities, queues, and delays, it also predicts crash frequencies as a function of geometry, thus permitting the user to design for safety as well as for capacity. These predictions can be used to test design options for new roundabouts and modifications to existing ones. The program has the ability to predict the variability of queues and delays. VISUAL ARCADY/4 for Windows was released in 1996. Pedestrian crossings can be included in the analysis and queue lengths can be viewed, animated, and printed.

RODEL Software

RODEL (ROundabout DELay) was developed by R.B. Crown in 1987 *(48)*. It is designed to facilitate experimentation

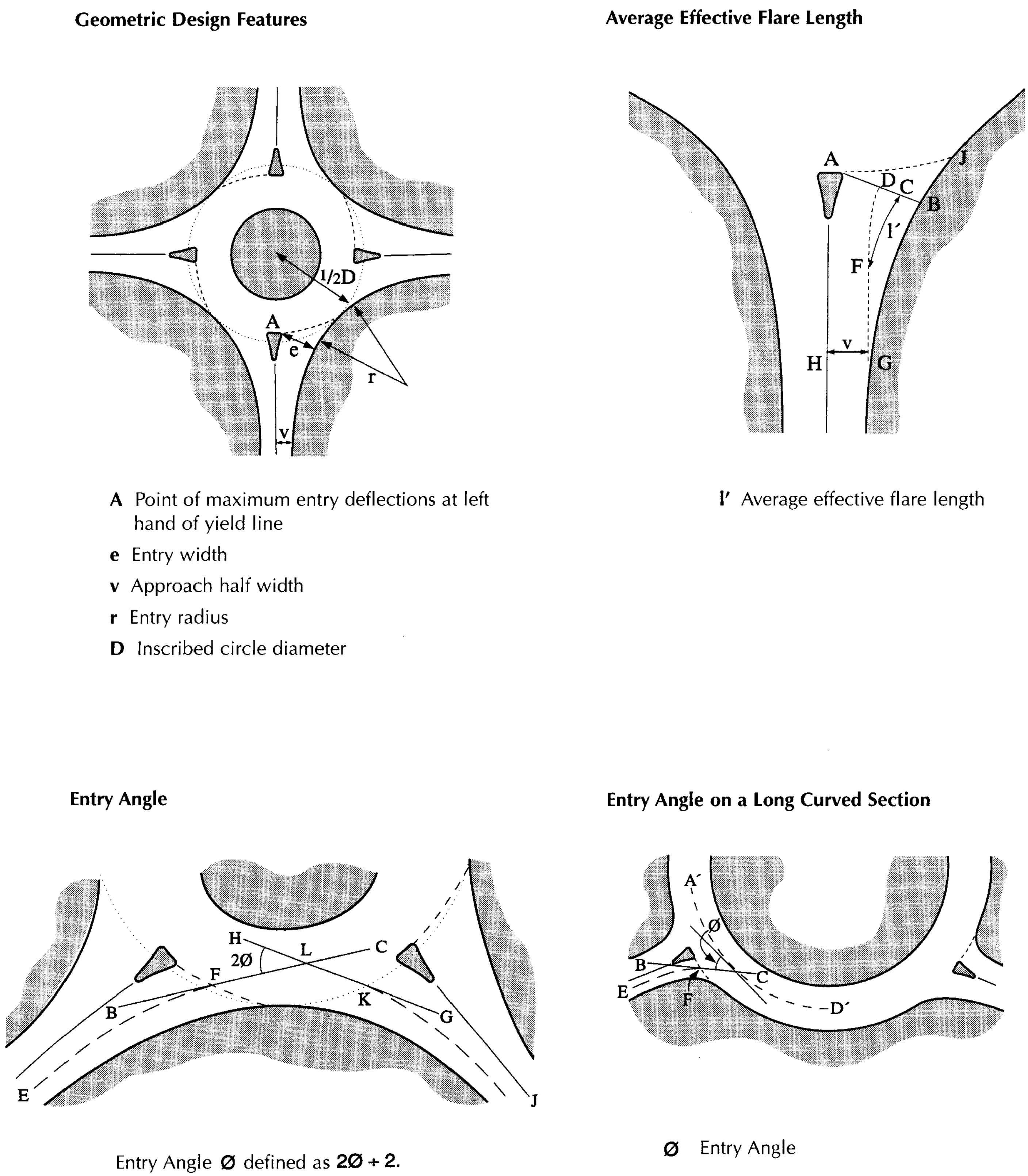


FIGURE 15 Geometric elements for British roundabout analysis *(19)*.

with the geometric design parameters as part of the design process. The capacity and delay estimates are also based on the empirical model described in LR 942. However, RODEL uses observed variation in capacity to allow the user to set any level of confidence that the capacity will meet or exceed the desired value. ARCADY/4 and RODEL will produce the same results if the confidence level for RODEL is set at 50 percent (ARCADY has an implicit confidence level of 50 percent). Capacity estimates by ARCADY and RODEL have been validated by direct field observations. RODEL includes a

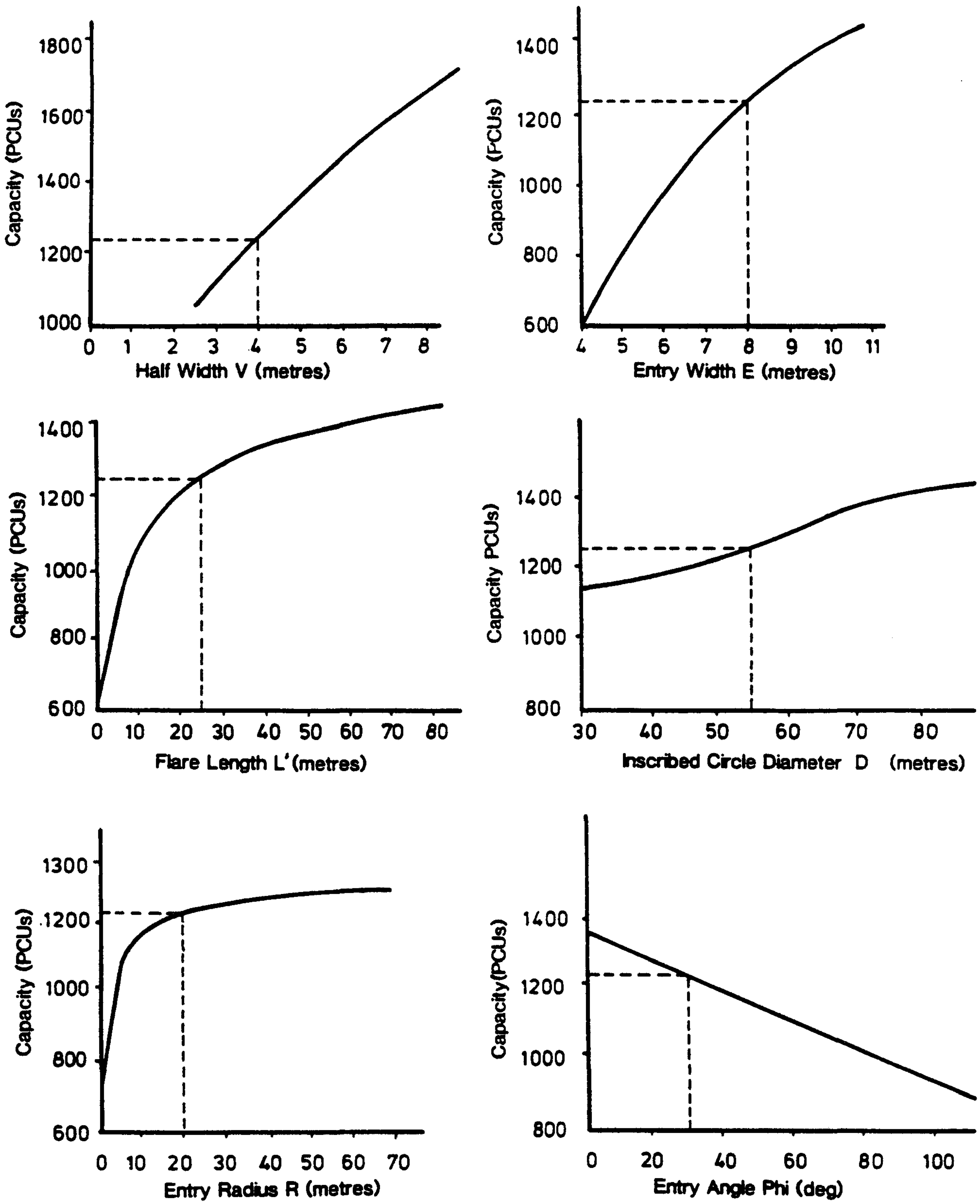


FIGURE 16 Capacity/geometry relationships according to RODEL *(48)*.

geometric refinement mode allowing interactive testing of geometric variables. Whereas ARCADY results are for the whole time period, the output from RODEL can be specified for the whole time period or for shorter analysis periods. A new version of RODEL with crash prediction capabilities is under development.

France

Capacity for Urban Conditions (CETUR Formula)

The original French formula for roundabout capacities was developed in 1988 by CETUR (now known as CERTU), a government organization responsible for urban transportation guidelines nationwide *(12)*. The CETUR formula expresses the entry capacity as a function of the *impeding flow* (as opposed to the circulating flow in the British and Australian methods). Similar to the U.S. method for unsignalized intersections, the impeding flow is a summation of circulating flow plus a proportion of the exiting flow at the same branch, or

$$Q_g = Q_c + \alpha Q_s$$

where:

Q_g = impeding flow,
Q_c = circulating flow,
Q_s = exiting flow,
α = variable that is a function of the width of the splitter island (0.2 on average).

The theory is that the entering traffic is hampered to some degree by the exiting traffic because of the uncertainty over whether these vehicles actually exit.

Q_g gets adjusted to a Q_g equivalent when the circulating roadway is at least 8 m (26 ft) wide. The entry capacity C is defined as:

$$C = 1500 - 5/6\, Q_g \text{ for } Q_g < 1800$$
$$\text{If } Q_g \geq 1800,\ C = 0.$$

With two entry lanes, entry capacity increases by 40 percent. The average delay t is:

$$t = (2000 + 2Q_g)/(C - Q_e) \text{ in seconds}$$

where Q_e = entering flow.

The capacity equation is a straight line expressing the entry capacity as a function of the impeding flow. The capacity is the maximum theoretical capacity, requiring a reserve capacity for design purposes.

Capacity for Rural Conditions (SETRA Formula)

The original capacity method for rural roundabouts was developed in 1987 by SETRA, the French national design service for rural (interurban) highways *(22)*. This same formula is also included in the provisional SETRA guide dated January 1996 *(23)*. It is similar to the CETUR formula, but with minor variations. Both formulas lead to linear equations relating the entry capacity to impeding traffic flows.

The following SETRA formula applies to roundabouts with central islands with a radius of 15 m (49 ft) or more:

$$C = (1330 - 0.7\, Q_g)\,(1 + 0.1[l_e - 3.5])$$

where

Q_g = $(Q_c + 2/3\, Q'_s)\,(1 - 0.085\,[l_a - 8])$,
l_e = entry width (m),
l_a = width of circulatory road (m),
Q'_s = $Q_s(15 - l_i)/15$,
l_i = width of splitter island,
Q'_s = 0 when $l_i > 15$ m,
reserve capacity = $C - Q_e$,
percentage of reserve capacity = $(C - Q_e)/Q_e$ %.

Girabase

Girabase is the software program developed by the regional technical study organization CETE OUEST in Nantes, France, and accepted by both the urban and interurban national design institutes (CERTU and SETRA) *(49)*. Girabase Version 3.0 (published in March 1992) is more complex than the manual methods and takes the following parameters into consideration:

- entry width,
- width of circulatory roadway,
- radius of central island,
- width of splitter island,
- exit width,
- angles between consecutive branches,
- traffic flows (vehicles or passenger car equivalent),
- pedestrian flows, and
- roundabout environment (urban, suburban, rural).

The empirical regression equations of Girabase are based on counts of 63,000 vehicles during 507 saturated periods of 5 to 10 minutes at 45 different roundabouts *(1)*. The result is an exponential curve expressing the entry capacity as a function of impeding traffic. Girabase can be used for roundabouts with three to eight branches, with central island radii of 3.5 to 87.5 m (11 to 287 ft), circulating widths of 4.5 to 17.5 m (15 to 57 ft), with entry widths of 3 to 11 m (10 to 36 ft), splitter island widths of 0 to 70 m (0 to 230 ft), and exit widths of 3.5 to 10.5 m (11 to 34 ft).

The 1992 version of Girabase incorporates the results of recent calibration counts, especially at multi-lane roundabouts. These counts found that the entry capacity of two-lane entries increased by 80 percent in comparison to one-lane entries (instead of the prior assumption by CETUR estimating a 40 percent increase only) *(49)*.

Girabase alerts the user to unusual or undesirable performance conditions, and suggests potential changes to the design assumptions.

Germany

German researchers in the 1980s attempted to develop capacity methodologies based on gap acceptance, but the results were not promising because they did not seem credible. Next, empirical regression models were developed leading to an exponential regression curve. As a result of several research studies funded by the federal government, more capacity measurements were undertaken between 1993 and 1996 that led to a revised linear formula taking into consideration only the circulating flow and the number of entering and circulating lanes *(50)*:

$$C_e = A + B * Q_c$$

where C_e is entry capacity, Q_c is circulating flow, and A, B are parameters based on number of entry and circulatory lanes and determined from empirical data.

Table 16 presents the A and B parameters used in the German capacity equation.

TABLE 16

PARAMETERS USED IN GERMAN CAPACITY FORMULA *(50)*

No. of Lanes Entry/Circle	A	B	N (Sample Size)*
1/1	1218	0.74	1504
1/2 or 3	1250	0.53	879
2/2	1380	0.50	4574
2/3	1409	0.42	295

*No. of observed 1-minute intervals.

Figure 17 shows a comparison of delays for a single-lane roundabout with a signalized intersection with four phases. For this comparison the researchers assumed four approaches, each carrying the same flow and a distribution of 20/50/30 percent for left/straight/right traffic. The signalized intersection has one lane in each direction plus an exclusive left-turning lane at each approach. It can be seen that the roundabout has significantly lower delays throughout the range of total entry flows and that, in this case, the single-lane roundabout has also higher capacity *(51)*. This comparison may vary from example to example, depending on the distribution of entering traffic between the four approaches and between each movement, and depending on the method used. For

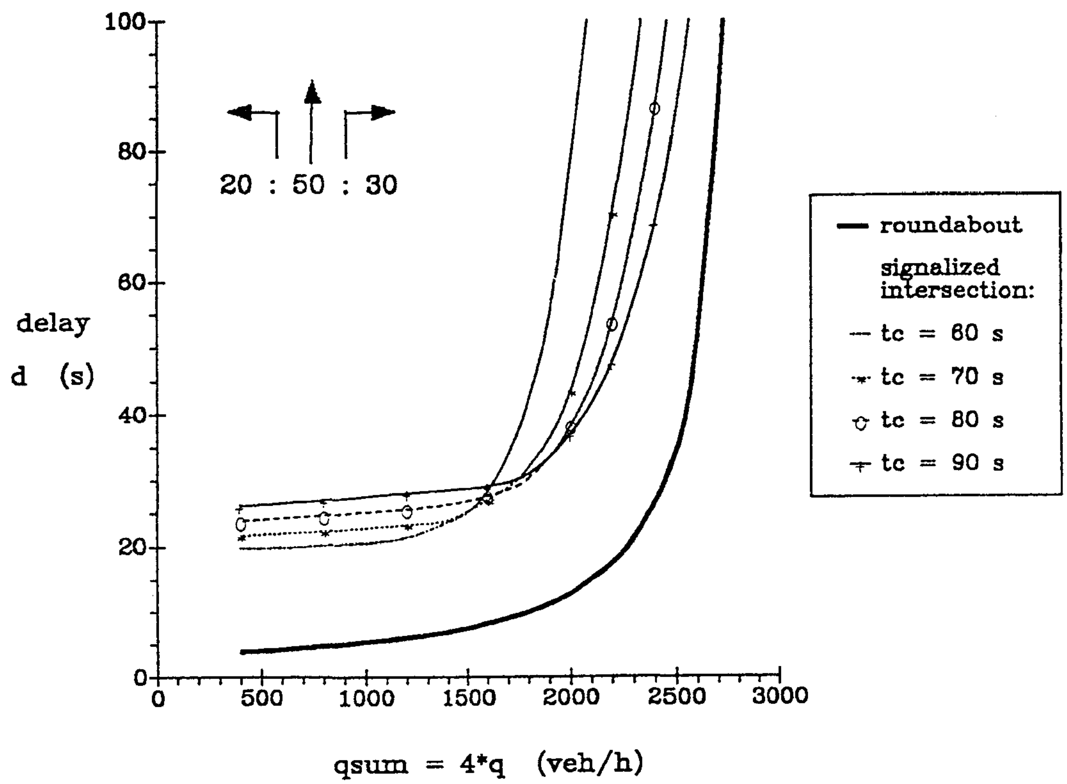


FIGURE 17 Delays as a function of the total traffic load of an intersection: comparison of a single-lane roundabout and a 4-phase-signalized intersection *(51)*.

