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Identifying Factors that Determine Bicycle and Pedestrian-Involved Collision Rates that Affect Bicycle and Pedestrian Demand at Multi-Lane Roundabouts

Lindsay S. Arnold, et al.

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FINAL REPORT

May 2010

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16. ABSTRACT

This project examined the safety and demand issues for pedestrians and bicyclists at multi-lane roundabouts through a literature review, case studies, in-field counts and surveys, focus groups, and video analysis. This document presents research findings, synthesizes current information on best practices, and makes recommendations to assist local agencies planning and designing safer multi-lane roundabouts. These findings should help local agencies and Caltrans create roundabouts that better and more safely address the needs of bicyclists and pedestrians. The current literature is referred to throughout the document to augment the research team's findings, especially for issues that were beyond the scope of this project. Key findings in the areas of pedestrian and bicyclist avoidance of, behavior around, and collisions at multi-lane roundabouts are presented along with recommendations for geometric design, design speed, sight distance, width of lanes, signage and pavement markings, and operational recommendations.

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Abstract

This project examined the safety and demand issues for pedestrians and bicyclists at multi-lane roundabouts through a literature review, case studies, in-field counts and surveys, focus groups, and video analysis. This document presents research findings, synthesizes current information on best practices, and makes recommendations to assist local agencies planning and designing safer multi-lane roundabouts.

These findings should help local agencies and Caltrans create roundabouts that better and more safely address the needs of bicyclists and pedestrians. The current literature is referred to throughout the document to augment the research team's findings, especially for issues that were beyond the scope of this project. Key findings in the areas of pedestrian and bicyclist avoidance of, behavior around, and collisions at multi-lane roundabouts are presented along with recommendations for geometric design, design speed, sight distance, width of lanes, signage and pavement markings, and operational recommendations.

Keywords: roundabouts, multi-lane, pedestrian, bicycle, bicyclist, collisions, demand, behavior

Executive Summary

Project Purpose

Caltrans and local agencies are installing roundabouts on roadways throughout the state of California. Research indicates that while single-lane roundabouts may benefit bicyclists and pedestrians by slowing traffic, multi-lane roundabouts may significantly increase safety problems for these users, especially those who are disabled. This project examines the safety and demand issues for pedestrians and bicyclists at multi-lane roundabouts through a literature review, case studies, in-field counts and surveys, focus groups, and video analysis.

The key goals of the project are to:

1. Identify factors at multi-lane roundabouts that influence bicyclist and pedestrian-involved collision rates;
2. Identify factors at multi-lane roundabouts that affect bicyclist and pedestrian demand; and
3. If effect found, recommend design treatments to mitigate these impacts on bicyclists and pedestrians.

Report Overview

This document presents research findings, synthesizes current information on best practices, and makes recommendations to assist local agencies planning and designing safer multi-lane roundabouts. These findings should help local agencies and Caltrans create roundabouts that better and more safely address the needs of bicyclists and pedestrians. The current literature is referred to throughout the document to augment the research team's findings, especially for issues that were beyond the scope of this project.

Findings

Key analysis findings include:

Avoidance

- While 25% of bicyclists and 14% of pedestrians intercepted in the field stated that they would change their route to avoid multi-lane roundabouts, in-field comparison counts did not show a significant difference in pedestrian or bicyclist activity at roundabouts compared to traditional intersections

- Video analysis at three roundabouts showed an inverse relationship between motor vehicle volumes and pedestrian volumes, as at most intersections.

- Self-reported comfort with multi-lane roundabouts differs by user mode. Bicyclists were more likely than pedestrians to report feeling uncomfortable traveling through the roundabout, with 32 percent of bicyclists feeling uncomfortable traveling through the roundabout, compared to 18 percent of pedestrians. Most respondents felt comfortable traveling through the roundabout (60 percent of bicyclists and 53 percent of pedestrians.)

- People's comfort level at a multi-lane roundabout appears to be affected by the age of the respondent, the motor vehicle, bicycle and pedestrian volumes at the roundabout, and also the geometric configuration of the roundabout. Of the three roundabout locations surveyed, respondents at the East Lansing roundabout reported being most comfortable walking and biking through the roundabout (62 percent). These respondents were generally young (69 percent between ages 18-25) and the roundabout has a shared-use path around the perimeter. In Rehoboth Beach, Delaware, 49% of people surveyed were comfortable using the roundabout. This roundabout has significant bicycle and pedestrian activity (88 bicyclists and 89 pedestrians per hour during the observation period).

- When given the choice of stop controlled, signalized and roundabout intersections, pedestrians equally prefer signalized intersections and roundabouts, but bicyclists prefer signalized intersections and not roundabouts. Neither bicyclists nor pedestrians prefer four-way stop-controlled intersections. The preference for more typical intersection types is probably not related to familiarity with these types and unfamiliarity with multi-lane roundabouts; all focus group participants were familiar with multi-lane roundabouts, and in the case of Maryland, had to travel through one or more multi-lane roundabouts to access the focus group location.

Collisions

- While data is limited, some studies suggest that multi-lane roundabouts have little effect on pedestrian crash numbers—either positively or negatively, however pedestrian volume data is rarely available to compare rates per pedestrian crossing.

- While there are no U.S. studies on the subject, non-U.S. studies have shown that circulating bicyclist-entering vehicle collisions are the most common bicyclist collision type in multi-lane roundabouts.

- Bicyclist and pedestrian crash rates, measured by crashes per million bicyclists and pedestrians, vary at different roundabouts in different locations (e.g., 1.09 per million at East Lansing and 0.49 per million at Santa Barbara.)

- European studies have shown that pedestrian and bicyclist crashes account for only 1 percent of the total crashes at roundabouts. By contrast, bicyclist and pedestrian crashes in the case study roundabouts accounted for a much larger percentage of total crashes (12 percent at Santa Barbara, 55 percent at East Lansing). This suggests that European roundabout design, bicycle and pedestrian facility design, or driving, walking and biking behavior may have a role in reducing the number of bike and pedestrian collisions.

- European studies have shown that the four factors with the strongest effect on total crash rates in roundabouts are total traffic volume, proportion of vehicles entering from the minor road, operating speed, and number of legs.

- Very few conflicts were observed in video analysis of case study multi-lane roundabouts.

Behavior

- Based on video observations at case study multi-lane roundabouts, pedestrians overwhelmingly chose to cross at a crosswalk, between 41-100% did not have to wait for a gap in traffic, depending on the roundabout and leg.

- Between 33 and 100 percent of pedestrians observed in the video analysis had to wait to cross a roundabout leg. The wait times averaged 3.6 seconds for crossing entering lanes and 5.6 seconds for crossing exiting lanes.

- Multi-lane roundabouts with higher pedestrian volumes see less wait time for pedestrians and higher yielding rates by motorists compared to multi-lane roundabouts with lower bicyclist and pedestrian volumes.

- The majority of bicyclists observed riding in the circulating lane of a roundabout rode on the outside edge of the lane, as opposed to the center of the lane, indicating discomfort, caution, or lack of understanding of the appropriate way to ride through a multi-lane roundabout.

- When a shared-use path is provided around a roundabout, between 27 and 62% of bicyclists choose to use the path, rather than travel through the roundabout on the roadway.

- Bicyclists would prefer multi-lane roundabouts with vehicle speeds that are close to average bicycling speed (12 to 15 mph)

Recommendations

The comprehensive set of recommendations in this document is designed to aid engineers and planners in determining where multi-lane roundabouts are appropriate, and how to best accommodate pedestrians and bicyclists at these intersections through design features. The recommendations may also be used to evaluate existing multi-lane roundabouts and determine if changes are necessary.