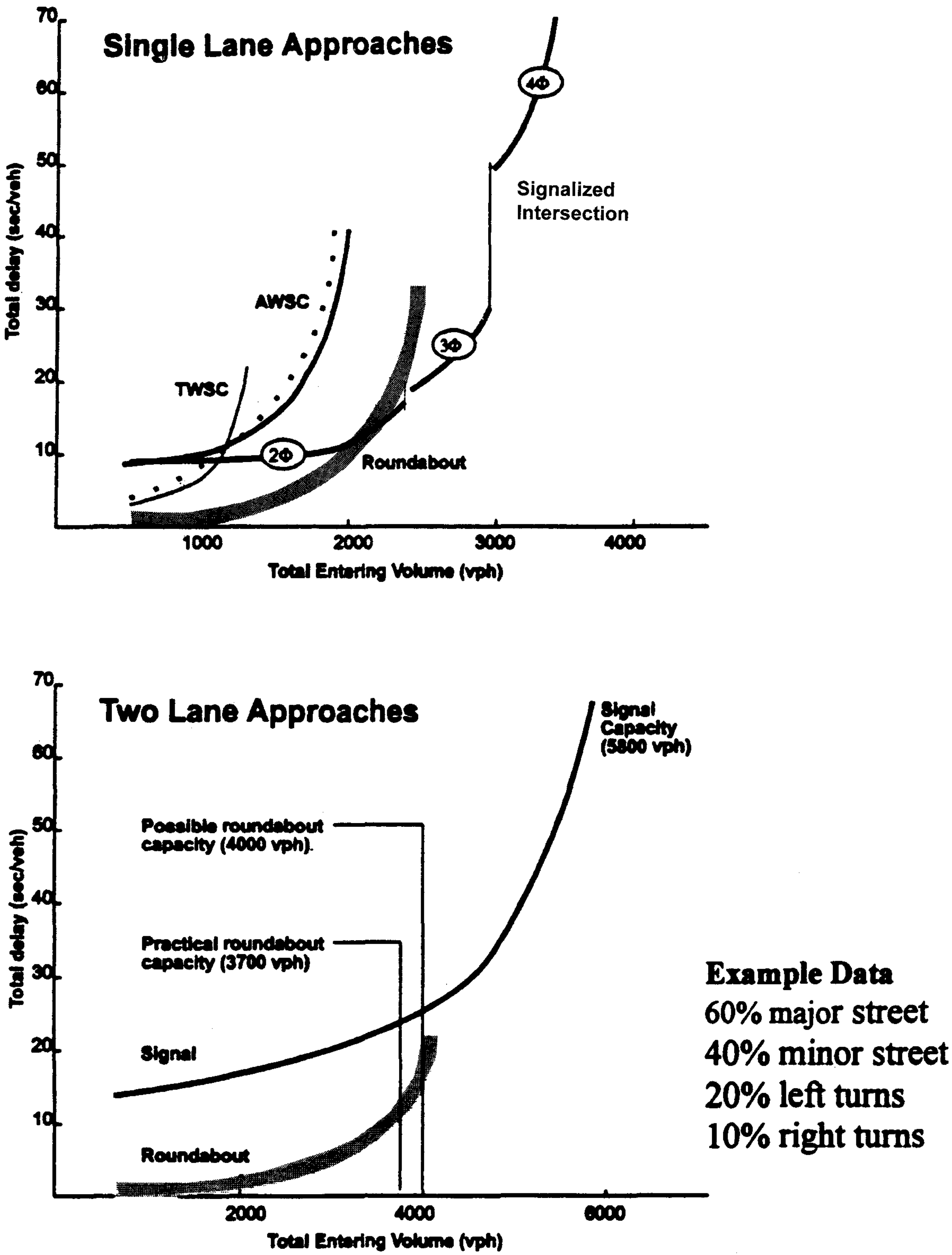


FIGURE 18 Performance comparison of control alternatives for the hypothetical example *(21)*.

example, the *Florida Roundabout Guide* (*21*) presents a similar comparison with a 60/40 split between the major and minor street and a 20/70/10 split for left/straight/right turns. Figure 18 shows these relative performances for single-lane approaches and for two-lane approaches, taking into consideration also the numbers of phases and presence of turn bays. The effect of three-lane or four-lane flared approaches to roundabouts is not shown.

Later investigations by B. Stuwe indicated that, in addition to the circulating traffic and the numbers of lanes, capacity was influenced by the inscribed diameter, the number of roundabout arms, and the distance between exit and entry conflict points of the observed arm with the circulating traffic, *(52)*.

In 1997, N. Wu proposed a Universal Gap-Acceptance Approach to calculate roundabout capacities as an exponential equation relating entry capacity to circulating flow, the number of circulatory lanes, the number of entry lanes, the critical gap, move-up time and minimum headway in circular stream *(53)*.

Kreisel Software

Kreisel is the software program developed by W. Brilon and his research team at the Ruhr University in Bochum, Germany to calculate roundabout capacities and delays. Version 4.1 of Kreisel was published in November 1996. The unique aspect of this program is that it calculates entry capacities for the German methods, as well as for the British method by Kimber, for the French methods (by Louah, CETUR, and Girabase), for the Swiss methods (Emch + Berger and ETH Lausanne) and for the Troutbeck method (1989). For the German method, Kreisel also takes into account the effect of the pedestrian crossings on entry capacity.

Switzerland

The Swiss Roundabout Guide, prepared by the Institute of Transportation of the Federal Polytechnic School of Lausanne under the direction of Professor Bovy and under contract with the Swiss Fund for Roadway Safety, proposes a linear empirical formula, similar to the CETUR formula, but with a different slope *(10)*. It also expresses the entry capacity C_e as a function of the impeding flow Q_g:

$$C_e = 1'500 - 8/9 * Q_g \ (pcph)$$

with

$$Q_g = b * Q_c + a * Q_s \ (pcph)$$

where

Q_c = circulating flow,
Q_s = exiting flow, and
$pcph$ = passenger car equivalents per hour.

The coefficient a takes into account the impedance of the entry due to the exiting flow. It has been determined by the simulation model to be a function of the distance between the conflict points of exit and entry (see Figure 19). The value of a is to be taken from the diagram in Figure 19.

Coefficient β takes into account the number of circulatory lanes as follows:

one circulatory lane: β = 0.9 - 1.0
two circulatory lanes: β = 0.6 - 0.8
three circulatory lanes: β = 0.5 - 0.6.

To determine the capacity in the case of several entry lanes, a saturation coefficient TCU is determined at the entry point e and at the point of conflict on the circulatory lane c:

$$TCU_e = \frac{\gamma * Q_e}{C_e} * 100$$

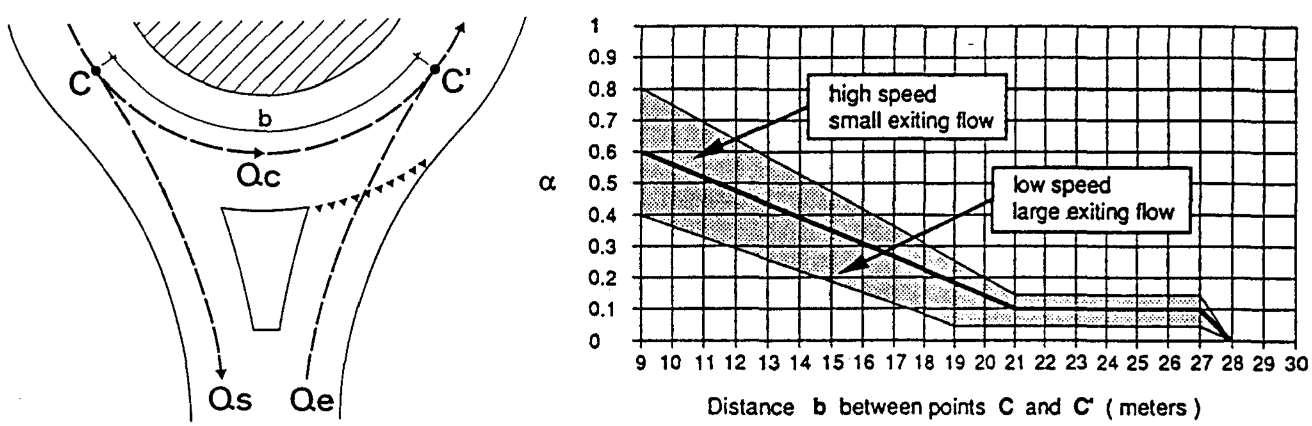
= percentage of saturation

$$TCU_c = \frac{\gamma * Q_e + 8.9 * Q_g}{1'500} * 100$$

= percentage of saturation at conflict point

The variable γ takes into account the number of entry lanes and its value is:

one entry lane: γ = 1.0
two entry lanes: γ = 0.6 - 0.7
three entry lanes: γ = 0.5.



Determination of α

FIGURE 19 Capacity factors from Swiss roundabout guide *(54)*.

CHAPTER EIGHT

ISSUES RELATED TO PEDESTRIANS, BICYCLISTS, AND THE VISUALLY IMPAIRED

SAFETY FOR PEDESTRIANS AND BICYCLISTS

The survey undertaken as part of this synthesis asked the respondents to submit before-and-after pedestrian injury statistics for each roundabout in their jurisdiction. The limited data obtained indicate a favorable trend regarding pedestrian safety, but no statistically significant conclusions can be drawn.

Safety studies from abroad, however, provide more significant results regarding pedestrians and bicyclists. The 1992 study performed in the Netherlands *(30)* of 181 roundabouts before and after the roundabout construction showed a reduction in pedestrian injuries of 89 percent. Moped and cycle injuries decreased from 0.55 per year per intersection to 0.31, a reduction of 44 percent for both modes. For mopeds (light motorcycles) alone the injuries decreased by 63 percent, and for bicycles alone the reduction was 30 percent. These roundabouts were mostly single-lane compact roundabouts.

The 1996 study by Brilon *(33)* analyzed before-and-after crash conditions at 34 roundabouts in Germany. Most of these were single-lane roundabouts with inscribed diameters of about 30 m (98 ft). Two of the 34 intersections were previously signalized, the others were stop-controlled. The number of pedestrian accidents for all 34 roundabouts decreased from 8 to 2. For those roundabouts with bicycle lanes at the outer edge of the inscribed circle, the number of accidents increased from 1 to 8, indicating that the continuation of a bicycle lane through the roundabout may not be safe. For the arrangements with bicycles in mixed vehicular traffic, no safety impacts could be detected. There were also no problems with arrangements where bicycles were mixed with pedestrians on pedestrian paths.

In France, the study by Alphand *(36)* showed that, in 1988, for 15 towns in the west of France, the annual frequency of two-wheel vehicle accidents at signalized intersections was 0.23 per year per intersection, in contrast with 0.13 per year per roundabout.

An important study related to pedestrian and bicycle safety and behavior at roundabouts is the 1988 project by Emch + Berger AG *(37)*, that included videos and interviews of 250 bicyclists or light motorcycle users. The interviews indicated that 93 percent of the bike/moped users preferred the roundabout to the previous type of intersection, 81 percent liked to bike through the roundabout, and 74 percent of the respondents felt safe in the roundabout, whereas 26 percent did not feel safe.

PERCEIVED SAFETY ISSUES IN THE UNITED STATES

A few respondents to the survey mentioned either the absence of clear pedestrian crossing controls, or the violation of pedestrian rights-of-way, as a drawback of roundabouts. The issue of pedestrian crossings at roundabouts is raised each time a roundabout is planned or being discussed in an urbanized area. Two aspects need to be considered: 1) the impacts of pedestrian crossings on the capacity of the roundabout, and 2) the question of real or perceived safety of pedestrians.

The pedestrian crossings issue can be addressed through the use of capacity models such as ARCADY, Girabase, or Kreisel. These software models take the pedestrian crossings into consideration to calculate the entry capacities. Interestingly, the impacts of pedestrians on the entry capacity appear to decrease as circulating flows increase, because entering vehicles are held up more by circulating traffic than by pedestrians. Pedestrian crossings may also affect the exit capacity, especially if the crossing is close to the circular roadway.

Pedestrian safety is an issue of perceived versus real risks. Even though pedestrian safety at roundabouts seems to be high (based on international experience and limited U.S. experience), many pedestrians do not perceive roundabouts to be safe. This issue is complicated by the fact that the general public and politicians believe that signalized intersections provide the greatest safety for pedestrians. One of the survey respondents mentioned that they have not considered roundabouts because "politicians and the public want traffic lights." In fact, studies have pointed out that pedestrians in signalized intersections face accident risks from left-turning vehicles crossing the intersection during the same phase as the pedestrian crossing *(55)*, and that the elimination of 199 unwarranted traffic signals in Philadelphia, Pennsylvania decreased the number of pedestrian accidents by 18 percent *(56)*.

Concerns about pedestrian safety are often raised before the construction of the roundabout. After the roundabout is built and pedestrians have had the opportunity to use it, their perception tends to be more positive. The Montpelier, Vermont, opinion survey, undertaken of persons living and working in the area near the roundabout, indicated that of the 111 respondents, 95 (86 percent) had neutral or favorable opinions regarding the roundabout. Eighty percent of the respondents had walked through the roundabout *(57)*.

In comparison to signalized intersections, roundabouts have the advantage of shorter delays for pedestrians as well. Long waiting times at signalized pedestrian crossings often motivate pedestrians to jay-walk.

PEDESTRIAN DESIGN FEATURES AT MODERN ROUNDABOUTS

Three reasons are generally cited to explain the improved pedestrian safety at roundabouts:

- The reduced speed of traffic, making it easier to avoid crashes and reducing the severity of injuries.
- The simplification of conflicts: The pedestrian has to look out for one vehicular conflict only, either the exiting flow or the entering flow, depending on his or her location. The splitter island acts as a pedestrian refuge area.
- The conflict area between pedestrian and vehicle is minimized. In most areas, there is only one exit lane to cross and entries are only widened when needed for capacity.

To maximize safety for pedestrians, certain design elements were found to be important *(1,10–12, 33, 37):*

- *Design of entries and exits*—These are designed to reduce speeds and to maximize the visibility of the central island. For entries in urban environments, the French guidelines recommend curve radii of 10-15 m (33-49 ft) and for exits 15-20 m (66 ft) *(1)*. German guidelines recommend 10-12 m (33-39 ft) for entries and 10-14 m (33-46 ft) for exits *(11)*. High-speed tangential exits are avoided in pedestrian environments *(1, 11)*.
- *Design of splitter island*—One of the purposes of the splitter island is to act as a pedestrian refuge island. It is recommended to be 1.6 to 2.5 m (5 to 8 ft) wide according to Brilon *(33)*, and 3.0 m (10 ft) wide according to the Ourston & Doctors guidelines *(19)*.
- *Provision and Location of Pedestrian Crossings*—Pedestrian crossings (high-visibility or zebra-striped crossings) are recommended when pedestrian flows reach a certain minimum. Brilon recommends zebra-type pedestrian crossings when peak-hour pedestrian flows exceed 100 *(33)*. The Ourston & Doctors guidelines recommend different types of pedestrian crossings depending on the vehicle/pedestrian conflict *(19)*. The location of the pedestrian crossing is generally recommended to be one vehicle length back from the outside diameter, i.e., about 5 to 6 m (16 to 20 ft). The British guides permit the crossings to be further away from the yield line. Bringing pedestrian crossings closer to the circle may reduce roundabout capacity (because of potential back-ups into the circle and because of the potentially longer waiting times at the entrance), and bringing them further away increases walking distances for pedestrians and may expose pedestrians to higher speeds. When entries are flared, the pedestrian crossing should be before the flaring, according to the British guide TD 16/93 *(20)*.

Pedestrian activated (push button) signals or regular signals with exclusive pedestrian phases can be installed at locations at least 20 m (66 ft) away from the circle. The phasing of the signal has to be set such that vehicles do not back into the roundabout.

Figure 20 shows a typical example of a pedestrian crossing at a roundabout in Germany.

FIGURE 20 Example of a pedestrian crossing at a German roundabout *(11)*.

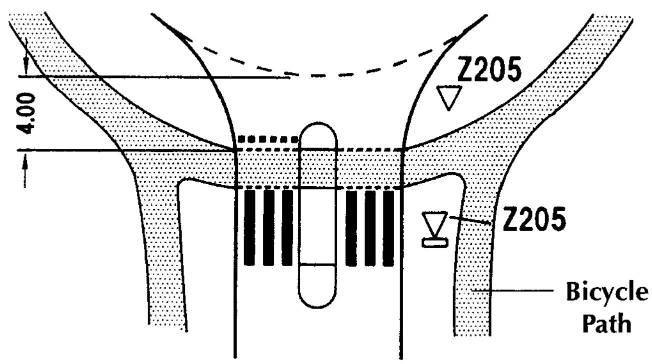


FIGURE 21 Bicycle path at roundabout entry *(11)*.