Recommendations are drawn from current FHWA, Caltrans and AASHTO guidance, emerging best practices in the literature, and the results from our data collection and analysis. Chapter 5 contains specific recommendations regarding the following design standards:

- Geometric Design

- Design Speed

- Sight Distance

- Width of Lanes

- Signage and Pavement Markings

- Operational Recommendations

- Example diagrams for addressing the needs of bicyclists and pedestrians at multi-lane roundabouts

We conclude with descriptions of innovative designs for roundabouts and recommendations for future research.

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1.1. Introduction

Caltrans and local agencies are considering installing roundabouts on roadways throughout the state of California. While appropriately-designed roundabouts can reduce traffic collisions and therefore increase safety effects, it is unclear whether bicyclists and pedestrians garner the same level of benefit as vehicle occupants. Research indicates that single-lane roundabouts may benefit bicyclists and pedestrians by slowing traffic. In general, multi-lane roundabouts reduce the number of pedestrian- and bicyclist-involved collisions in before-and-after studies, but most analyses do not account for changes in pedestrian and bicyclist volume and do not use rates. Globally, there are few studies of bicyclist and pedestrian behavior at roundabouts, and even fewer studies conducted in the U.S. In response to current bicyclist and pedestrian data needs, this research initiative sought to complete the following key tasks:

1. Identify factors at multi-lane roundabouts that influence bicyclist and pedestrian-involved collision rates.

2. Identify factors at multi-lane roundabouts that affect bicyclist and pedestrian travel demand.

3. If effect found, recommend design treatments for multi-lane roundabouts to mitigate impacts on bicyclists and pedestrians.

This project examines the safety and demand issues for pedestrians and bicyclists at multi-lane roundabouts through a literature review, case studies, in-field counts and surveys, focus groups, and video analysis. The report concludes with recommendations for design guidelines for multi-lane roundabouts as well as for circumstances under which multi-lane roundabouts should or should not be installed.

1.2. Relevant Related Research

Roundabouts have long been used in many parts of the world and continue to gain popularity in places with little previous experience with roundabouts. Though roundabouts have generally been proven to decrease the number and severity of automobile collisions, there is little, if any, consistent data on the safety of non-motorized users in roundabouts. A literature review was conducted to consolidate research on modern roundabouts, pedestrian and bicyclist behavior, and the interaction that occurs when these users attempt to navigate multi-lane roundabouts. Some conclusions can be drawn about the safety impacts on pedestrians and bicyclists at multi-lane roundabouts, mostly from European and Australian experience. Additionally, there are a number of innovative treatments and recommendations aimed at making multi-lane roundabouts safer for more vulnerable users. A full annotated bibliography is included as an Appendix.

1.2.1. Definition of a Roundabout

Though modern roundabouts are circular intersections, they are different from traditional traffic circles. The modern roundabout has several unique characteristics, the most prominent being the rule that drivers (both motorists and bicyclists) yield on entry. Other key characteristics include a central island with deflection, which forces motorists and bicyclists to slow down, and a splitter island which separates traffic on the entry and exit legs. The articles reviewed in this section not only define these characteristics, but also provide design guidelines that can be followed when designing a modern roundabout.

1.2.2. California Traffic Laws Regarding Roundabouts

California Vehicle Code (CVC) does not have specific provisions that govern how motorists (referred to as "drivers of vehicles" in the CVC), pedestrians and bicyclists must use a roundabout. However, it does have general provisions governing all users that are applicable to roundabouts.

Generally, motorists and bicyclists must yield to pedestrians within crosswalks, but pedestrians are required to exercise due caution when crossing a roadway at a marked or unmarked crosswalk. (CVC Section 21950) When bicyclists walk their bikes across a crosswalk, they become a pedestrian with the same rights and responsibilities as other pedestrians. Bicyclists riding in crosswalks are not discussed in the CVC, and it is therefore unclear whether a motorist's duty to yield to pedestrians in a crosswalk also applies to bicyclists riding in a crosswalk.

CVC Section 21950.

Right-of-Way at Crosswalks

21950. (a) The driver of a vehicle shall yield the right-of-way to a pedestrian crossing the roadway within any marked crosswalk or within any unmarked crosswalk at an intersection, except as otherwise provided in this chapter.

(b) This section does not relieve a pedestrian from the duty of using due care for his or her safety. No pedestrian may suddenly leave a curb or other place of safety and walk or run into the path of a vehicle that is so close as to constitute an immediate hazard. No pedestrian may unnecessarily stop or delay traffic while in a marked or unmarked crosswalk.

(c) The driver of a vehicle approaching a pedestrian within any marked or unmarked crosswalk shall exercise all due care and shall reduce the speed of the vehicle or take any other action relating to the operation of the vehicle as necessary to safeguard the safety of the pedestrian.

(d) Subdivision (b) does not relieve a driver of a vehicle from the duty of exercising due care for the safety of any pedestrian within any marked crosswalk or within any unmarked crosswalk at an intersection.

When riding on the road “at a speed less than the normal speed of traffic moving in the same direction at that time,” bicyclists have the same rights and responsibilities as drivers, with the exception that they must "ride as close as practicable to the right-hand curb or edge of the roadway," except under circumstances provided in CVC Section 21950.. (CVC Section 21202) These circumstances, which may apply to bicyclists traveling through roundabouts at some point, are:

1. When overtaking and passing another bicycle or vehicle proceeding in the same direction.
2. When preparing for a left turn at an intersection or into a private road or driveway.
3. When reasonably necessary to avoid conditions (including, but not limited to, fixed or moving objects, vehicles, bicycles, pedestrians, animals, surface hazards, or substandard width lanes) that make it less safe to continue along the right-hand curb or edge, subject to the provisions of Section

21656. For purposes of this section, a "substandard width lane" is a lane that is too narrow for a bicycle and a vehicle to travel safely side by side within the lane.

4. When approaching a place where a right turn is authorized.

These situations may apply at some point to bicyclists riding through roundabouts. The CVC requires drivers approaching a yield-controlled intersection to yield the right of way to any motor vehicles that are in the intersection or close enough to create a hazard. (CVC Section 21803) As stated in CVC Section 21200, the same provisions for drivers of vehicles apply to bicyclists, except where they are specifically not applicable.

1.2.3. Quality of Existing Vehicle, Pedestrian, and Bicyclist Statistics Regarding Roundabouts

A group of articles addresses the availability of data used to conduct statistical analyses of collisions at roundabouts, and identifies gaps in current practices. Auto collision data is generally available, but not always for specific roundabouts. The available information regarding pedestrian and bicyclist collisions is often ambiguous or incomplete, and pedestrian and bicyclist-involved collisions, in general, are not always reported. In the United States, lack of data may be mainly due to the fact that there are few roundabouts for observation, particularly multi-lane roundabouts, and to the limited number of pedestrians and bicyclists traveling through these roundabouts. In addition, the distinction between single-lane and multi-lane types is usually not made in existing data collected on roundabouts. While pedestrian and bicyclist volumes and collisions can be modeled and simulated, there is a lack of substantiated data on these specific users within roundabouts.

1.2.4. Available Information on Existing Pedestrian and Bicyclist Behavior

The literature reviewed concerning existing walking and bicycling behavior focuses mainly on two topics: route choice and perceived risk. The route choice articles attempt to define variables that influence route selection for pedestrians or bicyclists when these users are faced with alternative routes, although the articles do not specifically discuss roundabouts. There is a general consensus that route directness is a primary consideration in determining route choice. However, there is evidence that non-motorized travelers, and bicyclists in particular, are willing to travel additional distance in exchange for other benefits that they find significant (Harvey et al. 2008, Howard & Burns 2001, Aultman-Hall et al. 1997). Some significant variables include travel time, safety, and pleasantness. Westerdijk et al. (1990) used a multiattribute utility model to quantify these tradeoffs and found, for example, that bicyclists were willing to travel an additional 250 meters (820 feet) to gain one extra point for traffic safety on a theoretical 7-point scale. Although these studies do not explicitly address roundabouts, they still provide insight into how far out of their way pedestrians and bicyclists will go in order to travel a more comfortable route.