BICYCLE DESIGN FEATURES AT MODERN ROUNDABOUTS

Generally there are three ways to accommodate bicyclists in roundabouts: 1) in mixed flow with regular traffic, 2) on bicycle lanes along the outside diameter of roundabouts, and 3) along separate bicycle paths. (Figures 21 and 22 show examples of bicycle paths and crossings.) Safety studies from the Netherlands, from Switzerland, Germany, Great Britain, and France *(30, 35-37)* seem to agree on the following points:

1) Bicyclists are the most vulnerable users of roundabouts, and special attention needs to be paid to them.
2) In low-speed, single-lane roundabouts, no negative safety impacts have been observed when bicycles are mixed in the traffic stream. Because of the small speed differential, bicyclists are expected to circulate in the traffic lane at more or less the same speed as vehicles. When bike lanes lead to this type of roundabout, it is preferable to discontinue them about 10 to 20 m (33 to 66 ft) before reaching the roundabout, rather than continuing the lane through the roundabout. Bike lanes at the outer portion of the

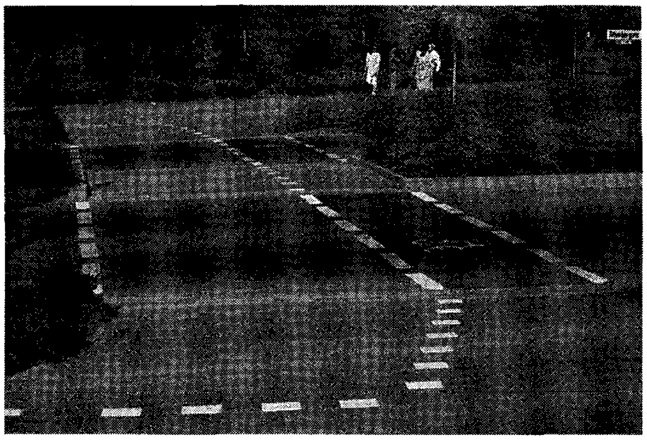


FIGURE 22 Bicycle crossing adjacent to pedestrian crossing *(11)*.

roundabout (solution 2 above) are generally not recommended *(33)*.

3) Bicycle safety tends to deteriorate at high-speed, multilane roundabouts and at flared entries. At these roundabouts, special solutions should be sought when warranted by bicycle volumes. Among the solutions are separate bikeways, possibly mixed pedestrian-bike ways, separate bike routing through other intersections, or grade separation for the vulnerable modes.

More than 50 percent of bike crashes at roundabouts involve entering vehicles and circulating bicycles, reinforcing the need to reduce entering speeds by providing ample deflection, to maintain good visibility for entering traffic, and to enforce right-of-way rules.

ISSUES FOR VISUALLY IMPAIRED PERSONS

Some concern has been expressed by organizations working with visually impaired persons regarding the ability of blind people to feel at ease in roundabouts *(personal communication, L. Franck, The Seeing Eye, Inc., Morristown, NJ, November 1996)*. A basic question is how can blind persons be made to feel safe when they step off the curb at a roundabout, or at least as safe as at a signalized intersection. This issue, based more on anecdotal evidence than actual experience, parallels the perceived issues for pedestrians mentioned above. Are pedestrians and blind users really safe at traffic signals, when in most cases they face left-turning and right-turning traffic during the same signal phase, in addition to right-turns-on-red? Left turns across oncoming traffic can be especially hazardous to pedestrians, when the left-turning driver concentrates on gaps in the opposing traffic stream and neglects to watch the pedestrian crossing *(55)*.

A blind person waiting to cross at a signalized intersection hears the parallel traffic starting at the beginning of the green phase and takes that for a walk message, but in most cases the person is still exposed to conflicts with turning traffic, and right-turn-on-red traffic. At a typical roundabout crossing located 5 to 6 m (16 to 20 ft) from the outer circle, and with a splitter island separating the inbound and outbound flows, the blind person can generally identify the stream of traffic in the nearby lane, and can cross that lane without having to worry about other turning traffic. When the person reaches the splitter island, the same process will be repeated for the other lane. Different pavement texture for the walkways will assist the blind user in finding the crosswalks.

The reasons for improved pedestrian safety at roundabouts (the lower speeds, the shorter crossing distances, and especially the simplification of the conflicts) can also lead to improved safety and feelings of ease for blind persons. To assist them, the design criteria related to pedestrian crossings are critical: keeping the crossing away from the circle lets the blind person distinguish the exiting traffic from the circulating traffic, and the splitter island constitutes the refuge where the attention shifts from one traffic stream to the other. The fact that pedestrian crossing distances are shorter than at signalized intersections should be an important advantage for visually impaired persons.

As for any other intersection, it is important to design the sidewalk and crossings so that blind persons can find their way through the intersection and can sense when they leave the sidewalk or the splitter island, and when they arrive at the splitter island or the sidewalk on the other side. Special pavement or textured pavement, in conjunction with ramps, included in the standard design is helpful in leading the blind to the crossings. Because the pedestrian area on the splitter island needs to be recognizable to blind persons, some changes in surface, texture, or grade for that portion of the splitter island is needed. For roundabouts in urban areas, designers should follow the requirements set forth in the Americans with Disabilities Act (ADA) Guidelines.

A visually impaired person living near the Montpelier, Vermont roundabout reported feeling at ease crossing this roundabout. After she found the new crossings and got used to the layout, she actually preferred the roundabout to the previous one-way stop-controlled intersection, primarily because vehicles on the main road now approach at slower speeds and are thus more likely to stop than they were before *(personal communication, J. Shiner, Vermont Center for Independent Living, July 1997)*.

CHAPTER NINE

LOCATION CRITERIA FOR ROUNDABOUTS AND U.S. EXAMPLES

APPROPRIATE LOCATIONS FOR ROUNDABOUTS

Most of the guidelines *(3, 10–12, 17–21, 23, 29)* describe appropriate locations or conditions for roundabout installation, listed as follows:

- High accident locations, especially locations with high accidents related to cross movements or left-turn or right-turn movements.
- Locations with high delays.
- Locations where traffic signals are not warranted.
- Four-way stop intersections.
- Intersections with more than four legs.
- Intersections with unusual geometry (Y-intersections or acute-angle cross intersections).
- Intersections with high left-turn flows.
- Intersections with changing traffic patterns.
- Intersections where U-turns are frequent or desirable, i.e., in conjunction with access management strategies (raised median) along commercial corridors.
- At locations where storage capacities for signalized intersections are restricted, or where the queues created by signalized intersections cause operational or safety problems, i.e. diamond interchanges, intersections near rail underpasses, bridges, and tunnels.
- To replace a pair of closely spaced intersections.
- Along congested arterials, in lieu of full-length road widening.
- Intersections where the character or speed of the road changes, e.g., at entry points to a community or at junctions where a bypass road connects to an arterial.
- Intersections that are important from an urban design or visual point of view (as long as the basic engineering and safety criteria can be satisfied).

INAPPROPRIATE LOCATIONS FOR ROUNDABOUTS

The following conditions are generally mentioned as being unfavorable for roundabouts:

- Locations where there is insufficient space for an acceptable outside diameter. Single-lane roundabouts generally consume more space than equivalent signalized intersections at the junction itself, but their approaches are often narrower. Multi-lane roundabouts compare more favorably in terms of space consumption.
- Locations where it would be difficult to provide a flat plateau for the roundabout construction. Most guides recommend maximum grades of three to five percent depending on design speed.
- Locations within a coordinated signal network, where the roundabout would disrupt the platoons.
- Locations with heavy flows on the major road and low flows on the minor road, where the equal opportunity treatment of the approaches causes undue delays to the major road.

Other conditions are sometimes mentioned as potentially problematic; however, they do not necessarily eliminate the roundabout as an improvement alternative. As for any other intersection, these conditions need special attention regarding design and operational aspects, and a detailed analysis of alternatives is required. Such conditions include:

- Presence of numerous bicycles or pedestrians. These can be addressed through special design features such as separate bicycle lanes, zebra striping, pedestrian underpasses, or pedestrian-activated signals farther away from the roundabout.
- Presence of numerous disabled and blind users. Provision of special surface treatment should be considered to mark the pedestrian paths. Pedestrian activated signals with audible messages can be considered.
- Large proportion of heavy vehicles. These can be addressed through more generous dimensions.
- Presence of fire station. Similar design precautions are taken as with signalized intersections. Special signals can be set up.
- Rail crossings. Precautions are taken similar to other intersections.
- Junction at top or bottom of grade. If the sight distances at the approaches are not adequate, special advance signs or signals need to be installed.
- Proximity of adjacent signals. Undisciplined drivers may block a roundabout as they do at a signalized intersection.

EXAMPLES OF ROUNDABOUTS IN THE UNITED STATES

Three examples of roundabouts built in the United States are presented to document their characteristics and the range of applications. The first of these cases is a simple one-lane roundabout in a rural environment in the state of Maryland; the second case is a retrofit of an old, multi-lane traffic circle in Long Beach, California; and the third is the roundabout interchange built at I-70/Vail Road in Vail, Colorado.

Lisbon, Maryland

This roundabout became operational in April 1993. It is a single-lane roundabout at the intersection of two state highways

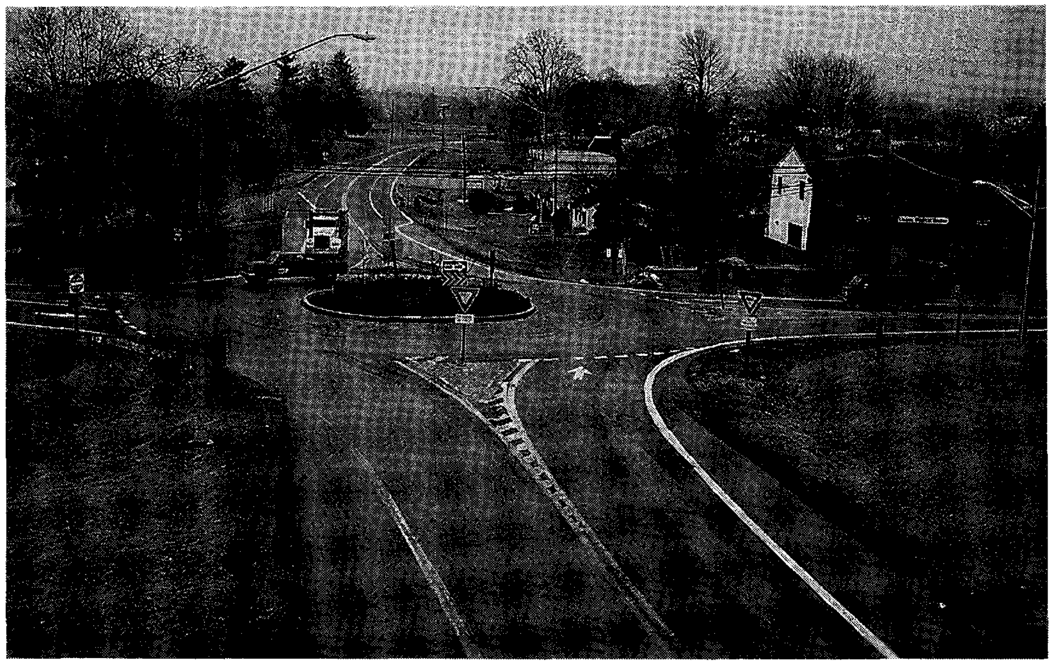


FIGURE 23 View of roundabout approach, Lisbon, Maryland *(courtesy of Maryland DOT).*

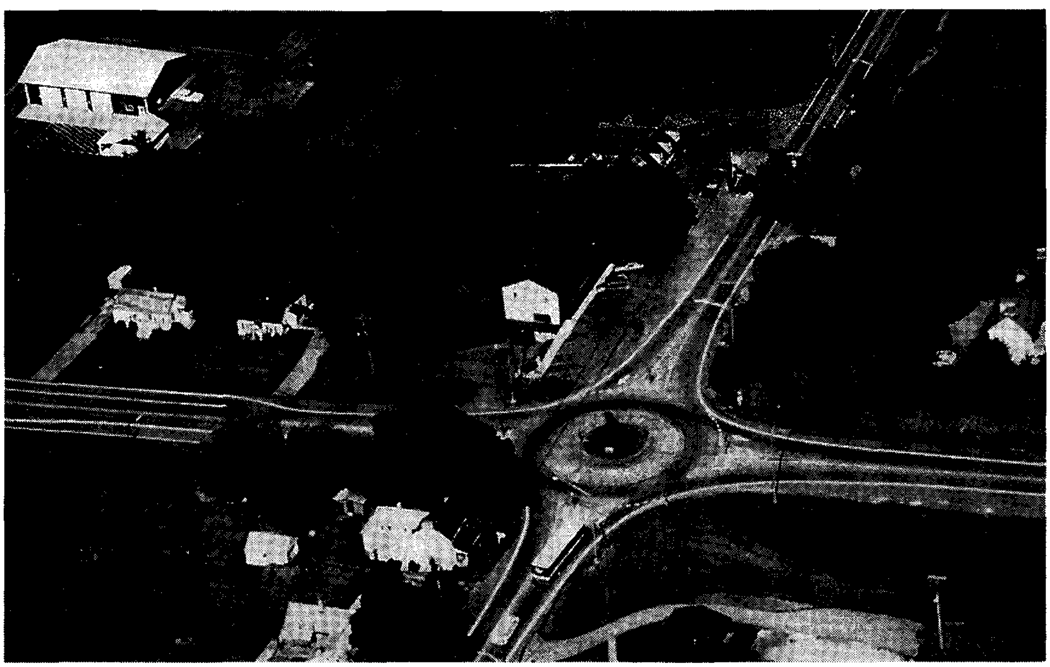


FIGURE 24 Aerial view of roundabout approach, Lisbon, Maryland *(courtesy of Maryland DOT).*

(Maryland Routes 94 and 144) in the town of Lisbon, Maryland, in a rural environment. See the approach view in Figure 23 and the aerial view in Figure 24. The layout diagram is shown in Figure 25. Figures 26 through 28 show approach and entrance details for the Lisbon roundabout. The AADT on the major road is 6,700 and on the minor road 4,200. This roundabout replaced a cross intersection regulated by a two-way flashing red beacon.

The geometry is relatively simple, with an inscribed diameter of 30.5 m (100 ft) and with entry and circulating widths of 5.5 m (18 ft). A truck apron of 3.6 m (12 ft) surrounds the landscaped, raised portion of the central island.

The total accident rates at this intersection decreased from an average of 7.4 accidents per year before the roundabout (measured over a 40-month period) to 1.4 accidents per year after the roundabout (measured over a 42-month period). Injury

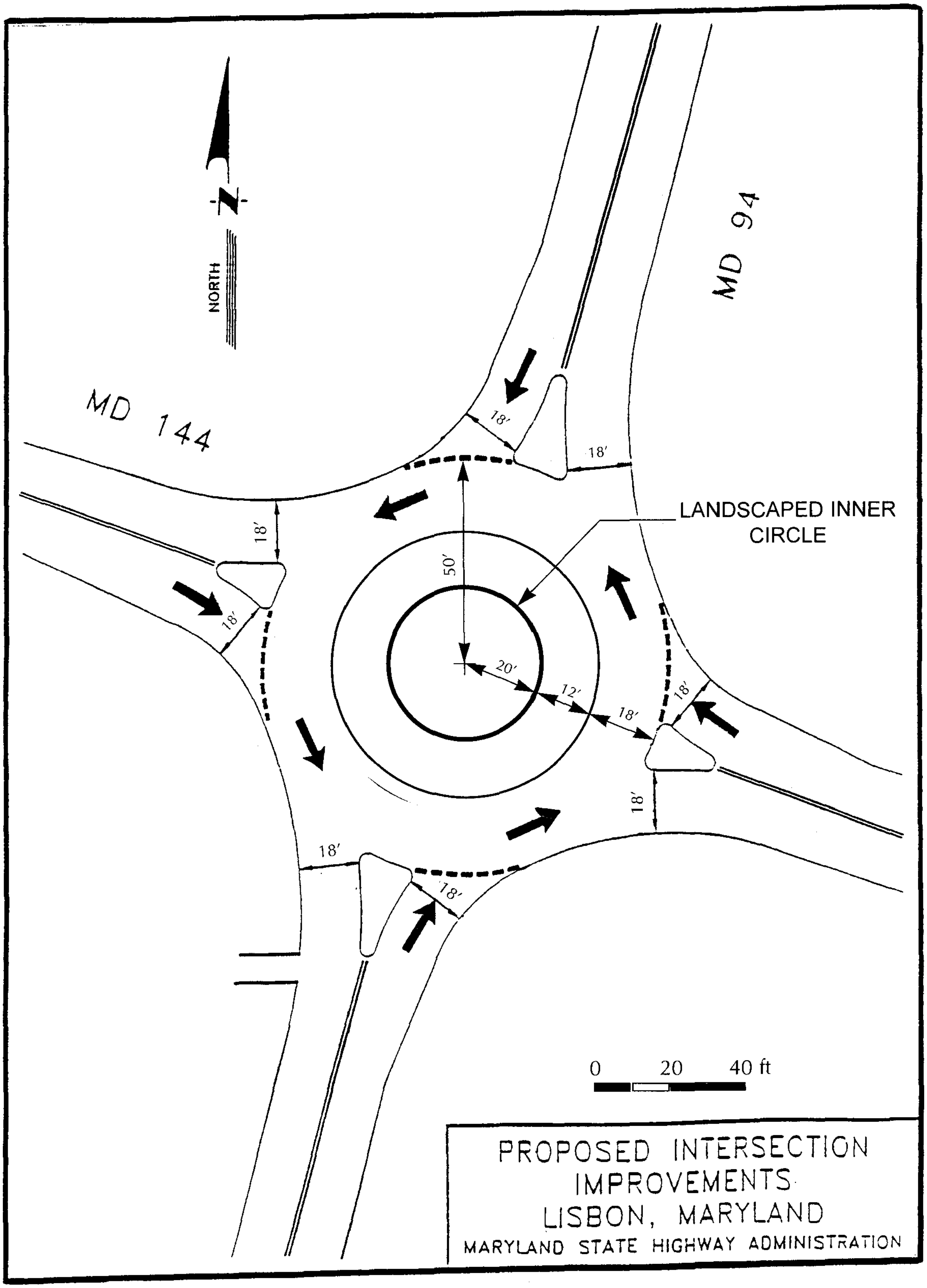


FIGURE 25 Layout of roundabout, Lisbon, Maryland.