This issue of self-reported comfort is also addressed in the articles that discuss cyclists' perceptions of risk. Parkin et al. (2006) studied perceived risk over an entire bike journey and concluded that roundabouts, two-way auto traffic, and the number of parked vehicles on the street are all factors that increase perceived risk for cyclists. Moller and Hels (2008) developed a model for variation in cyclists' perceived risk, specifically at roundabouts. They found that the most significant variables were gender, having experienced a near-collision in the past year, auto volume through the roundabout, and the existence of a cycle facility. While the existence of a cycle facility in a roundabout decreased perceived risk, this study did not attempt to compare perceived risk with measures of actual risk or investigate how this perception affects behavior. However, the route choice studies imply that these perceptions of risk might be a significant variable affecting route choice.

Two reports specifically address how non-motorized users react to roundabouts. One study conducted in New Zealand included a comprehensive survey of bicyclists regarding their attitudes toward multi-lane roundabouts (Campbell et al., 2006). The authors found that while 85% of the survey respondents identified themselves as experienced cyclists, 93% felt that multi-lane roundabouts were a hazard and a deterrent to bike riding. Over 60% said they were willing to make some attempt to avoid multi-lane roundabouts. Novice cyclists demonstrated even higher levels of aversion to multi-lane roundabouts.

1.2.5. Correlations between Pedestrian and Bicyclist Injuries, Fatalities, and Activity Levels and Multi-lane Roundabouts

Much of the existing literature on roundabout safety supports the well-documented conclusion that roundabouts have the potential to increase both motor vehicle capacity and motor vehicle safety. But much less attention has been paid to the impact of multi-lane roundabouts on pedestrians and bicyclists. Most studies, especially in the U.S., have found that there is too little data to conduct meaningful analyses of bike and pedestrian collisions in roundabouts. However, there have been some studies on this relationship outside the U.S.

Generally, the effect of multi-lane roundabouts on pedestrian safety perceptions and behavior is unclear, although some studies have found that roundabouts result in no significant change in levels of pedestrian safety. Observational studies have found that pedestrians are more likely to hesitate at multi-lane roundabouts than at other types of intersections (Harkey & Carter, 2006) and that visually impaired pedestrians experience longer waiting times and more risky crossings at multi-lane roundabouts (Ashmead et al., 2005).

Roundabout design is a critical factor in safety for all users; if the roundabouts are designed to allow for speeds in excess of 25 mph, more collisions can occur. In addition, multi-lane roundabouts have more cyclist collisions when compared to comparable single-lane roundabouts, as a result of a greater difference in speeds between modes (Furtado, 2004). Several studies (including Furtado, Brüde & Larsson (2000), Harkey & Carter (2006), Shen (2000), and USDOT FHWA (2000)) have found that multi-lane roundabouts are perceived as more dangerous, and often result in more collisions for all users when compared to single-lane roundabouts. Exposure rates were not available for these studies. This leads to a conclusion that multi-lane roundabouts can significantly increase bicyclist safety risk. Chapter 5 of the U.S. DOT FHWA publication, "Roundabouts: An Information Guide," (2000) states that adding an additional lane to a one-lane roundabout is likely to increase overall injury crashes by 25%. Brude and Larsson (2000) found that in Sweden, bicycle collisions were six times more frequent on multi-lane roundabouts compared to single-lane roundabouts.

Daniels et al. have conducted some comprehensive studies of the effects of roundabouts on bicyclists in Flanders-Belgium. In their 2008 study, they investigated whether a safety effect could be quantified and if this effect was influenced by particular characteristics of the roundabout location. They include both single- and multi-lane roundabouts in their sample. Their study of before-and-after roundabout installation reveals that roundabouts increased injury collisions involving bicyclists by 27% and severe injury collisions by up to 46%. Roundabouts constructed inside built-up areas had a negative effect on bike safety, as did roundabouts that replaced previously signalized intersections. Daniels, et al. followed up with a 2009 study to determine if bicycle facilities within roundabouts have any effect on bicyclist safety. They arrived at the unexpected conclusion that roundabouts with cycle lanes increased bicycle injury collisions significantly (as opposed to roundabouts with separate cycle paths, grade separated paths, or no bicycle facility) and suggested that a clear distinction should be made between roundabouts with cycle lanes and those with other types of facilities.

1.2.6. Accommodating Pedestrians and Bicyclists at Multi-lane Roundabouts

Several articles were reviewed that specifically address accommodations for pedestrians and bicyclists within roundabouts. Some of the literature consists of general design manuals, which note that special considerations need to be made for non-motorized users when designing any roundabout. Several of these discuss the relatively new practice of roundabout signalization for pedestrian access. Inman and Davis (2007) discovered that roundabout signalization has mainly focused on improving traffic operations and not necessarily on benefits to other users. However, it has been shown that certain pedestrians, particularly pedestrians with disabilities, may require special treatments to safely and efficiently travel through roundabouts. Rouphail et al. (2005) and Schroeder et al. (2008) both used simulation models to study the effects of pedestrian signalization treatments on roundabout operations. Schroeder, et al. found that delays for all users could be mitigated using a two-stage pedestrian signal or a HAWK (High-Intensity Activated Crosswalk) system (more recently renamed a Pedestrian Hybrid Beacon in the 2009 MUTCD), both of which minimize the red time for auto traffic. Rouphail et al. suggest that a mid-block crossing downstream of exiting traffic minimizes the possibility of disruptive queues forming; but the tradeoffs between traffic operations and increased pedestrian travel distance have not been examined. There is also still some dispute regarding when and where pedestrian signalization should be implemented. The U.S. Access Board has proposed guidelines, referred to as "PROWAG," that would require pedestrian-actuated signals at all multi-lane roundabout crossings. (Access Board, 2005) However, there are some who believe that further research must be conducted before any generalized guidelines should be enforced (Baranowski 2005). Additional research is underway as part of NCHRP 3-78A, "Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities" and as part of a project of the National Institutes of Health, National Eye Institute, "Blind Pedestrians' Access to Complex Intersections," which may provide additional information to engineers and designers of roundabouts.

Three studies propose new ideas for road treatments and roundabout design intended to benefit pedestrians and bicyclists. The first study evaluates a new road treatment to audibly alert visually-impaired pedestrians to the presence of yielding vehicles at multi-lane roundabouts (Inman et al., 2005). Two other papers present new versions of a roundabout design that are more amenable to non-motorized users. Campbell, et al. (2006) introduce the concept of a cyclist-roundabout (or C-roundabout), which has very specific geometric guidelines intended to reduce the 85th percentile auto circulating speed to 30 kilometers/hour (19 miles/hour),which reduces the differential between cars and the typical bicyclist to 10 kilometers per hour. The most distinctive feature of the multi-lane C-roundabout is the narrow entry lanes, which encourages operators of heavy vehicles to travel in a single file. Campbell, et al. also suggest using economical vertical deflection devices (such as speed humps) at entry legs, but concede that these may be opposed by drivers of buses, emergency vehicles, and other heavy vehicles. Another novel multi-lane roundabout design, the turbo-roundabout, was described by Fortuijn in 2003. The turbo-roundabout design prohibits lane changing among the circulatory traffic and has been implemented in the Netherlands. This design benefits non-motorized users by lowering the circulatory speed and reducing the number of potential conflict points.

Much more research is needed on the best way to accommodate pedestrians and bicyclists at roundabouts. But some valuable work has been done to show that a combination of innovative solutions and efficient use of current treatments may ultimately benefit all users.