FIGURE 26 Sign at northbound approach, Lisbon, Maryland.

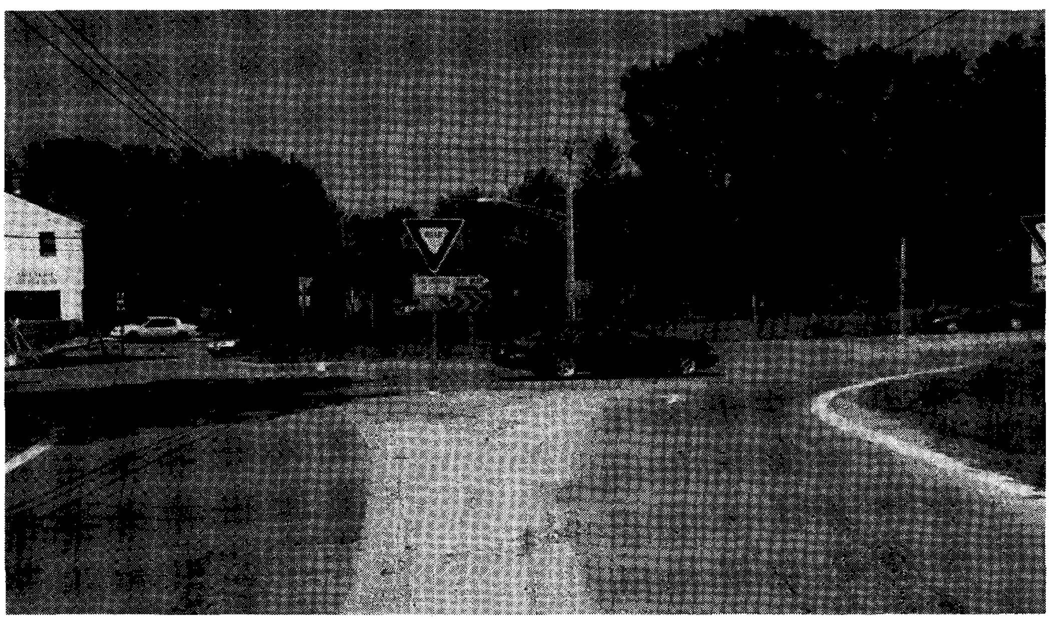


FIGURE 27 Westbound entrance to Lisbon, Maryland roundabout.

crashes decreased from 4.3 per year to 0.3, and property-damage-only accidents decreased from 3.1 to 1.1. Before the roundabout, the crashes were almost all angle accidents, whereas after the roundabout, half were single-vehicle crashes against fixed objects and the remaining accidents were angle or rear-end crashes.

Total delays decreased from 1.2 vehicle hours to 0.34 vehicle hours in the morning peak hour and from 1.09 vehicle hours to 0.92 vehicle hours in the afternoon peak hour, an overall reduction of 45 percent.

This was the first roundabout built by Maryland DOT. It was constructed by their maintenance forces at a total cost of $194,000 plus engineering costs of $40,000. The roundabout was first built as a temporary roundabout to test the installation. Maryland DOT distributed a seven-page informational brochure explaining the change and inviting residents to call a toll-free number for more information. Media coverage before and after the construction of the Lisbon roundabout is shown in Appendix E.

Los Alamitos Circle in Long Beach, California

The Los Alamitos traffic circle in Long Beach, California was built in the early 1930s as one of the major intersections

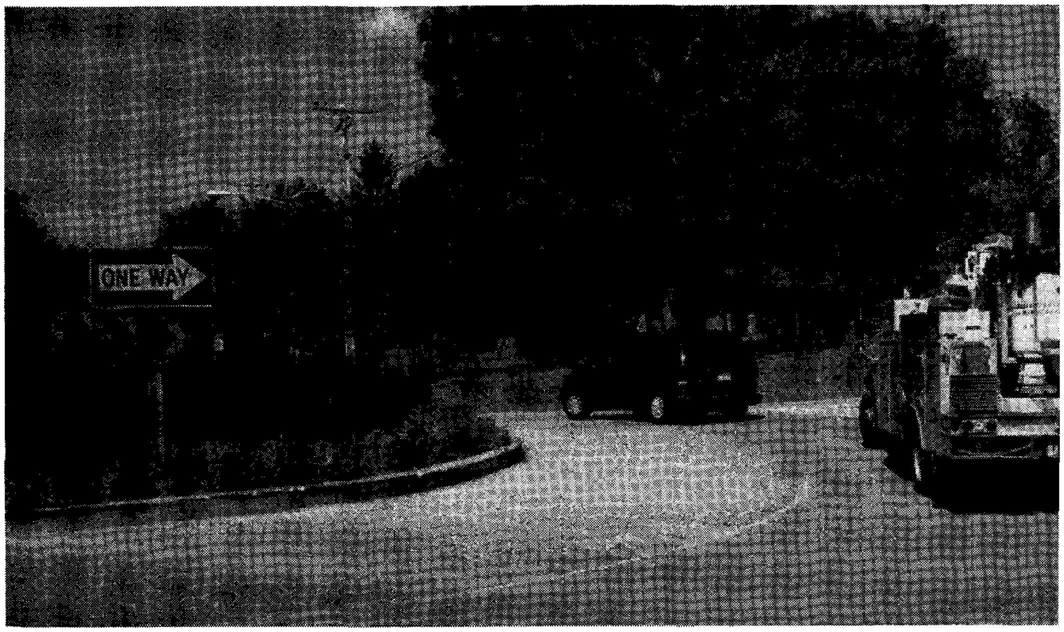


FIGURE 28 Central island and truck apron of Lisbon, Maryland roundabout.

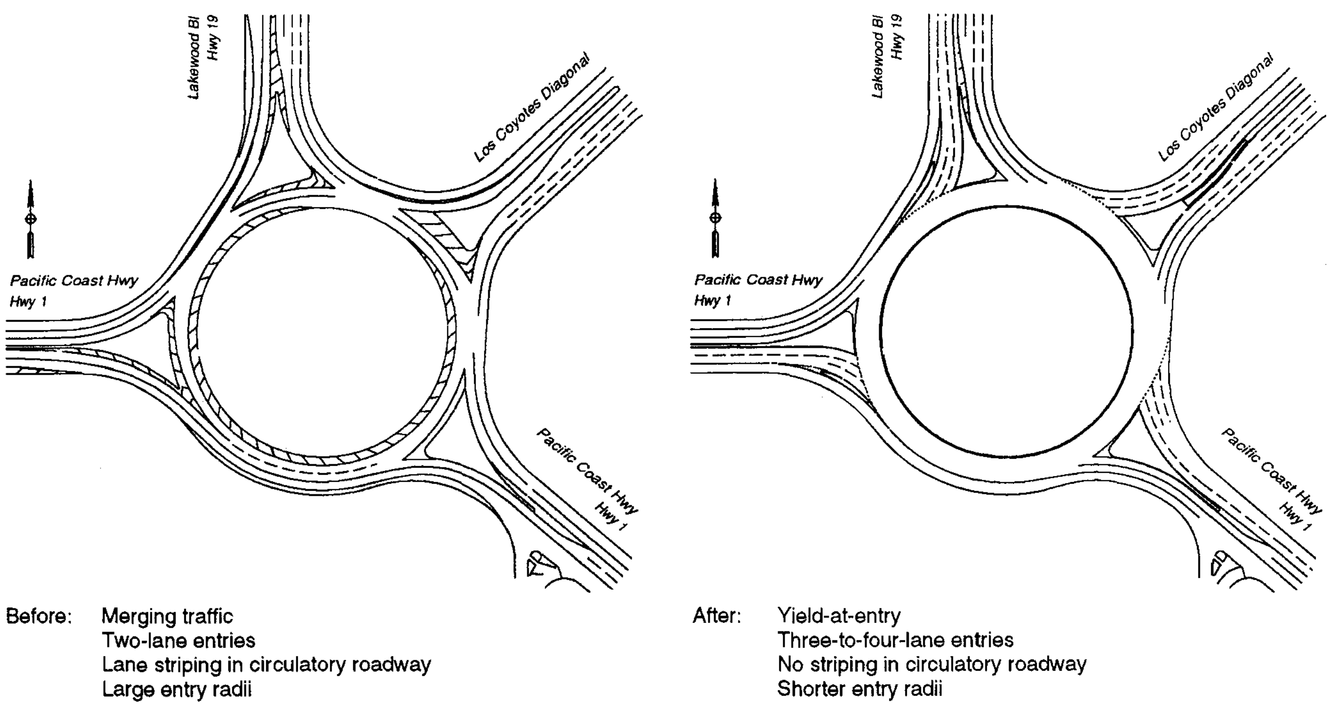


FIGURE 29 Los Alamitos traffic circle in Long Beach, California, on left; roundabout on right *(58)*.

along the Pacific Coast Highway. Previously two of the entries were uncontrolled. Long queues formed regularly at the approaches and in the circle.

In June 1993, the old "nonconforming" circle became the first to be converted to a modern roundabout. This conversion involved a change to all entries, bringing greater deflection to the entering movement (by reducing the entry angles and making them less tangential), by changing them to yield control entries (with YIELD signs, yield lines, and YIELD legends at the entries and "YIELD AHEAD" signs and markings on the pavement), and by flaring the entries to three or four lanes to increase entry capacity. Lane stripings in the circulatory roadway were eliminated. Two bypass lanes are provided for the major right-turn movements (see Figure 29). Figure 30 shows details of two entries before and after roundabout conversion. The inscribed diameter of the circle was kept at 143 m (470

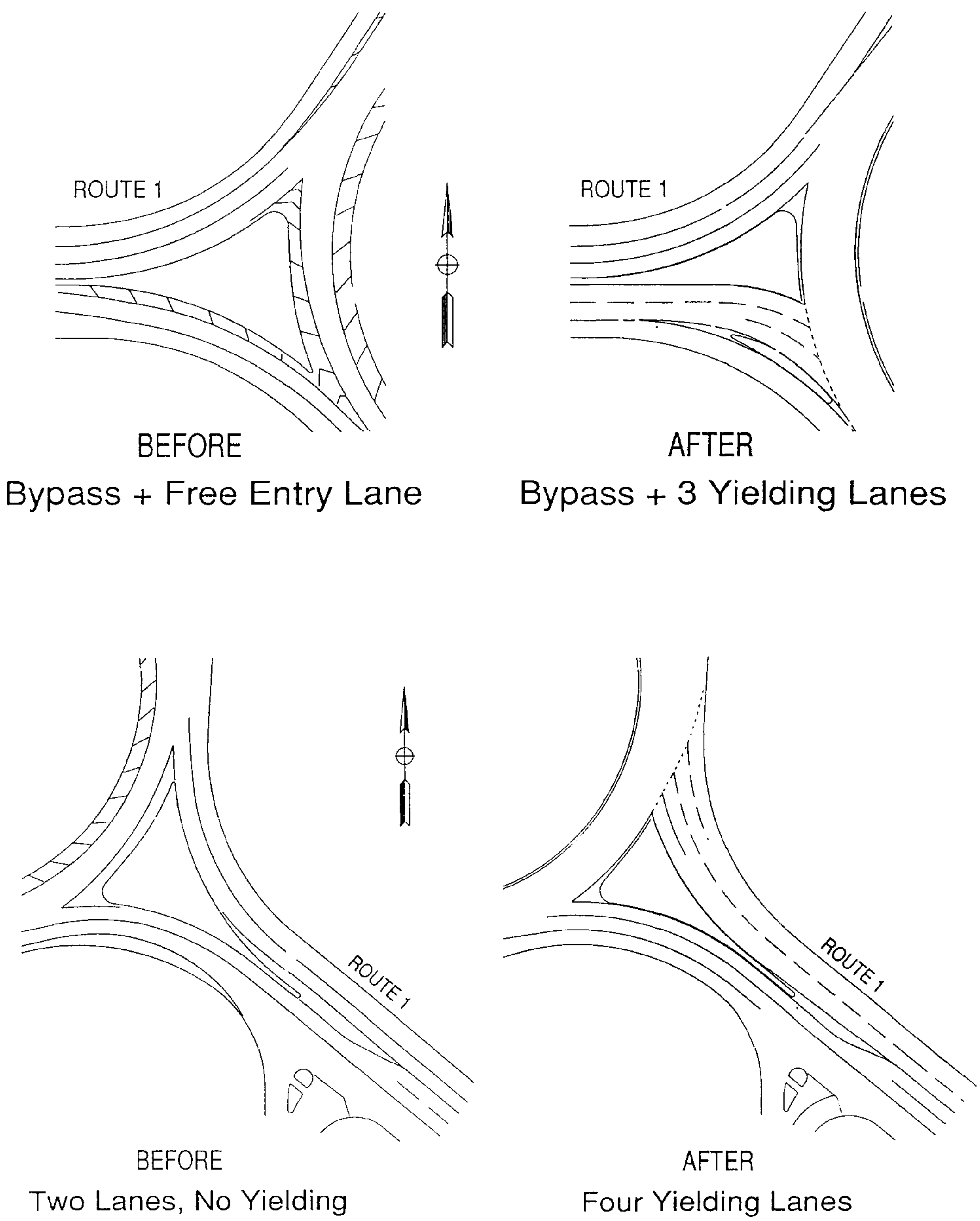


FIGURE 30 Los Alamitos entries, before and after roundabout design *(58)*.

ft), which is unusually large for a modern roundabout. The cost of this conversion was $238,000, plus $162,000 for study, design, and engineering (1993 dollars).

Peak-hour flows entering the roundabout are 4,400 vehicles in the morning and 4,700 in the evening. After roundabout construction peak-hour delays, averaged over all approaches, were between 4 and 5 seconds per vehicle (level of service A). Each approach operated at level of service A or B *(58)*.

Total annual accidents decreased from 37.3 before the roundabout to 24 after the roundabout, a reduction of 36 percent. Injury accidents decreased from 11.3 to 9, a reduction of 20 percent. A summary of the accidents during the first 8 months of roundabout operation indicates that practically all of the vehicles involved in an accident were registered locally, and that no accidents involved large trucks, buses, pedestrians, or bicycles. The predominant accident type involved entering or exiting vehicles.

The final study performed for this roundabout conversion recommended an alternative roundabout design with a smaller diameter of 91 m (300 ft). This smaller roundabout would lower average speeds from about 52 kmph (32 mph) to 40 kmph (25 mph), and would tend to reduce the number of accidents, especially the injury accidents. The relatively small reduction in injury accidents observed at this roundabout (compared to the reduction in total accidents and to the reduction in injury accidents at the other roundabouts) is probably

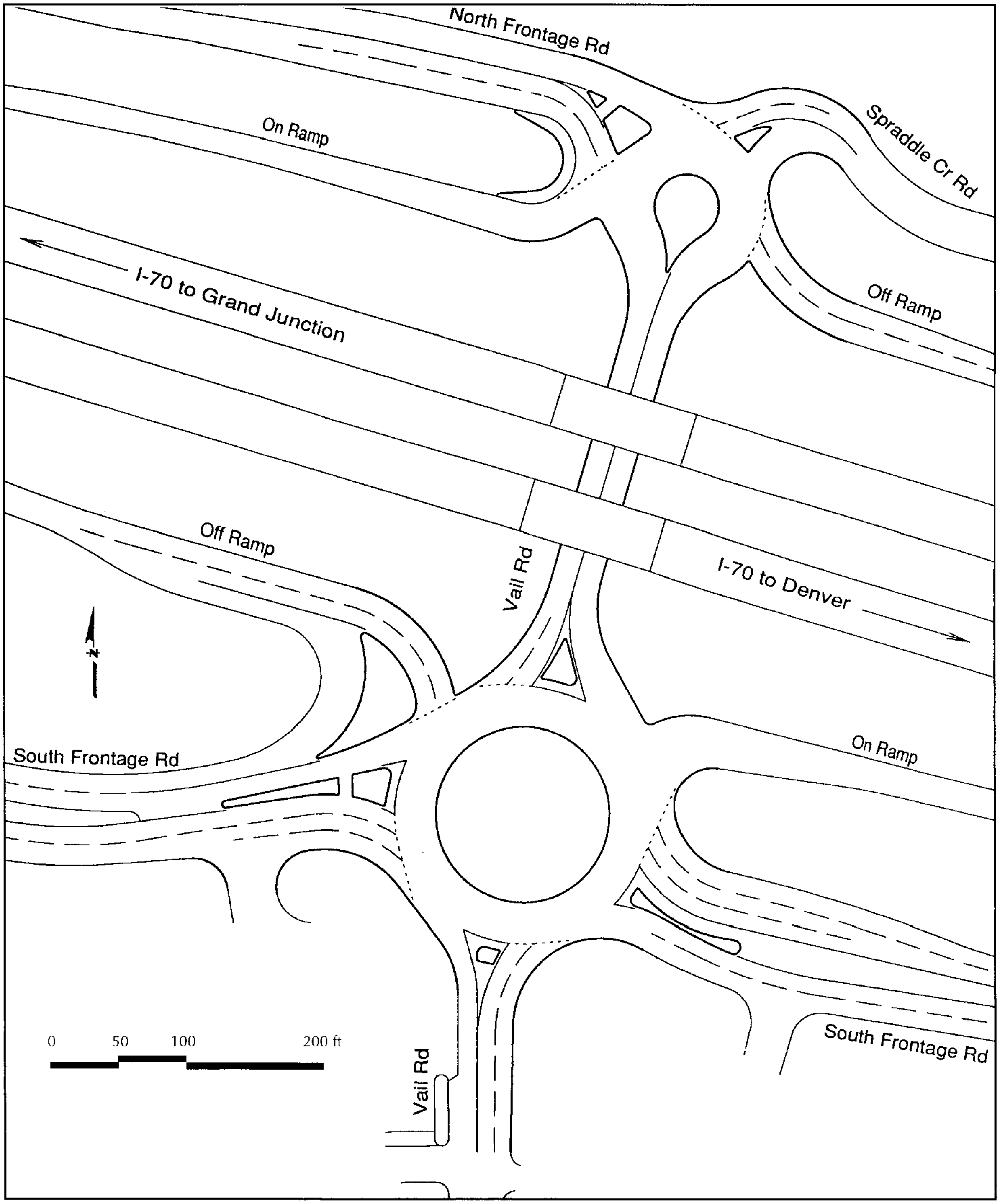


FIGURE 31 I-70/Vail Road interchange layout, Vail, Colorado *(59)*.

due to the fact that the average speed is still relatively high. The smaller roundabout was not implemented because some natural features of the central island would be lost.