2. Methodology

Between January 2007 and February 2009, the researchers collected both qualitative and quantitative data regarding pedestrian and bicyclist usage of multi-lane roundabouts. Methods used to collect data were:

- Bicyclist and pedestrian counts at four case study multi-lane roundabouts and at nearby comparison sites.
- Comparison of bicyclist and pedestrian volumes along three corridors, one of which contained a multi-lane roundabout.
- Summary of police-reported collision data at two case study multi-lane roundabouts.
- In-field intercept surveys of bicyclists and pedestrians at three case study multi-lane roundabouts.
- Video documentation of bicyclists and pedestrians at three case study multi-lane roundabouts.
- Four focus groups held in two communities with multi-lane roundabouts.

Figure 1 illustrates how our different data collection efforts work together to answer the three main questions in the report:

1. Do pedestrians and bicyclists avoid multi-lane roundabouts? If so, why?
2. Are pedestrians and bicyclists more likely to be involved in crashes or more severe crashes at multi-lane roundabouts than at other types of intersections? Why?
3. Given the answers to the above questions, where should multi-lane roundabouts be installed? Where should they not be installed? And what type of specific design treatments are recommended for improving safety, mobility and comfort of bicyclists and pedestrians at multi-lane roundabouts?

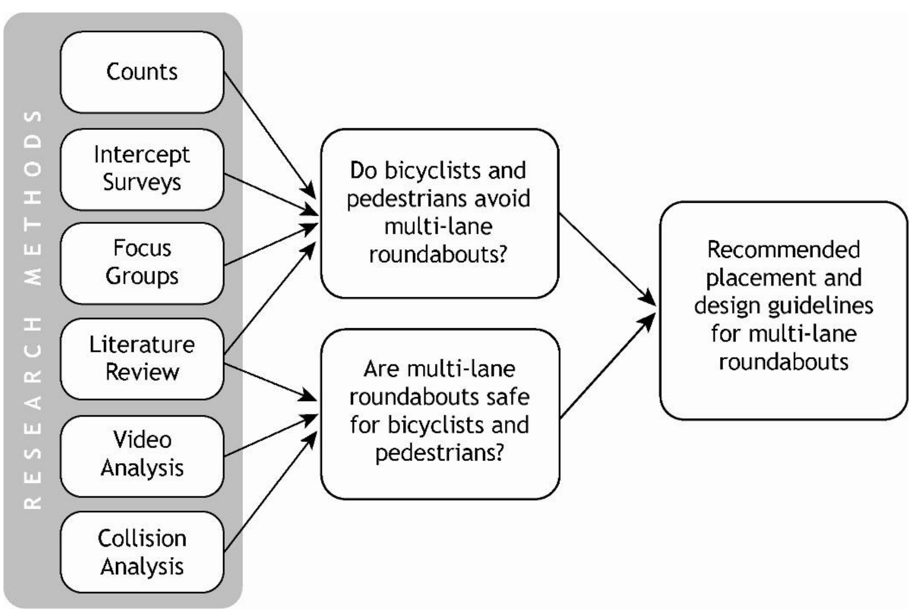

Figure 1: Illustration of How Research Answers Three Key Questions

2.1. Selection of Case Study Roundabouts

Data was collected at five case study multi-lane roundabouts. Bicyclist and pedestrian counts were conducted at all five locations, while more in-depth analysis (surveys, video documentation, focus groups) were conducted at a subset of locations.

Table 1: Data Collection by Roundabout Location

Location	Bike & Ped Counts and Comparison to Nearby Intersections	Bike & Ped Counts and Comparison to Nearby Corridors	Bike & Ped Collision Summary	Intercept Surveys	Video Documentation	Focus Groups
Santa Barbara, CA Milpas Road & Hwy 101	X	X	X	not conducted	not conducted	X
Annapolis, MD Spa Road, Taylor Avenue & MD 450	X	not conducted	not available	X	X	not conducted
Kentlands (Gaithersburg), MD Kentlands Boulevard & Market Street	X	not conducted	not available	not conducted	not conducted	X
Rehoboth Beach, DE Rehoboth Avenue & Grove Street	X	not conducted	not available	X	X	not conducted
East Lansing, MI Shaw Lane & Bogue Street	X	not conducted	X	X	X	not conducted

2.2. Bicycle and Pedestrian Counts

2.2.1. Intersection Comparison Counts

Researchers conducted bicyclist and pedestrian counts at four case study multi-lane roundabouts and at nearby comparison sites to determine if bicyclists and/or pedestrians were avoiding roundabouts. Corridor counts were used at the Santa Barbara, CA site because of roadway configuration and presence of the U.S. Route 101. The researchers hypothesized that if bicyclist and/or pedestrian counts were higher at comparison sites than at nearby roundabouts, that may indicate that bicyclists and/or pedestrians were avoiding the multi-lane roundabouts.

Methodology

The count methodology consists of comparing bicycle and pedestrian volumes at a roundabout to comparable signalized or stop-controlled sites within a half a mile. The ideal case study site had standard multi-lane geometry, was surrounded by a grid network of streets, and had similar land uses at the roundabout and at potential comparison sites within half a mile of the roundabout. Very few multi-lane roundabouts met all of these conditions.

Table 2 lists the final case study sites that were selected. More information on the selection and characteristics of the comparison sites is available in *Identifying Factors that Determine Bicyclist and Pedestrian-Involved Collision Rates and Bicyclist and Pedestrian Demand at Multi-Lane Roundabouts: Year One Report.*

Table 2 Case Study Roundabouts Selected for Intersection Comparison Counts

Location	Roundabout Intersection	Standard Multi-Lane Geometry	Surrounded by Grid Network	Similar Land Uses at Roundabout and Comparison sites
Annapolis, Maryland	Spa Road/Taylor Avenue/MD 450	yes	yes	yes
Kentlands Development, Gaithersburg, Maryland	Kentlands Boulevard and Market Street	yes	yes	yes
Rehoboth Beach, Delaware	Rehoboth Avenue and Grove Street	No – only major east-west movement has multiple lanes	no	no comparison sites selected, due to lack of grid network
East Lansing, Michigan	Shaw Lane and Bogue Street	No – right slip turn is provided	yes	yes

Two-hour bicyclist and pedestrian counts were conducted during peak weekday and weekend periods at each of the case study locations. At each case study location, counts were conducted at a roundabout location and at one or two comparison sites. Field observations included identification of users by mode, general age, and other attributes, and quality and extent of the existing bicycle and pedestrian facilities (such as quality of sidewalks, bicycle facilities, driveways, etc.) within three blocks or 1,000 feet of the roundabout, or within proximity of the actual count locations.

2.2.2. Corridor Count Comparisons

In addition to the counts conducted at the four east coast locations, the project team conducted counts along parallel corridors in Santa Barbara, California. The Santa Barbara counts were conducted to compare bicyclist and pedestrian counts along three parallel corridors, one of which contains a multi-lane roundabout.

Methodology

To determine whether bicyclists and pedestrians avoid multi-lane roundabouts, researchers conducted counts along three parallel corridors in Santa Barbara. The three corridors represent three different types of interfaces with Highway 101: an undercrossing, signal-controlled on-off ramps, and a multi-lane roundabout. Counts were conducted north of 101, at the interface of 101, and south of 101 during weekday and weekend peak hours. Count data was collected at a total of nine locations. Figure 2 shows the corridors and count locations that were sampled.

Figure 2: Map of Count Locations in Santa Barbara

These corridors were selected with the assumption that a large volume of pedestrian and bicycle movement occurs between the commercial and residential areas northwest of the highway and the beach. By examining bicyclist and pedestrian flows from north to south and south to north along the three corridors, we hoped to establish whether interfaces with Highway 101 affect bicyclist and pedestrian movements.

At all count locations except the Milpas roundabout, trained counters recorded the number of bicyclists and pedestrians that passed a screenline. At the Milpas roundabout, counters recorded turning movements.

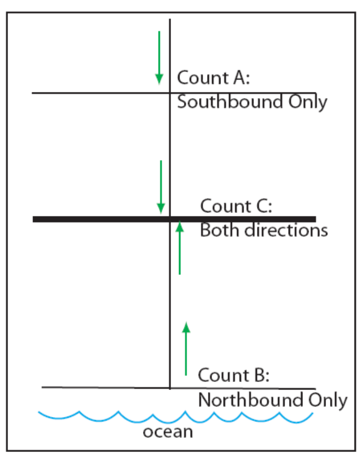

Figure 3: Schematic of How Data was Analyzed

To analyze the counts, we counted the number of bicyclists and pedestrians that traveled toward the interface of Highway 101 and compared it to the total number of bicyclists and pedestrians that were counted at that interface. Using Figure 3 as an illustration, we compared the sum of Count A and Count B to Count C. If Count C was higher than the sum of Count A and Count B, then it was assumed that bicyclists and pedestrians were being funneled toward the interface to cross Highway 101. If Count C was lower than the sum of Count A and Count B then it is assumed that bicyclists and pedestrians had a destination off the corridor or were avoiding the interface with Highway 101.

2.3. Collision Analysis

Researchers collected historical collision data for two of the five case study roundabouts. This collision data was compared with estimated levels of bicycle and pedestrian activity levels to calculate a collision rate.

2.4. Video Analysis

The video documentation methodology consisted of video-recording pedestrian, bicyclist, and vehicles at the roundabouts for a period of time and reviewing the videos to look for particular behaviors. Videos were recorded at the following three sites:

Maryland—Annapolis, Spa Road/Taylor Avenue/MD 450 Roundabout
Delaware—Rehoboth Beach, Rehoboth Avenue and Grove Street Roundabout
Michigan—East Lansing, Shaw Lane and Bogue Street Roundabout

At each roundabout, a video camera was set up at the center median of the roundabout, facing out, at each of two or three approaches to each roundabout, and allowed to record for the periods of time indicated in

Table 3. The locations of the cameras are summarized in

Table 3 below:

Table 3: Video Camera Locations and Recording Times

	Camera Location Number	Approach	Total Recorded Time (min)
Rehoboth Beach, DE	1	Southeast	186.15
	2	Southwest	209.77
	3	Northwest	125.13
East Lansing, MI	1	South	156.75
	2	North	170.60

Annapolis, MD[8]	1	East	30.56
	2	North	11.87
	3	Northwest	147.69
Total recording time for all locations, minutes:			1,038.52
Total recording time for all locations, hours:			17.31

The video review was conducted in two phases using a video playback tool developed by the California Partners for Advanced Transit and Highways (PATH). In the first phase, analysts played the video and recorded the times of each type of event using numbers (pedestrian = 1, bicycle = 2). The recorded times and events were then exported to an Excel spreadsheet. In the second phase, analysts re-played the video and recorded behaviors associated with each event in the spreadsheet, based on a pre-established protocol. The behaviors reviewed included:

Pedestrians: whether pedestrians were in a group or not, crosswalk crossing times and directions, delay at crosswalk, position with respect to crosswalk, and pace (normal or running).

Bicycles: whether bicyclists were in a group (2 or more bicyclists) or not, riding or walking the bicycle, location within the roundabout (on the road, on the crosswalk, on the sidewalk or on the multi-use path), position in the lane (center or edge), direction (with traffic, against traffic), and whether the bicyclist changed behavior (e.g. from walking the bicycle on the sidewalk to riding the bicycle on the road).

Vehicles (with respect to pedestrians): whether motorists yielded to pedestrians, or forced pedestrians to wait for a gap in traffic in order to cross.

The data was then analyzed to look for patterns in behavior. The video recordings were also used to estimate vehicular volumes based on 15-minute counts, and vehicles entering, exiting, or circulating in the roundabout were counted separately.

2.5. Intercept Surveys

During the summer of 2008, bicyclists and pedestrians were surveyed at three of the case study multi-lane roundabouts. The purpose of the surveys was to find out which characteristics attract or deter bicyclists and pedestrians from multi-lane roundabouts, and to provide guidance for the placement and design of multi-lane roundabouts to accommodate all transportation modes.

Surveys were conducted on Friday, August 22, 2008 in the early afternoon. At each location, bicyclists and pedestrians were asked to participate in a ten-question survey. The survey asked questions related to the following topics:

- Method of traveling through the roundabout
- Comfort of traveling through the roundabout[9]

[8] Please note, the camera batteries failed on two of the approaches in Annapolis which resulted in low recording time for the East and North approaches.

[9] Survey question: "What was your comfort level as you traveled through the roundabout? A. Comfortable B. Neutral (neither comfortable nor uncomfortable) C. Uncomfortable"

- Preference for different types of intersections, and reason for preference
- Demographic information

2.6. Focus Groups

The primary purpose of the focus groups was to solicit information from a variety of roadway users regarding bicycling and walking through multi-lane roundabouts. It is important to note that all other data collection efforts for this project sample only people who were already using roundabouts. The focus groups were intended to sample all types of roadway users and not only those who were already using roundabouts.

Methodology

A total of four focus groups were held: two in Kentlands, Maryland, and two in Santa Barbara, California. Focus groups were held in January 2009 during the weekday morning and weekday evening, each consisting of nine participants. Participants ranged in age from 18 to over 65. Slightly more women than men participated in the groups (20 women versus 16 men). Participants were recruited by posting flyers at local establishments in each community, as well as through ads posted on craigslist.org.

The focus groups were conducted in five sections, each concentrating on a particular topic area:

- Section 1 – Pedestrian and Bicycle Behavior
- Section 2 – Understanding of the Operations and Self-reported Comfort with Roundabouts
- Section 3 – Bicycle Design Options
- Section 4 – Pedestrian Design Options
- Section 5 – Final Comments/Suggestions

The groups were conducted by a lead facilitator with the help of an assistant. Participants were paid a $50 cash honorarium for their participation at the end of the focus group. Comments were recorded using a digital audio recorder, and the assistant also took notes. Comments were later transcribed from the digital recordings. In most cases, comments were transcribed word for word as provided by the participants. But in some cases, comments were paraphrased to capture their essence. As with most focus groups, short discussions between participants often arose when a particular topic was addressed, and in these cases those comments were recorded which reflected the nature of the discussion related to the designated topic.

Table 4: Summary of Roundabout Features, Conditions, and Operations

Location	Lane Configuration	Bicycle Facilities	Pedestrian Facilities	Speeds (Approach Circulating Exit)	Land Uses	Notes
Santa Barbara, CA Milpas Road & Hwy 101	2 circulating, exiting and some circulating lanes are delineated 5 legs	Bike lanes on Milpas.	Sidewalks, high visibility ladder crosswalks. Pedestrians prohibited from crossing southeast and northwest legs at roundabout.	25-30 mph n/a 25-30 mph (posted)	Single family, industrial, grocery store	Non-standard design. Circulating roadway is oval, lanes are delineated, and deflection at southeast and northwest legs is smaller than recommended. Intersection includes on and off-ramps for Highway 101.
Annapolis, MD Spa Road, Taylor Avenue & MD 450	2 circulating, 4 legs	none	Sidewalks, high visibility ladder crosswalks, brick pavers, pedestrian warning signage	22 mph 17 mph 17 mph (radar)	National cemetery, single-family and duplex, some retail and office	Drivers entering from Taylor Ave outside lane are not permitted to circulate the roundabout.
Kentlands (Gaithersburg), MD Kentlands Boulevard & Market Street	2 circulating, 4 legs	none	Sidewalks, colored pavers, sidewalks on Kentlands are 2 car-lengths back	n/a	Large retail stores, surface parking lots.	Kentlands Blvd narrows before it enters roundabout. Market Street serves as driveway to adjacent retail stores.
Rehoboth Beach, DE Rehoboth Avenue & Grove Street	1.5 circulating (only inside lane travels around entire roundabout), 4 legs (2 multi-lane, 2 single-lane), exiting and circulating lanes are delineated	none	Sidewalks, brick pavers, pedestrian warning signage	25 mph 18 mph 14 mph (radar)	Retail, residential	Rehoboth Avenue is a heavily traveled thoroughfare with access to the beach from state highway Route 1A to the west. Bicycle, pedestrians, fixed route transit, and auto traffic is high and as such drivers are more aware of bicycle and pedestrian presence.
East Lansing, MI Shaw Lane & Bogue Street	1.5 circulating (only inside lane travels around entire roundabout), 4 legs	Side path	Sidewalks, high-visibility ladder crosswalks, "Yield to Peds in X Walk" sign	29 mph 19 mph 19 mph (radar)	University	

3. Summary of Findings and Discussion

3.1. Bicycle and Pedestrian Activity Levels at Multi-Lane Roundabouts

Do multi-lane roundabouts deter bicyclists and pedestrians?