I-70/Vail Road Interchange Roundabouts in Vail, Colorado

Built in 1995, this is the first two-roundabout interchange in the United States. It replaces stop-controlled intersections that needed the assistance of traffic officers directing traffic during the seasonal peaks. It includes a raindrop roundabout with an inscribed diameter of 37 m (120 ft) at the northern side of the interchange and a regular roundabout with an inscribed diameter of 61 m (200 ft) at the southern side. The raindrop roundabout on the northern side has its circulatory roadway interrupted at the branch connecting to the southern roundabout. This feature provides for one free-flowing entry and, in this case, eliminates one minor left-turn movement and

FIGURE 32 Aerial view of roundabout at I-70 and Vail Road, Vail Colorado *(courtesy of MK Centennial).*

two minor U-turn movements. Those minor movements can be made at the other roundabout. In this case the raindrop roundabout, built on a four-percent grade, prevented circling the low side of the central island, where adverse superelevation could have caused trucks to overturn. The south roundabout has two- and three-lane entries and a right-turn bypass lane for the eastbound I-70 off-ramp. The circular roadway is 11 m (36 ft) wide. This roundabout carries a peak hour flow of 3,400 vehicles and is designed for a flow of 5,500 vehicles. The north roundabout is smaller and carries less traffic.

Figure 31 shows the layout of this interchange. The circulatory roadways are not divided into lanes. Figure 32 shows an aerial view of the I-70 interchange. A critical feature of the two-roundabout interchange is the narrow link under the freeway between the two roundabouts. A more traditional signalized interchange would have required the widening of this underpass, which would be the most expensive item of such an improvement. This is a good illustration of the "wide node and narrow link" concept of roundabouts.

This interchange cost a total of $2.8 million (including $200,000 for maintenance of traffic). Design and engineering costs were $375,000. This cost is substantially less than traditional alternatives that would have required a widening of the underpass. It also saves the town of Vail $85,000 per year in traffic direction officers.

Total crashes for both roundabouts decreased from 27 to 22 in the first year of operation. Injury accidents decreased from 6 (including one bicycle accident) to 3. The north roundabout experienced the greatest reduction in crashes, whereas the south roundabout actually experienced a slight increase in PDO accidents.

Before the roundabout, long delays were observed, with frequent backups onto the freeway during the peak season. After the roundabout construction peak-hour delays were less than 4 seconds per vehicle.

CHAPTER TEN

CONCLUSIONS

Although there are fewer than 50 roundabouts in use in the United States, they represent a variety of designs and applications. Roundabouts have been built in urban, suburban, and rural environments, and on arterial roads, collectors, and local streets. Of those roundabouts described in the survey responses, about two-thirds are single-lane roundabouts and one-third are multi-lane. Three diamond freeway interchanges operate with two roundabouts each and the town of Avon, Colorado, built a string of five high-capacity roundabouts along a commercial arterial, tying them together with a cultural theme in the central island treatment.

Peak-hour traffic volumes entering the existing roundabouts range from a few hundred to 4,700 vehicles. Peak-hour flows at a quarter of the roundabouts in the United States exceed 2,500 vehicles. For most roundabouts, the outside diameters are in the range of 30 to 60 m (100 to 200 ft), with the single-lane roundabouts in the lower ranges, and the multi-lane roundabouts and those with more than four branches in the upper ranges. One roundabout with an outside diameter of 143 m (470 ft) is a conversion from an old traffic circle.

All of the survey respondents agreed that U.S. roundabouts performed well in terms of the following criteria:

- Shorter delays,
- Increased capacity,
- Improved safety, and
- Improved aesthetics.

The opinions of the survey respondents were unanimous in that they reported only positive or neutral impacts of their roundabouts on the above criteria. No negative impacts were reported for those key criteria.

Delay measurements at seven roundabout sites showed that the peak-hour delays decreased by about 75 percent, in relation to the previous traffic control.

Before-and-after crash statistics at 11 existing roundabouts showed a reduction of 37 percent in total crashes, 51 percent in injury crashes, and 29 percent in property-damage-only crashes. For the eight small-to-moderate-size roundabouts, with an outside diameter of up to 37 m (121 ft), the crash reductions were statistically significant for total crashes (a reduction of 51 percent) and for injury crashes (a reduction of 73 percent). Property-damage-only crashes showed favorable trends, but were not statistically significant. For the three larger roundabouts, the crash statistics also showed favorable trends (a 10-to-31-percent reduction in crashes, depending on the category), but the changes were not statistically significant. Safety benefits were achieved even though drivers may have been confused by the new type of intersection.

In addition to the design and operational reasons for greater safety, roundabouts appear to have positive impacts on driver behavior and attitude. Slower speeds make drivers more aware of their environment and of the other users. Yielding to traffic in the circle induces a higher level of responsibility by the driver as compared to the "go" message perceived with a green light.

The roundabout marks a departure from traditional highway design practice, where greater safety is generally achieved through higher design speeds. The roundabout is a clear case where the safety benefits come from lowering design speeds, by installing, in effect, an "obstacle" in the straight path of vehicles. Deflection around the central island is one of the most important design criteria of the modern roundabout. It is a key reason for its greater safety. By contrast, at signalized intersections traffic does not slow down during the green signal phase.

Reaction to roundabouts by the general public and by the media has been positive. The survey respondents indicated that the attitude changed from 65 percent negative or very negative to zero percent negative or very negative. This was confirmed by a public attitude survey in Montpelier, Vermont, where 86 percent of the respondents had neutral or favorable opinions about the roundabout, and by a tracking of comments in Santa Barbara, California, where 72 percent of the individual comments were in favor of the roundabout, and 28 percent were negative. The negative comments in Santa Barbara concerned mainly the lack of pedestrian crossings across some of the legs, and the violation of right-of-way rules.

Most of the guidelines describe appropriate locations or conditions for roundabout installation. They generally include high-accident locations (in particular locations with accidents related to cross movements or turning movements), locations with high delays, locations where signals are not warranted, locations where U-turns are frequent or desirable (possibly in conjunction with access management strategies), and intersections where the character or speed of the road changes. Substantial cost savings can be achieved at locations where space for storage capacities needed for signal control is restricted. These include roundabouts at freeway interchanges, such as the two-roundabout interchanges in Vail, Colorado and in Avon, Colorado, and intersections near rail underpasses, bridges, and tunnels.

Inappropriate locations include cases where there is not enough room for an acceptable outside diameter or where it would be difficult to provide a flat plateau (maximum three to five percent grade) for roundabout construction. Locations within a coordinated signal network may not be appropriate because of the dispersion of the platoons caused by the roundabout. Intersections with heavy flows on the major road and low volumes on the minor road may also not be appropriate, because of the undue delays imposed on the major flows.

Other conditions are sometimes mentioned as potentially problematic; however, they would not necessarily eliminate the roundabout as an improvement alternative. As with any other intersection, these conditions need special attention in the design phase. Such conditions include the presence of numerous bicycles or pedestrians, or numerous disabled or blind users, the presence of a fire station or rail crossing, and the proximity of signalized intersections.

The most significant new opportunity introduced by the roundabout is the aesthetic and visual impact that this type of intersection can have. Unlike other traffic control measures, the roundabout can bring very positive visual changes to a location. A landscaped central island or an island with a sculptural feature creates a break in a visual corridor; it can mark a place and add some importance to the environment. These benefits are perceived by drivers as well as by the non-driving public. Positive commercial and real estate impacts can be expected from this type of aesthetic improvement.

Some towns have built roundabouts where one of the primary objectives is the urban design improvement. The town of Avon, Colorado, has built a string of five roundabouts along Avon Road with a cultural theme through a common treatment of the central islands.

This study and associated survey found that more information is needed to familiarize planners, engineers, and government officials with the characteristics of roundabouts and with their potential advantages and disadvantages. The difference between modern roundabouts and nonconforming traffic circles needs to be made clear. It would be useful for transportation programs at the college or university level to include roundabouts in their courses.

Survey respondents expressed a need for guidelines and standards at the national level regarding geometric design, signing, and markings, to assist state and local communities in implementing roundabouts and avoiding mistakes. Useful guidelines would address the variety of roundabouts currently existing in the United States, i.e., single-lane, multi-lane, interchange roundabouts, and mini-roundabouts.

Research regarding roundabout construction procedures and costs will be useful to develop the most cost-effective techniques to build them and to maintain traffic flow during construction. Appropriate maintenance procedures, especially as they relate to design elements, e.g., mountable curbs or islands, will be very beneficial.

The integration of pedestrians (including those who are blind), bicycles, and mopeds with roundabout traffic requires further study and consensus building. Standard treatments for the more vulnerable users will be helpful to the designers. Criteria are needed to determine whether the roundabout design is appropriate for these types of users and whether special features, such as pedestrian-actuated signals, should be implemented.

Finally, the survey identified a need for further research regarding alternative methods to analyze the performance of roundabouts. The methods currently used to estimate capacities and delays of roundabouts are not always consistent, although their predictions are moving closer to each other. The analytic gap acceptance method, currently used most often in the United States, is mentioned as the most appropriate approach, because of the lack of saturated U.S. roundabouts that would provide more specific data on capacity. However, it represents an indirect way to estimate capacities and to assist in the geometric design of roundabouts. Empirical formulas in use throughout Europe are simpler and allow the designer to test different design solutions in a more interactive manner. These alternative methods need to be evaluated and compared, and their validation processes need to be researched to determine the best way to design roundabouts and to analyze their performance. Research related to crash rates and roundabout geometry could lead to safer roundabout design.

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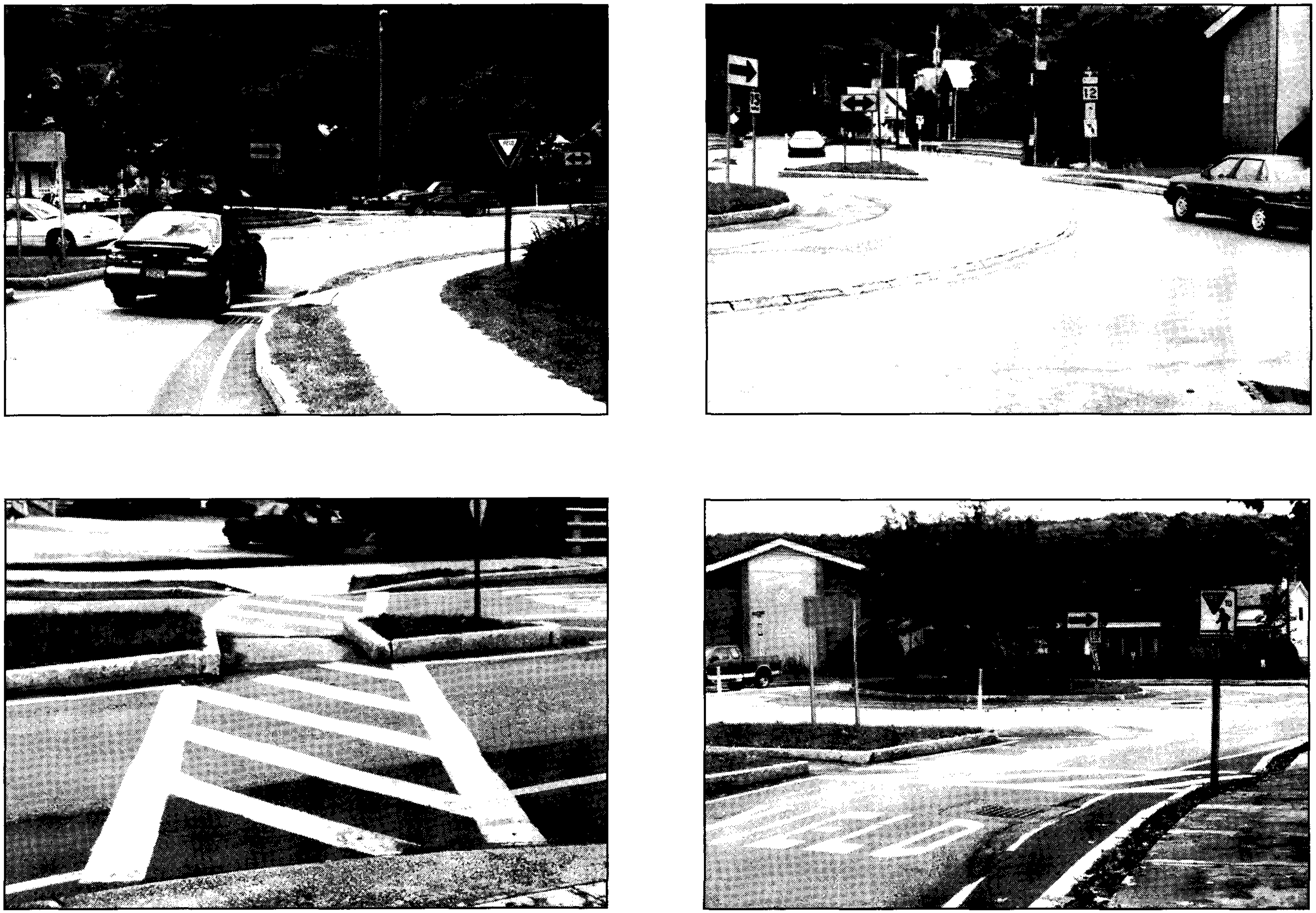
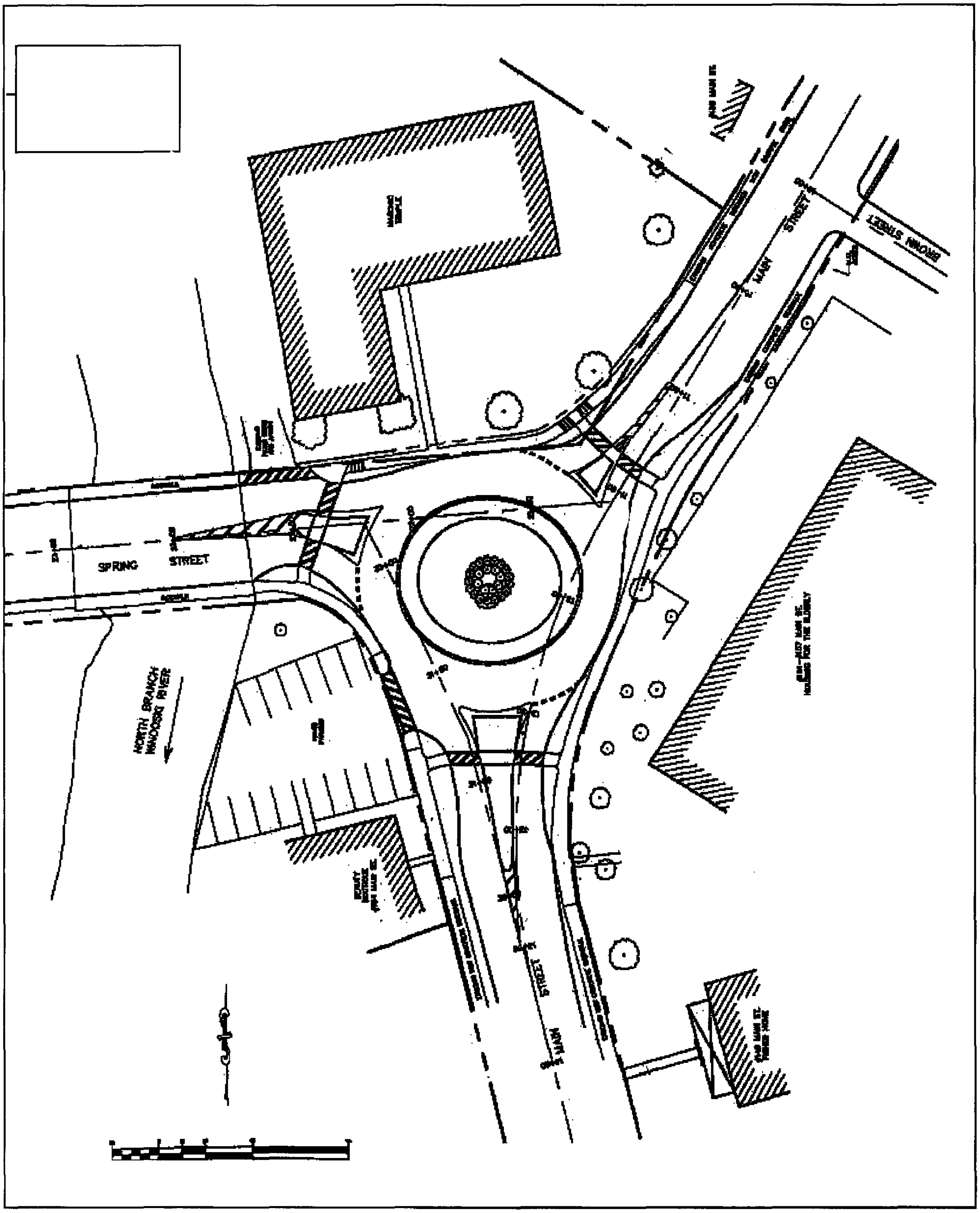
APPENDIX A

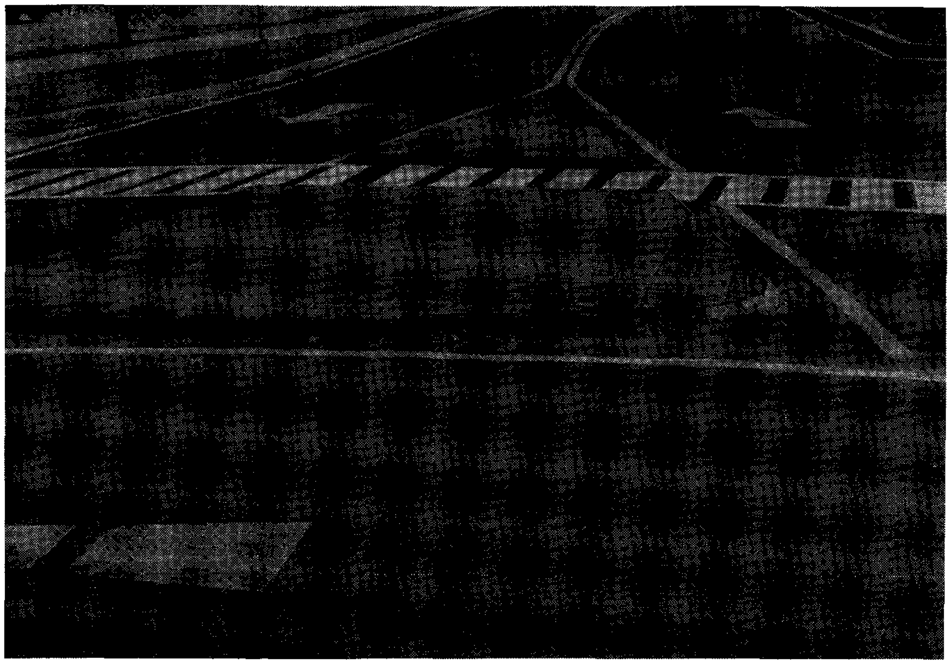
Layouts of Typical Roundabouts Built in Recent Years



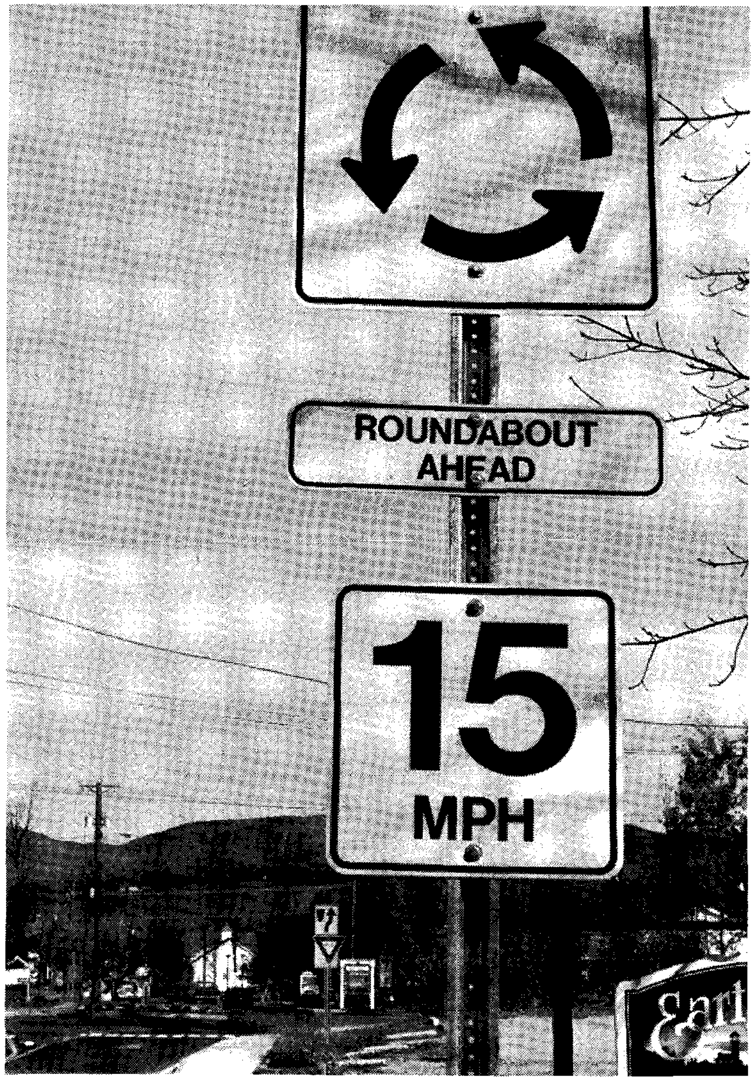
Signs and markings at Keck Circle in Montpelier, Vermont *(Courtesy of Tony Reddington).*



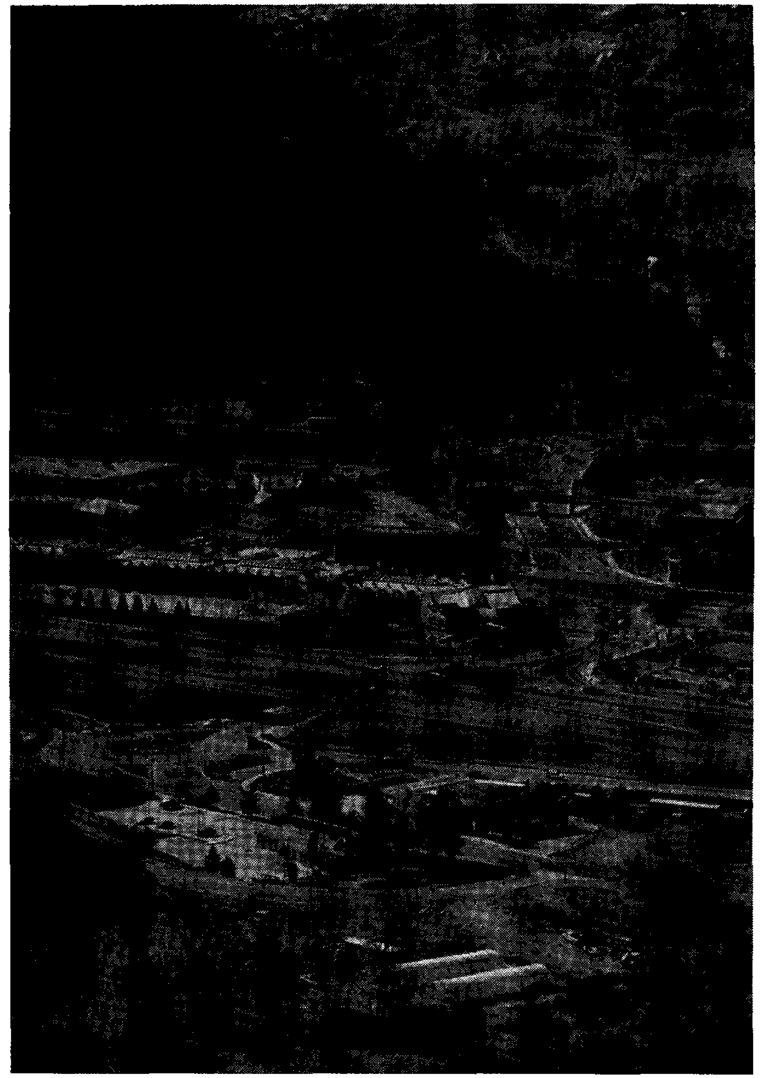
Spring and Main Streets, Montpelier, Vermont *(Courtesy of Pinkham Engineering Associates, Inc.)*



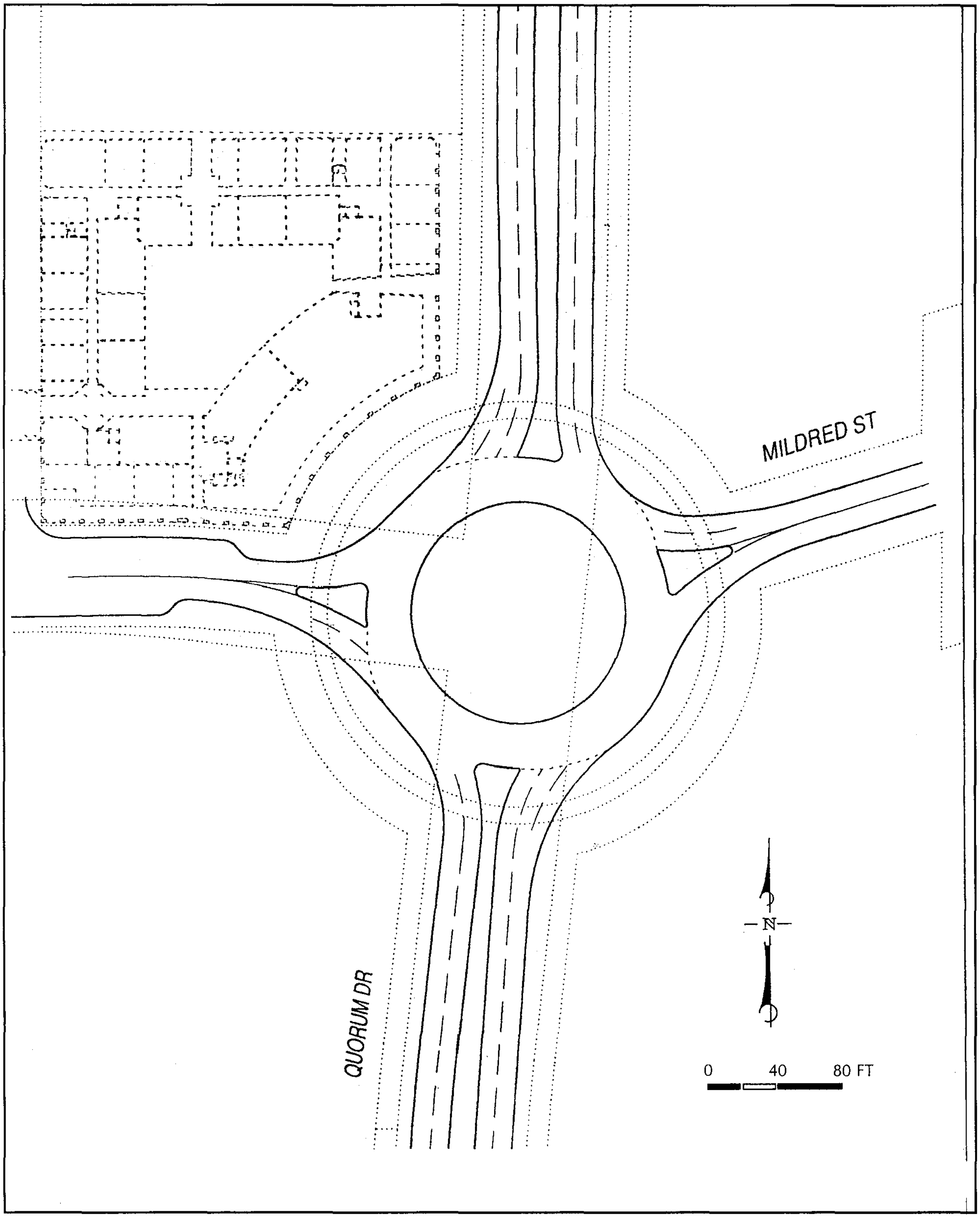
Mountable splitter island, signs and markings in Manchester, Vermont *(Courtesy of Tony Reddington).*



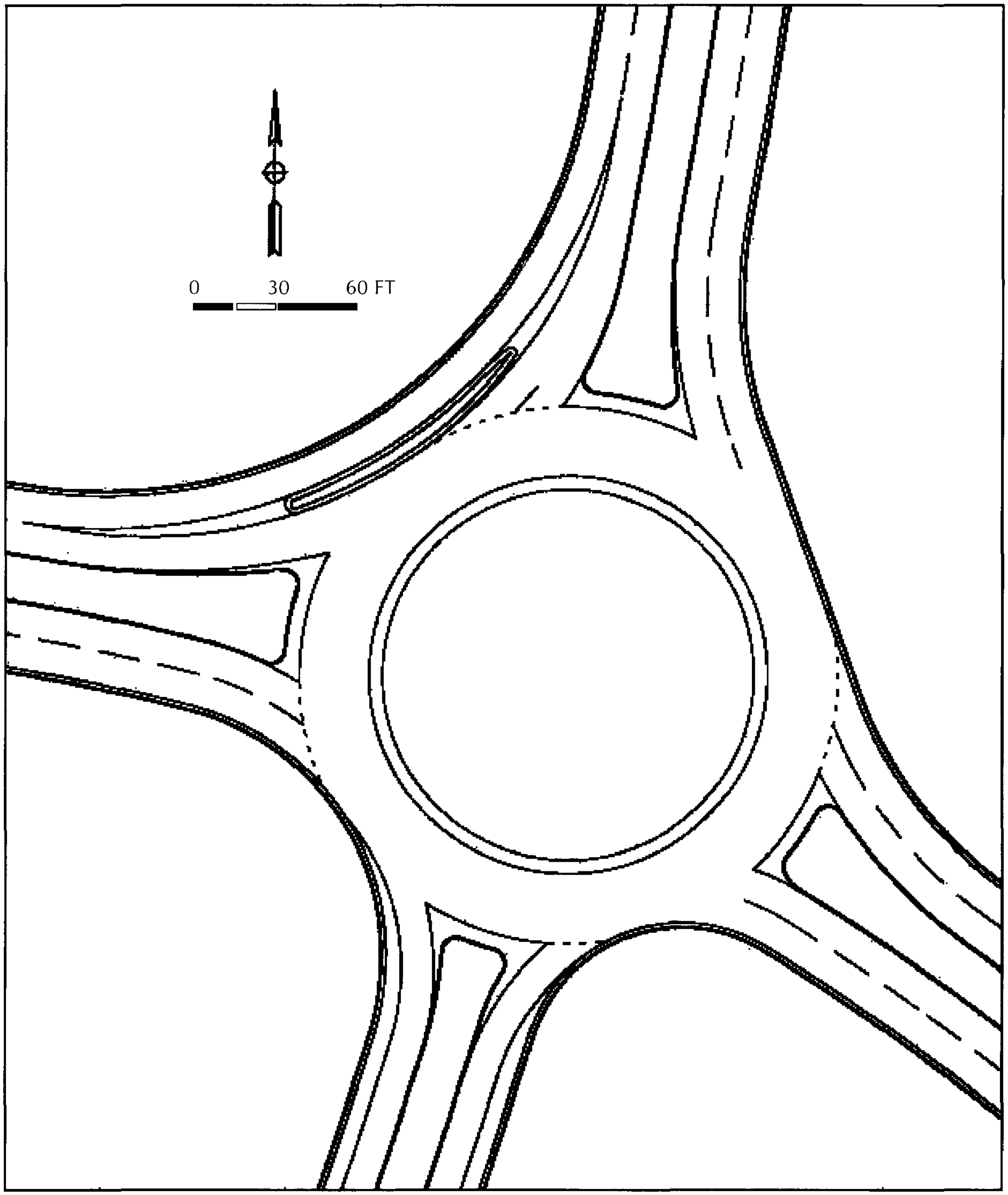
Advance signs in Manchester, Vermont *(Courtesy of Tony Reddington).*