The collected data from roundabouts did not show a significant difference in pedestrian or bicyclist activity at roundabouts compared to surrounding traditional intersections. As can be seen in Table 5 and Table 6, even when considering motor vehicle volumes, average hourly bicyclist and pedestrian counts at roundabouts were not universally higher or lower than at comparison sites.

Table 5: Average Hourly Weekday Counts

	Bicycle Volumes			Pedestrian Volumes			Motor Vehicle Volumes		
	Roundabout	Comparison 1	Comparison 2	Roundabout	Comparison 1	Comparison 2	Roundabout	Comparison 1	Comparison 2
East Lansing	13	5	11	89	35	81	972	413	552
Rehoboth Beach	59.5	n/a	n/a	43	n/a	n/a	2054.5	n/a	n/a
Gaithersburg	2.5	1.5	1	28	30.5	99.5	1049	254.5	257.5
Annapolis	7	7	9	14	20.5	1.5	2221.5	3368	3520.5

Source: Field counts by authors.

Table 6: Average Hourly Weekend Counts

	Bicycle Volumes			Pedestrian Volumes			Motor Vehicle Volumes		
	Roundabout	Comparison 1	Comparison 2	Roundabout	Comparison 1	Comparison 2	Roundabout	Comparison 1	Comparison 2
East Lansing	15.5	3.5	n/a	60	20	n/a	602.5	198	n/a
Rehoboth Beach	88	n/a	n/a	89	n/a	n/a	2348	n/a	n/a
Gaithersburg	3.5	7	7.5	28	89.5	286.5	1079.5	300	319
Annapolis	6	3.5	2.5	27.5	58	2	2377	2901	3017

Source: Field counts by authors.

However, it is difficult to determine from this data if bicyclists' or pedestrians' route choices are influenced by the location of the roundabouts or a variety of other possible factors. The case study locations vary in terms of land use, attractors, street networks, demographics and other factors that affect bicyclist and pedestrian activity levels. It was also difficult to select comparison sites that had traffic volumes, land uses and activity centers similar to those of the roundabout sites. Not surprisingly, the ratio of pedestrian and bicyclist activity levels at roundabouts and traditional intersections varied across study locations. (See Table 7 and Table 8 on page 26.)

Among overall ratios (Table 9), the highest roundabout/comparison site ratio was in East Lansing, where approximately two bicyclists were counted at the roundabout for every one bicyclist counted at the comparison sites. At this site, 1.6 pedestrians were counted at the roundabout for every one pedestrian counted at comparison sites. Bike lanes and sidewalks are provided on the approach to this roundabout, and a bike ramp at each leg permits bicyclists to ride onto the sidewalk and use it while traveling around the circular part of the roundabout. Though this roundabout is multi-lane with two entry lanes, its configuration is not typical. The circular portion of the roadway has two lanes, with an outer lane striped as right-slip lanes and an inner lane for vehicles [10] traveling past the first exit leg. The site is located near a large university.

The lowest ratio of bicyclist and pedestrian activity levels was found at the Gaithersburg site. The roundabout at this site is close to housing developments, and the immediate vicinity consists of auto-oriented retail stores and large parking lots. Motor vehicle volumes are significantly higher at the roundabout than at comparison sites, suggesting that bicyclists and pedestrians may be avoiding motor vehicle traffic rather than the roundabout itself. However, the East Lansing site also had high volumes of motor vehicle traffic at the roundabout compared to the comparison sites.

Table 7: Weekday Ratios of Bicyclist and Pedestrian Counts at Roundabouts vs. Comparison Sites

	Bicyclists	Pedestrians
East Lansing	1.6 to 1	1.53 to 1
Rehoboth Beach	n/a	n/a
Gaithersburg	2.0 to 1	0.43 to 1
Annapolis	0.88 to 1	1.27 to 1

Source: Field counts by authors.

Table 8: Weekend Ratios of Bicyclist and Pedestrian Counts at Roundabouts vs. Comparison Sites

	Bicyclists	Pedestrians
East Lansing	4.43 to 1	3 to 1
Rehoboth Beach	n/a	n/a
Gaithersburg	0.48 to 1	0.15 to 1
Annapolis	2 to 1	0.92 to 1

Source: Field counts by authors.

Table 9: Overall Ratios of Bicyclist and Pedestrian Counts at Roundabouts vs. Comparison Sites

	Bicyclists	Pedestrians
East Lansing	2.19 to 1	1.64 to 1
Rehoboth Beach	n/a	n/a
Gaithersburg	0.71 to 1	0.22 to 1
Annapolis	1.18 to 1	1.01 to 1

Source: Field counts by authors.

[10] Including bicyclists who choose to ride on the roadway, rather than on the separated path.

3.1.1. Milpas Corridor Analysis

Bicyclists and pedestrians did not appear to avoid the Milpas roundabout. On average, there were 122% more bicyclists and 29% more pedestrians counted at the roundabout than would be expected from counts on both ends. Bicyclists and pedestrians traveling on Milpas Street must travel 0.38 miles out of their way if they wish to avoid the Milpas roundabout.

This suggests that bicycle and pedestrian activity may be more highly related to factors such as attractors, land use, directness of bicycle routes, and other factors, rather than the presence of a multi-lane roundabout. Bicyclists may be using the roundabout as a connection point to destinations such as the northern end of the corridor where counts were high, or a grocery store. Additionally, the bicyclist volumes at the Milpas roundabout were much higher than at the other Highway 101 interfaces, suggesting that the roundabout may be a more desirable interface than either undercrossings on State or Garden Street. It may also be that Milpas is a more popular destination.

These results should be considered in light of the limitations of the experiment. Variations in land use along the corridors, destinations at the interfaces with the highway, and with the types of alternative routes available to bicyclists and pedestrians may be primary reasons for the differences seen between the corridors. In particular, the grocery store located at the Milpas Roundabout may be a key destination that attracts both bicyclists and pedestrians. There are no nearby key destinations at the State Street or Garden Street undercrossings. This finding suggests that land use/attractors/destinations may in fact override any effects of intersection type on pedestrian and bicyclist route choice. All three of the interfaces with Highway 101 (undercrossing, signalized ramps, roundabout) are somewhat challenging for bicyclists, therefore it is possible that the bicyclists using the three corridors are more experienced as cyclists.

3.1.2. Intercept Surveys

Intercept surveys found that self-reported comfort with multi-lane roundabouts differed by user mode. Bicyclists were more likely than pedestrians to report feeling uncomfortable traveling through the roundabout, with 18 percent of walkers saying they felt uncomfortable traveling through the roundabout compared to 32 percent of bicyclists. However, a large percentage of respondents said they felt comfortable traveling through the roundabout. Fifty-three percent of walking respondents reported being comfortable traveling through the roundabout, compared to 60 percent of bicyclists. This study surveyed only those who were using the roundabout and does not include people those who avoid the facility and take other routes instead. Further research is necessary to find out more definitively if bicyclists and pedestrians avoid these roundabouts

The final question related to respondents' comfort of using roundabouts was: "In general, do you change your route to avoid traveling through a roundabout?" This question was asked separately about walking and biking, of both pedestrians and bicyclists. The results are illustrated in Table 10. The majority of respondents would not change their route to avoid the roundabout if walking.