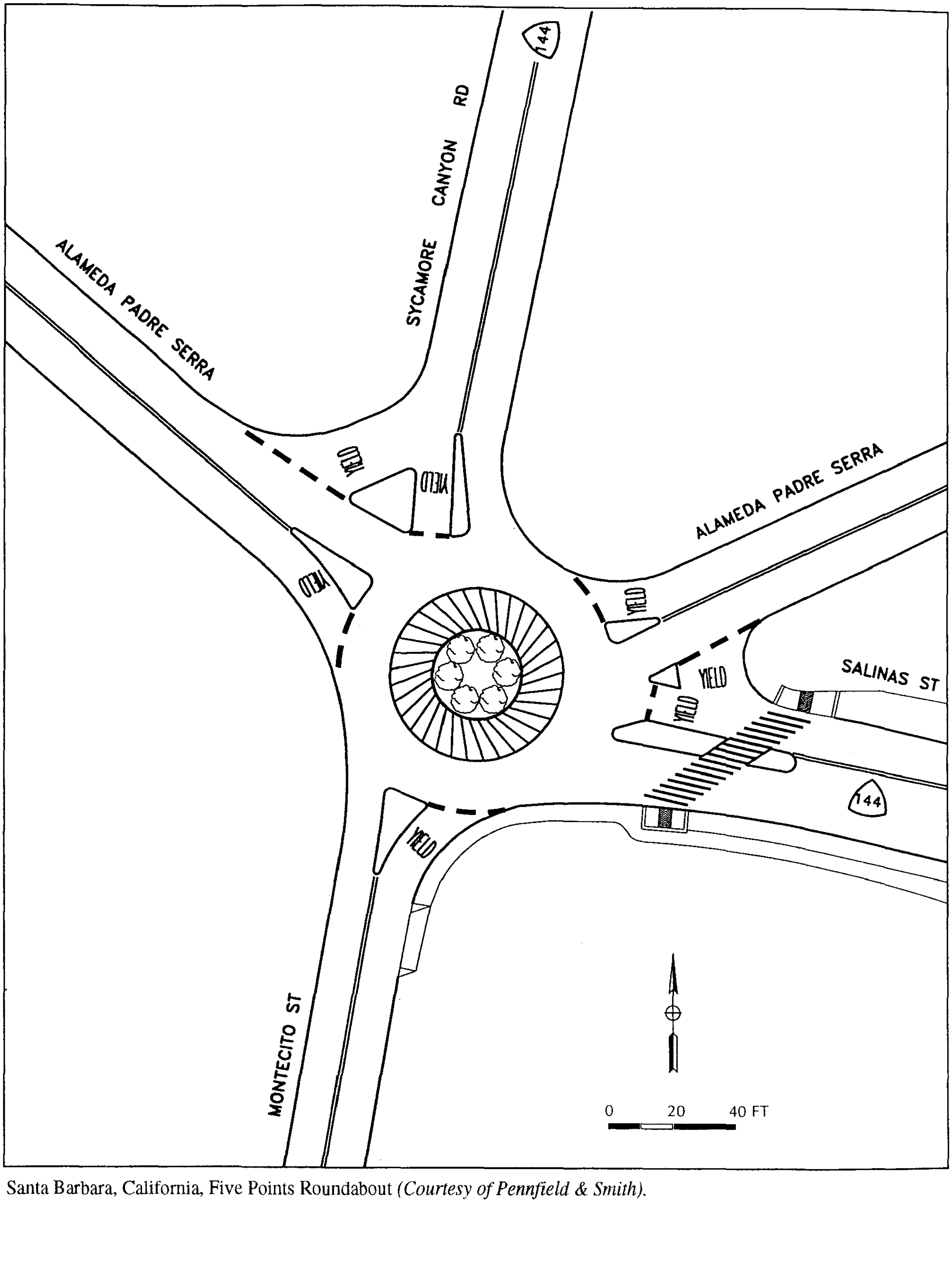
Five roundabouts in Avon, Colorado *(Courtesy of Peter Doctors).*



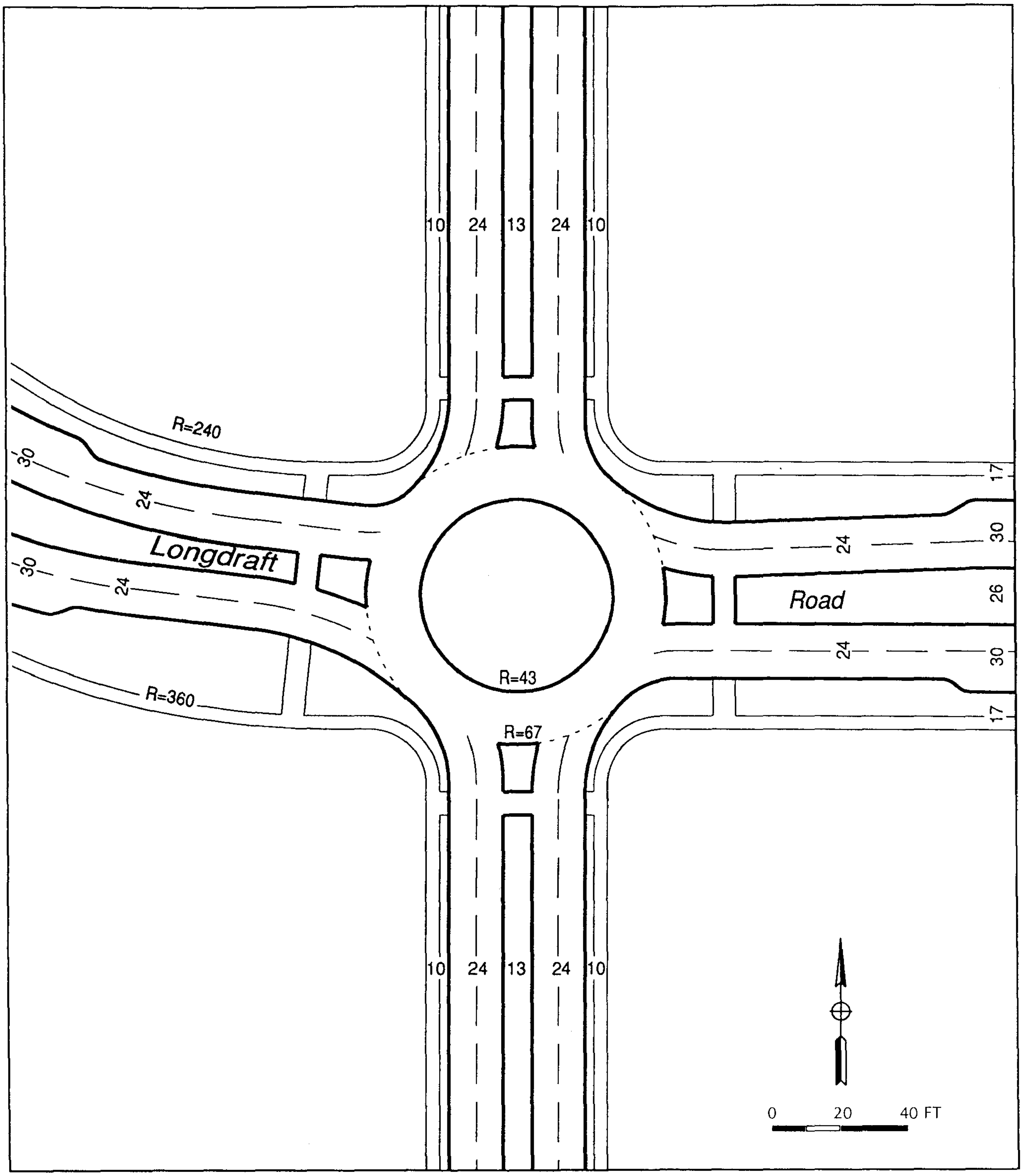
Quorum Drive and Mildred Street, Addison, Texas *(Courtesy of Ourston & Doctors).*



Summerlin, Las Vegas, Nevada, North Roundabout *(Courtesy of Ourston & Doctors).*



Santa Barbara, California, Five Points Roundabout *(Courtesy of Pennfield & Smith).*



Gaithersburg, Maryland, Kentlands Roundabout *(Courtesy of Ourston & Doctors).*

APPENDIX B

Survey Questionnaire

NCHRP Project 20-5
Synthesis Topic 28-09
Survey of Use of Roundabouts in the US
1997

Dear State or Local Traffic Engineer:

As part of the National Cooperative Highway Research Program (NCHRP), the Transportation Research Board (TRB) is preparing a Synthesis of existing practices in the planning, design and construction of modern roundabouts. Please take a moment to complete the following questionnaire and return it to the consultant working on this assignment. Thank you for your assistance.

Please provide the name of the person completing this questionnaire or who may be contacted in your agency to obtain follow-up information:

Name ______________________________
Title ______________________________
Agency ______________________________
Address ______________________________
Town/State/Zip ______________________________
Telephone ______________________________
Fax ______________________________

Definition of Modern Roundabouts

For the purposes of this Synthesis, the modern roundabout is defined as a circular intersection with yield-at-entry rule (vehicles in the circle always have priority) and with a deflection for entering traffic. Parking is not allowed in the roundabout and pedestrians are not permitted to travel to the central island. Roundabouts can have more than one lane entering and circulating around the central island. Modern roundabouts have been built during the last 8 years. Mini-roundabouts or traffic calming circles, typically built within the existing confines of four-way or T-intersections, are not the subject of this Synthesis.

Survey Structure

If your agency has built a modern roundabout over the last 8 years please respond to Questions No. 1 through 15. If your agency has modern roundabouts under construction or in final design, respond only to Questions 1 through 7. If no modern roundabouts exist in your jurisdiction and none are under construction or in design, proceed directly to Question 16. All respondents should feel free to add comments at the end of the questionnaire.

Question No 1: Roundabout Characteristics

Please fill out the attached form "Individual Roundabout Characteristics" for each roundabout (built, under construction or in design) in your jurisdiction. Make additional copies as needed.

Question No 2: What is the source of the guidelines your agency followed to design the roundabouts in your jurisdiction?

Britain ________________ Australia ________________

Maryland ________________ Florida ________________

Other (please explain) ________________________________

Question No 3: Did you follow these guidelines rigorously or did you adapt them to your area's conditions?

Followed the guidelines rigorously ________________________

Made the following adaptations ________________________

____

Question No 4: What were the major reasons that led your agency to build a roundabout?

Better safety ________________________________

Shorter delays ________________________________

Higher capacity ________________________________

Lower costs ________________________________

Aesthetic/urban design improvements________________________

Responding to request from local jurisdiction________________________

Responding to request from elected official________________________

Geometric complications of intersection________________________

Lower speeds/traffic calming________________________

Other, please explain________________________

____

____

Question No 5: Did your agency make special accommodations for any of the following? Please explain.

Pedestrians ________________________________

Bicycles ________________________________

Visually impaired persons ________________________________

Wheelchair-bound persons________________________________

Question No 6: Has your agency made any statutory modifications to accommodate roundabouts (e.g. code revision or legislation)? If yes, please explain and send a copy. ________________________

____

Question No 7: What computer software does your agency use to analyze the performance of roundabouts? ________________________

____

____

Question No 8: In comparison to the previous traffic control, what have been the general impacts of roundabouts relative to the following criteria?

	Improved	Worse	Same
Safety	________	________	________
Vehicle Delay	________	________	________
Capacity	________	________	________
Desired Vehicle Speeds	________	________	________
Pedestrian Movements	________	________	________
Bicycle Movements	________	________	________
Maintenance (signing, snow plowing grass cutting, etc.	________	________	________
Aesthetics	________	________	________
Noise	________	________	________
Other? ____________________	________	________	________

Explain____
____
____

Question No 9: What problems arose with the roundabout, if any, and what were some of the disadvantages? Please explain. ____________________________
____
____
____

Question No 10: Does the maintenance of roundabouts vary from conventional intersections? If yes, how is it different and does it require special training and equipment? ____
____
____
____

Question No 11: Overall are you satisfied ________ or unsatisfied ________ with the roundabout as a form of traffic control? Please elaborate. ________________
____
____

Question No 12: Will your agency build more roundabouts in the future?
Yes ____________________
No ____________________
Maybe ____________________

Question No 13: Does your agency intend to change the guidelines used in the past? What improvements or adjustments would you recommend for future design? Please explain. ______________________________________
____
____

Question No 14: What was the public attitude (press, politicians, residents) towards the roundabout before construction?
Very negative ____________________
Negative ____________________
Neutral ____________________
Positive ____________________
Very positive ____________________

And after the construction of the roundabout?
Very negative ____________________
Negative ____________________
Neutral ____________________
Positive ____________________
Very positive ____________________

Question No 15: Did your agency undertake any special public education efforts before introducing the roundabout? Please explain and attach any examples of educational brochures or material____________________
____
____

Question No 16: (Only for those agencies that have not built any roundabouts)
What are the major reasons why your agency has not built any roundabouts?
They are not part of the AASHTO design standards ____________________
Not sure that they work efficiently ____________________
Not sure that they are safe ____________________
Not sure that the drivers will get used to them ____________________
Concerned about liability issues ____________________
Other, please explain ____________________
Is your agency considering the construction of roundabouts? ____________________

Comments: Feel free to add any comments and to make suggestions. ____________________
____
____
____
____

Please mail completed questionnaire to:

Mr. Georges Jacquemart, PE, AICP
Buckhurst Fish & Jacquemart Inc.
72 Fifth Avenue, 6th floor
New York, NY 10011

If you have additional questions or comments, please feel free to call Georges Jacquemart at (212)620-0050 ext. 213 or fax (212)633-6742.

THANK YOU FOR YOUR ASSISTANCE

NCHRP Synthesis Topic 28-09
Use of Roundabouts in the U.S.
Individual Roundabout Characteristics

Agency ______________________________

Name or Identification of Roundabout ______________________________

Please fill out one of these forms for each roundabout in your jurisdiction. For the roundabouts that are operational, try to respond to all questions, for those that are under construction or in design, respond to questions **1** through **33** only. Make more copies as needed. Please attach photos, slides, plans, drawings or evaluations as needed. Thank you.

1. Date of installation (month, year) __________ Under Construction __________
   In Design __________
2. Intersecting Road (major) ______________________________
3. Intersecting Road (minor) ______________________________
4. Classification of Major Road ______________________________
5. Classification of Minor Road ______________________________
6. Environment (Urban, fringe of urban area, suburban, rural, etc.) ______________
7. AADT Major Road ____________ AADT Minor Road ______________
8. Number of approaches to roundabout ______________________________
9. Inscribed Circle Diameter ________ Diameter of Central Island ______________
10. Width of Mountable Apron around Central Island (if any) ______________
11. Width of Circulatory Roadway ______________________________
12. Outer curbs? __________ Raised splitter islands? ______________
13. Acquisition of additional right-of-way? ______________________________
14. Width of Entry #1 ______________ Name ______________________
15. Width of Entry #2 ______________ Name ______________________
16. Width of Entry #3 ______________ Name ______________________
17. Width of Entry #4 ______________ Name ______________________
18. Width of Entry #5 ______________ Name ______________________
19. Width of Entry #6 ______________ Name ______________________
20. Total Entering Volumes, AM Peak Hour: __________ PM Peak Hour __________
21. Projected peak-hour flow (total entering vehicles) ______________________
22. Hourly pedestrian volumes crossing all approaches, AM Peak Hour ____________
    PM Peak Hour ____________
23. Total entering bicycles, AM Peak Hour ____________ PM Peak Hour __________
24. Percentage of heavy vehicles __________
25. Prior Intersection Control: Two-Way stop __________ Four-Way Stop __________
    Traffic Signal __________
26. <u>Calculated</u> average delays:

	Before Roundabout	After Roundabout
AM Peak Hour	________	________
PM Peak Hour	________	________

27. Is the roundabout sloped towards the outside _____ inside _____ or crowned _____
28. Level of nighttime street lighting ______________________________

29. Advance warning signs: None ________
MUTCD W3-2a symbolic "yield ahead"_____
Legend per MUTCD Section 2C-16 ________
Non-conforming to MUTCD ______________
With __________ or without _____ supplemental plate.
30. Pavement markings: Yield Line ______ "YIELD" legend on pavement ____________
Lane lines on multi-lane circulating roadways ________________________________
31. Pedestrian crosswalks: ____________ ft. back of yield line or none ______________
32. Internal signing: ONE-WAY signs on central island? __________________________
Other central island delineators ____
33. Unique design or operational features: ______________________________________
____
____
____
____
34. Accident Rate (or frequency)

	Before Roundabout Installation:	After Roundabout Installation:
Total Accidents	______________	______________
Injury Accidents	______________	______________
Fatal Accidents	______________	______________
PDO Accidents	______________	______________
Pedestrian Accidents	______________	______________
Bicycle Accidents	______________	______________

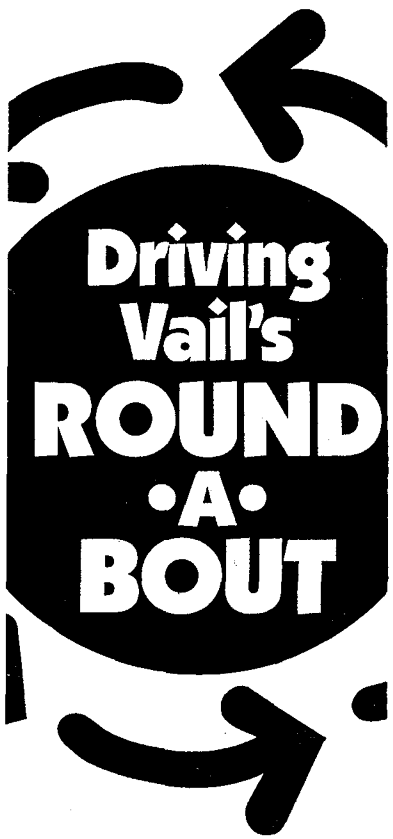
Please explain the duration of the before and after periods. Attach any relevant data if needed. ____
35. Did you collect any capacity data, i.e. maximum entry flow rates for various circulating volumes? Please attach any relevant information. ____________________
____
____
____
36. Measured average delays:

	Before Roundabout	After Roundabout
AM Peak Hour	__________	__________
PM Peak Hour	__________	__________

37. Costs of Roundabout: Right-of-Way Costs (if any) ____________________________
Construction Costs ____________________________________
Maintenance of Traffic Costs ____________________________
Design and Engineering Costs ___________________________
38. Annual Maintenance Costs ____

APPENDIX C

Examples of Public Information Leaflets



Full Circle

If you're visiting Vail this season, you'll likely come into contact with our most recent infrastructure improvement, the Roundabout. Constructed on the north and south side of Vail's main entryway off Interstate 70 (exit 176), the Roundabout uses technology from the Europeans to dramatically improve traffic flow and to maintain our pristine mountain air.

Of course, you really don't need a vehicle to enjoy Vail's destination experience. But just in case, we've prepared this quick user guide to keep you moving in the right circles. Enjoy your stay.

SLOW DOWN upon entry. Speeds of 15 mph or less are adequate.

YIELD to your left before you enter the Roundabout. Remember to be prepared to stop.

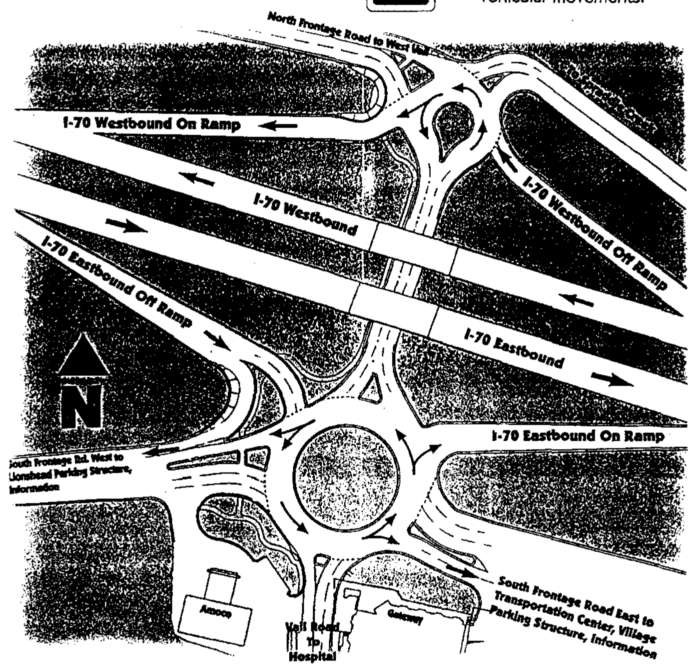
ENTER the Roundabout. Once inside, do *not* stop. You have the right-of-way.

LOOK for your destination sign.

EXIT the Roundabout toward your destination. Remember to use your turn signals.

MISS YOUR EXIT? No problem — just "go around" one more time.

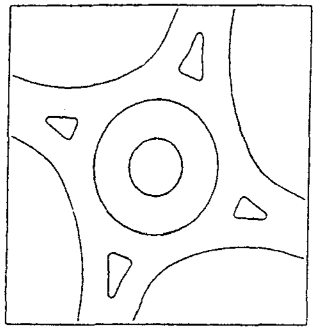
ON A BICYCLE? Use the same vehicular movements.



For more information, please call the Department of Public Works and Transportation at (970) 479-2158, or FAX (970) 479-2166

TOWN OF VAIL

MARYLAND STATE HIGHWAY ADMINISTRATION



THE MODERN TRAFFIC ROUNDABOUT

KEEPING YOU MOVING

At the Maryland State Highway Administration (SHA), keeping our roadways safe and efficient are top priorities. But as communities grow, it becomes more difficult to keep up with the increasing traffic demands placed on our roads. SHA traffic engineers are aware of the problems heavy traffic can create, especially at signalized intersections. Heavy traffic prevents cars from clearing intersections, thereby wasting time and money. There is also the potential for serious injury accidents at intersections.

SHA is always looking for new ways to meet the needs of motorists. One solution to relieve traffic problems at intersections is the modern traffic roundabout. This brochure will familiarize you with the modern roundabout.

WHAT ARE THEY?

A modern roundabout is an intersection having one-way circulation around a central island in which entering traffic yields the right-of-way to circulating traffic. Roundabouts can reduce injury accidents, traffic delays, fuel consumption, air pollution, and operating costs. A well landscaped roundabout can also enhance the beauty of your neighborhood.

WHERE ARE THEY NOW?

Roundabouts have been used successfully in Britain, France, Switzerland, Denmark, the Netherlands, Norway and Australia as well as other countries as an alternative to traffic signals in controlling speed, managing traffic and reducing accidents.

HOW DO I USE ONE?

You'll be surprised how easy it is to travel through a roundabout, but don't confuse roundabouts with the traffic circles you may have driven around in Washington, D.C. or New Jersey. Roundabouts are smaller and vehicle speed is slower, usually about to 15 to 25 mph. You enter the roundabout by selecting a gap in the circulating traffic. The only decision is whether or not the approaching gap is large enough for you to safely enter. You can adjust your speed and enter without stopping. The small diameter, low entry speeds and low circulating speeds provide easy access for motorists.

Modern roundabouts, though more compact than traffic circles, have a larger traffic capacity due to their wider entries which allow more vehicles to safely enter.

SAFETY

A key difference between roundabouts and customary intersections is safety. Roundabouts have a lower potential for accidents compared to intersections. No one can run a red light and cause a right angle collision. The driver who enters the roundabout has to yield to only one traffic movement. By contrast, at a stop sign, the driver has to deal with two or three different movements.

Research shows a 30 to 90 percent reduction in injury accidents at roundabouts compared with signalized or signed intersections. Accidents that do occur at roundabouts are generally side-swipe or rear-end types. They are low speed, low impact collisions that result in few if any injuries. Additionally, SHA is paying special attention to the needs of pedestrians and bicyclists in the roundabout design.

SAVING MONEY

Roundabouts can also save taxpayers money. They need little maintenance, such as resurfacing, landscaping and sign replacement. Traffic signals, on the other hand, cost about $3000 per year for maintenance, electricity, controllers, lamps and other upkeep.

In spite of these advantages, roundabouts are not the only solution to traffic problems. Rather, they are an option to be considered. Roundabouts are not needed at locations where traffic from a minor road can enter the intersection safely and without delay. They also should not be used where a nearby signal could back-up traffic into the roundabout.

APPENDIX D

Roundabout Design and Analysis Resources

ROUNDABOUT DESIGN GUIDELINES

Florida Roundabout Guide

Florida Department of Transportation
Maps and Publications Sales
605 Suwannee Street
Tallahassee, Florida 32399–0450
Tel: (850) 414–4050
Fax: (850) 487–4099

Roundabout Design Guidelines, Maryland Department of Transportation, State Highway Administration

Maryland Dot
Office of Traffic and Safety
7491 Connelley Drive
Hanover, Maryland 21706
Attn. Michael Niederhauser
Tel: (410) 787–5879
Fax: (410) 582–9469

Roundabout Design Guidelines, Ourston & Doctors

Ourston & Doctors
5290 Overpass Road, Suite 212,
Santa Barbara, California 93111
Tel: (805) 683–1383
Fax: (805) 681–1135

Geometric Design of Roundabouts, The Department of Transport, U.K.

DoE/Dot Publication Sales Unit
Building One
Victoria Road
South Ruislip
Middlesex HA4 0NZ
United Kingdom
Tel: 011 44 71 276–0870

SETRA Design Guide (for rural conditions)

SETRA
Bureau de Vente des Publications
46 avenue Aristide-Briand
BP 100
92223 BAGNEUX Cedex
France
Tel: 011 331 46 11 31 53
Fax: 011 331 46 11 31 69

CERTU Design Guide (for urban conditions)

CERTU
Bureau de Vente
8 avenue Aristide-Briand
92220 BAGNEUX
France
Tel: 011 331 46 11 35 35
Fax: 011 331 46 11 35 00

Guide Suisse des Giratoires

Ecole Polytechnique Fédérale de Lausanne
Département GC - ITEP-TEA
Attn. Mme A. Zwilling
CH-1015 LAUSANNE
Switzerland
Tel: 011 41 21 693 24 59
Fax: 011 41 21 693 53 06

Guide to Traffic Engineering Practice, Part 6: Roundabouts

ARRB Transport Research Ltd.
Stores Supervisor
500 Burwood Highway
Vermont, South Victoria 3133
Australia
Tel: 011 61 3 9881 1547
Fax: 011 61 3 9887 8144

Kleine Kreisverkehre: Empfehlungen zum Einsatz und zur Gestaltung

Ministerium fur Stadtentwicklung und Verkehr des Landes Nordrhein-Westfalen
Breite Strasse 31
40190 Dusseldorf
Germany
Tel: 011 49 211 837-4203
Fax: 011 49 211 837-4444

ROUNDABOUT ANALYSIS PROGRAMS

ARCADY

Systematica North America
PO Box 313
Mt. Vernon, VA 22121
Tel: (800) 874-7710
Fax: (703) 780-7874

GIRABASE

CETE OUEST
Division Sécurité et Techniques Routières
MAN - rue René Viviani
BP 46 223
44262 Nantes cedex 2
France
Tel: 011 332 40 12 85 01
Fax: 011 332 40 12 84 44

Kreisel

Ruhr University Bochum
Institute for Transportation and Traffic Engineering
Universitaetsstrasse, 150
Building 1A, Room 2/126
D-44780 Bochum
Germany
Tel: 011 49 234 700-5936
Fax: 011 49 234 7094-151

RODEL

R. B. Crown
Rodel Software Ltd.
Staffordshire County Council
11, Carlton Close
Cheadle
Stoke-on-Trent ST10 1LB
United Kingdom
Tel: 011 44 78 527-6582
Fax: 011 44 78 521-1279

SIDRA

McTrans
University of Florida
Transportation Research Center
512 Weil Hall
PO Box 116585
Gainesville, FL 32611–6585
Tel: (800) 226–1013
Fax: (352) 392–3224

APPENDIX E

Media Coverage of Lisbon, Maryland Roundabout

SHA officials again try to bring Lisbon residents around to seeing their way

By Erik Nelson
Staff Writer

The way Neil Pedersen of the State Highway Administration sees it, the people of Lisbon are not much different from residents of a small town in Australia.

The Australians didn't want a traffic circle either.

Mr. Pedersen, director of planning and preliminary engineering, was among about a dozen SHA representatives who last night tried to convince about 140 Lisbon residents that they ought to be part of an experiment in traffic engineering.

But most residents who spoke said they didn't want to be guinea pigs in the experiment, which would put a "roundabout," otherwise known as a traffic circle, at the intersection of routes 94 and 144. The intersection had nearly 40 accidents during a five-year period ending in 1989, and residents asked for a traffic light to alleviate the problem.

Traffic on Route 94 is governed by flashing yellow lights and on Route 144 by flashing red lights with stop signs. The circle is expected to make the intersection safer, partly by forcing vehicles to slow down to 10 to 20 mph from the current 45 mph speed limit.

The circle would cost $100,000 to $150,000 and would be the first of its kind in Maryland. The circle is an old-fashioned idea that has recently come back into vogue with traffic engineers in other parts of the world.

In the small town in Australia, the idea received a poor public reception, but was later shown to reduce traffic accidents by 75 percent, Mr. Pedersen told residents in the Lisbon fire hall. "They drive on the wrong side anyway," heckled one resident.

Lois Clark, a school bus driver for 14 years, asked how school buses were going to get around the 100- to 110-foot circle. SHA officials said they addressed that question earlier yesterday by having local school bus contractor Walter Sirk drive through a traffic-cone mock circle in the parking lot of George's supermarket.

Mr. Sirk was "delighted" with the circle, said Doug Rose, SHA district engineer.

Mr. Sirk disagreed. "We're not delighted with the thing at all," he said later. He told Mr. Rose that he drove around it with little trouble because he has 40 years of experience driving a bus.

"I love an obstacle course in a school parking lot," Ms. Clark said. "But I don't wish an obstacle course on anybody with a school bus full of kids."

More than a few residents were convinced that the experiment would improve the intersection.

"I think this is a great solution. I don't understand why there's so much opposition," said Sheila Jones, who lives south of town. About a third of those at the meeting applauded hers and other positive comments about the roundabout.

But many others said the idea seemed an unnecessary and unwelcome expenditure by a strapped state government. "This looks like a done deal to me and I want to catch the World Series. Can you just tell men when you're going to start building the thing?" said one man as he headed for the door.

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Howard County Sun / October 21, 1992

THE SUN
LIGHT FOR ALL

Coming Around to Roundabouts

When the State Highway Administration announced last fall that it would build Maryland's first modern roundabout at the intersection of Routes 144 and 94 in Lisbon, many residents of the west Howard County community objected.

Less than a year later — and four months after the roundabout opened — few Lisbonites are complaining about the one-way, single-lane circle that works much like a revolving door; vehicles approaching the circle from any of the four directions enter only after an opening has emerged. The roundabout's circular layout and low speed limit keep accidents to a minimum. Accidents also are expected to be less violent than the perpendicular collisions common at large intersections.

HOWARD COUNTY

To date, only one minor side-swiping has occurred in the circle. And now the residents like it so much that they might take up arms if the state decides to change the roundabout back into a standard intersection with lights and stop signs.

Even defenders of the former configuration at Routes 144 and 94 would have to concede that it used to be a dangerous crossing. State officials say it was one of the worst in the state: 40 accidents and 49 people injured in a recent five-year period.

The danger factor, as well as the relatively low volume of area traffic, convinced the state to pick the Lisbon intersection for the roundabout experiment. According to SHA officials, a roundabout is safer and more cost-efficient than a traffic signal, as borne out by studies of modern circles in foreign countries.

It didn't take long for Lisbonites to be sold on the concept. The circle was only six weeks old when a local citizens' committee voted overwhelmingly to make the roundabout permanent. The state will do so by the end of the summer, finishing work on the center island and installing a raised lane that only trucks will be able to use but at reduced speeds.

State officials hope to install several more roundabouts in Maryland this year, including one in Columbia, two in Western Maryland and another on the Eastern Shore. The Howard County government plans to build two others in Columbia.

Finding potential sites is easy, officials say. The roadblocks will be when local folks won't accept the idea. Why not simply refer them to all those Lisbonites who came around to liking roundabouts?

4/5/94

From Berated to Beloved

We won't pretend we knew ahead of time that the roundabout in Lisbon was destined to be the toast of that small western Howard County town. Frankly, that wouldn't have been a smart bet, because local residents avidly opposed the State Highway Administration's plans to turn the traditional four-way crossing at Routes 144 and 94 into Maryland's first modern traffic circle.

HOWARD COUNTY

But wonder of wonders: The roundabout was installed a year ago, the once-dangerous intersection became virtually accident-free and erstwhile opponents found it easier to negotiate than they had feared. Instead of cursing the circle, they sing its praises. One Lisbon resident has even begun marketing baseball caps ($8 a pop) and shirts ($12) that trumpet the town as "Home of Maryland's First Round-About."

No, we won't say we foresaw the roundabout's success. Yet anyone with a long memory of controversial civic projects might have felt somewhat safe predicting the happy ending for Lisbon's traffic circle. For instance, when the Rouse Co. hatched a plan to make a people-magnet out of Baltimore's rat-infested Inner Harbor, critics hooted at the improbability of the idea. Fourteen years later, Harborplace remains one of the region's top tourist draws, having opened the way for the National Aquarium, the Pier 6 Pavilion and the Gallery. Another downtown development denigrated in its planning stages as a waste of public money: Oriole Park at Camden Yards. Its bedazzling mixture of old and new quickly earned it status as the current standard for baseball stadiums.

Other examples? The Chesapeake Bay Bridge, which is at least as important to Ocean City's economy as skee ball. Towson Commons, the retail-dining-movie complex fought bitterly by community groups but now credited with bringing needed nightlife to the Baltimore County seat. Light rail, spurned at first by communities (Hunt Valley and Glen Burnie, to name two) that later put themselves on the list for future stops.

Certainly the public and private sectors have created their share of flops. But as in the case of the Lisbon roundabout, government and business officials deserve credit for having the vision and the persistence to create important civic institutions, often for a citizenry whose initial enthusiasm for them is less than overwhelming. (April 5, 1993)

THE TRANSPORTATION RESEARCH BOARD is a unit of the National Research Council, a private, nonprofit institution that provides independent advice on scientific and technical issues under a congressional charter. The Research Council is the principal operating arm of the National Academy of Sciences and the National Academy of Engineering.

The mission of the Transportation Research Board is to promote innovation and progress in transportation by stimulating and conducting research, facilitating the dissemination of information, and encouraging the implementation of research findings. The Board's varied activities annually draw on approximately 4,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

The National Academy of Sciences is a nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. Upon the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Bruce Alberts is president of the National Academy of Sciences.

The National Academy of Engineering was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encouraging education and research, and recognizes the superior achievements of engineers. Dr. William A.Wulf is president of the National Academy of Engineering.

The Institute of Medicine was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences, by its congressional charter to be an adviser to the federal government and, upon its own initiative, to identify issues of medical care, research, and education. Dr. Kenneth I. Shine is president of the Institute of Medicine.

The National Research Council was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Bruce Alberts and Dr. William A. Wulf are chairman and vice chairman, respectively, of the National Research Council.

Transportation Research Board
National Research Council
2101 Constitution Avenue, N.W.
Washington, D.C. 20418

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