For the bicycling question, three-quarters of respondents overall would not change their routes. Respondents at Rehoboth Beach were the most likely to take another route when bicycling, in order to avoid the roundabout. Also, people more familiar with bicycling (i.e., those who were surveyed while bicycling) may be generally more comfortable using a roundabout than other users. For example, 16 percent of people who were bicycling when given the survey reported that they would change their route if walking, whereas 28 percent of people who were pedestrians at the study roundabout said they would change their route if they were on bicycles.

Table 10. Roundabout Avoidance

	All Data		East Lansing, MI		Rehoboth Beach, DE		Annapolis, MD	
if I were walking…	**No. of Participants**	**%**	**No. of Participants**	**%**	**No. of Participants**	**%**	**No. of Participants**	**%**
I would change my route	12	14%	3	7%	8	22%	1	25%
I would not change my route	75	86%	43	93%	29	78%	3	75%
Total	87		46		37		4	
if I were biking…	**No. of Participants**	**%**	**No. of Participants**	**%**	**No. of Participants**	**%**	**No. of Participants**	**%**
I would change my route	22	25%	7	15%	14	38%	1	25%
I would not change my route	65	75%	39	85%	23	62%	3	75%
Total	87		46		37		4	

3.1.3. Summary of Findings

Multi-lane roundabouts most likely do pose a deterrent to both bicyclists and pedestrians. Bicyclists are more likely than pedestrians to change their route to avoid a multi-lane roundabout. Intercept surveys showed that 14% of respondents would change their route when walking to avoid a multi-lane roundabout, and 25% of respondents would change their route when biking.

Intercept survey results show that pedestrians equally prefer four-way stop lights at intersections to roundabouts, while more bicyclists reported preferring four-way stop lights at intersections. This is supported by literature indicating that multi-lane roundabouts are considered a risk factor for bicyclists (Furtado, 2004; Bruce and Larsson 2000).

Comparison counts of bicyclists and pedestrians at multi-lane roundabouts and nearby signalized intersections did not show a consistent pattern of usage. However, this is may be due to the variations in land use between the comparison sites, including the existence of important attractors such as grocery stores

Comparison of three freeway interfaces along parallel corridors in Santa Barbara showed that more bicyclists were counted at the freeway interfaces than at the endpoints, suggesting that bicyclists were being funneled toward these interfaces. Interestingly, the highest percentage increase was seen at the Milpas Roundabout, (122% at the roundabout for all count times combined) suggesting that issues of connectivity, directness, and land use are more important than traffic considerations.

Similarly, a higher number of pedestrians were counted at the Milpas Roundabout than would be expected from counts on each end, suggesting that the roundabout does *not* serve as a hindrance to walkers. On average, 29% more pedestrians were counted at the roundabout than would be expected from the counts on either end. In comparison, pedestrians along State Street and Garden Street were actually seen in lower numbers at the highway interface than would be expected by the counts on either end. It is likely that for most pedestrians—especially those shopping or making other discretionary trips—noise and land uses factors near US 101 discourage walking.

3.2. Bicycle and Pedestrian Safety at Multi-Lane Roundabouts

Are pedestrians and bicyclists more likely to be involved in crashes or more severe crashes at multi-lane roundabouts than at other types of intersections?

3.2.1. Literature Findings

As stated in Section 1.2. Relevant Related Research, several studies conducted in the U.S. and abroad have examined roundabout safety but few focus on bicycle/pedestrian/auto safety. In a broad sense, researchers have demonstrated that roundabouts typically perform better in terms of crashes and crash rates than traditional forms of traffic control. Some specific insights into collision numbers, rates and severity can be gleaned from a review of this literature.

Collision data at 39 U.S. roundabouts over 3.8 years showed that bicyclist and pedestrian collisions each accounted for approximately 1% of collisions both single-lane and multi-lane roundabouts, with a total of five reported pedestrian crashes and eight reported bicycle crashes *(NCHRP 572: Roundabouts in the United States)*. While this study does not examine pedestrian and bicyclist volumes, it is assumed that bicyclist volumes are much lower than pedestrian volumes, and that therefore the crash rate for bicyclists (crashes per bicyclist traveling through the roundabout) is even higher than indicated by the total crash numbers.

A study for the Australian Road Research Board analyzed bicycle crash data at multi-lane roundabouts over a ten-year period (1995 to 2004). The study found that multi-lane roundabouts are safer for bicyclists than traditional intersections and made some key points about bicycle collisions:

- Cyclists are over-represented by a significant factor in injury crashes at multi-lane roundabouts
- The predominant crash type is entering vehicle-circulating cyclists at multi-lane roundabouts (68% of total bicycle crashes)
- Nighttime crashes with cyclists accounted for 25% of all cyclists' crashes
- Thirty-nine of the 58 reported bicyclist crashes were injury crashes (67%)
- At locations with higher cyclist traffic, cyclist crash rates are lower (drivers are more aware of their presence)
- There are indications that reducing the speed differential between vehicles and cyclists should reduce cyclists' injury rates
- In the United Kingdom and the United States, studies have found that higher approach and entry speeds have been found at roundabout locations with more approach visibility.

Research on pedestrian safety at multi-lane roundabouts is unfortunately limited and to some extent dated.

Brilon conducted a study of 32 newly-constructed single-lane roundabouts in Germany in the 1990s. While he noted a 40% reduction in crash frequency and an even more impressive reduction in injury crashes, there was only a small reduction in pedestrian crashes at the study locations. (Brilon, 2005)

A review of the safety study by Lalani investigated the performance of 38 roundabouts in London, England in the 1970s (20 mini-roundabouts; 9 small roundabouts; 5 large roundabouts and 4 double mini-roundabouts). The authors compared the before and after safety performance of roundabouts with an average study period of 19 months and found that pedestrian crashes were reduced by 46%, compared to the traditional intersections that were replaced by the roundabouts. (Lalani, 1975)

The most comprehensive study conducted in the U.S. was recently completed as part *of NCHRP 3-65 Roundabouts in the United States*, published as NCHRP Report 572. As noted above, the occurrence of pedestrian crashes was minimal at the study locations with only five reported pedestrian crashes out of 726 crashes collected from 55 study locations. This limited amount of data greatly hindered the researchers' ability to draw any conclusions regarding pedestrian before/after crash occurrences at roundabouts, except to say that they accounted for approximately 1% of total crashes at the study locations.

3.2.2. Comparison of Collision Points between Signalized Intersections and Multi-Lane Roundabouts

According to a synthesis of twenty-eight non-U.S. studies, roundabouts reduce injury accidents from between 30 and 50 percent, and fatal crashes from between 50 and 70 percent. (Elvik) Many researchers attribute this reduction in crashes to the reduction in potential collision points at roundabouts as compared to conventional traffic control strategies.

When looking at bicyclist and pedestrian collision points at a traditional intersection in comparison to a multi-lane roundabout, a different picture emerges. As can be seen in Figure 4 and Figure 5, bicyclists have more collision points at multi-lane roundabouts than they do at the intersection of two four-lane roads. Pedestrians have the same number of collision points at both intersection types.

At a signalized intersection and at a multi-lane roundabout, pedestrians have 12 potential collision points where motorists must yield.

Bicyclists see an increase in collision points in signalized intersections compared to multi-lane roundabouts. Bicyclists who travel the roundabout like a motor vehicle are exposed to 16 potential collision points where motorists must yield to bicyclists. Bicyclists who travel the roundabout on a sidewalk or path, crossing like a pedestrian, experience 12 potential collision points where motorists must yield. By comparison, bicyclists traveling a four-way intersection like a motor vehicle see 12 collision points.

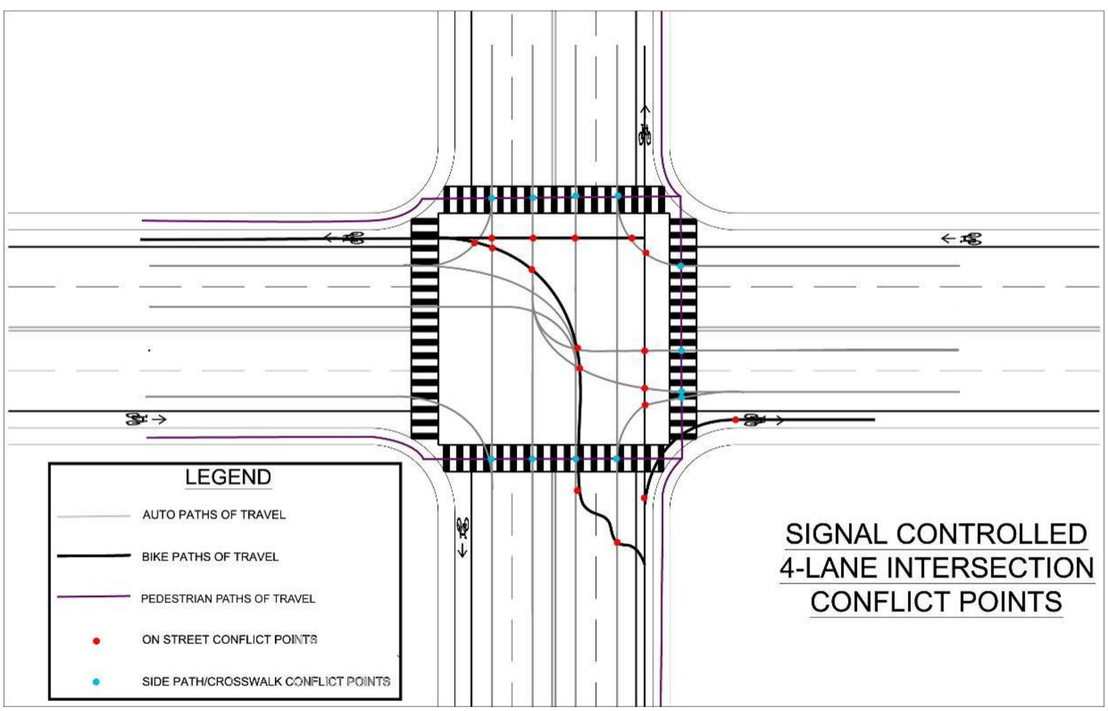

Figure 4: Bicyclist and Pedestrian Conflict Points at Signalized Intersection

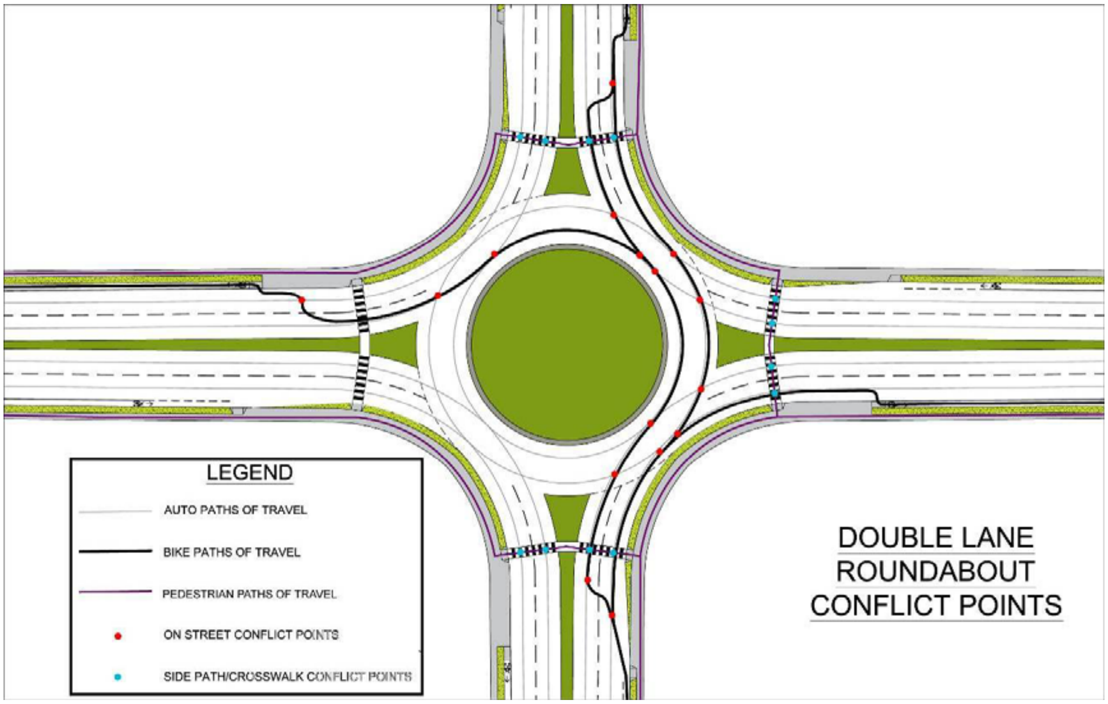

Figure 5: Bicyclist and Pedestrian Conflict Points at Multi-Lane Roundabout

3.2.3. Crash Frequency and Severity

Table 11: Summary Collision Data 2002 through 2008 summarizes the collision data collected for the East Lansing, Michigan and Santa Barbara, California roundabouts.[11] Collision data were collected for 2002 through 2008 for both locations. The two study locations are multi-lane roundabouts, each with two circulating lanes. An estimated annual number of pedestrians and bicyclists was extrapolated from the bicycle and pedestrian counts collected at the roundabouts during this study. As can be seen from the table, the collision rate at the East Lansing location is more than double the collision rate at the Santa Barbara location. It should be noted that the roundabout in East Lansing Michigan is designed with a multi-use cycle path that allows bicyclists to travel around the roundabout separated from vehicle traffic, except when crossing the legs or approaches to the roundabout. The Santa Barbara, California roundabout is an oval shaped roundabout that serves the exit ramps from Highway 101. These geometric differences may account for the difference in collision rates.

Table 11: Summary Collision Data 2002 through 2008

Roundabout location	# ped/bike collisions	# vehicle collisions	Percent ped/ bike	Estimated annual # peds & bikes**	Estimated collisions per million bicyclists/pedestrians
East Lansing, MI*	5	42	11.9%	895,000	1.09
Santa Barbara, CA*	5	11	45.5%	1,825,000	0.47
**East Lansing collision data is from January 2002 to January 2008; Santa Barbara collision data is from 2002 to 2008*					
***Preliminary estimates, subject to change.*					

[11] Collision data was not available to researchers for the Delaware and Maryland roundabouts.

3.3. Bicyclist, Pedestrian and Driver Behavior

How do bicyclists, pedestrians and drivers interact at multi-lane roundabouts? How does this relate to safety, comfort of bicyclists and pedestrians?

3.3.1. Video Analysis

Results of the video analysis indicate an inverse relationship between vehicle traffic volume and pedestrian volumes at roundabouts. Typically, the roundabouts with the least vehicle traffic volume had higher pedestrian and bicycle volumes. Although we cannot conclude causality, it is possible that there would be an adverse effect on pedestrian demand at locations where roundabouts are placed with the purpose of optimizing road capacity.

Pedestrian Delay

At the Maryland roundabout, of 63 pedestrians observed, 31% waited to cross the entering lane and 29% waited to cross the exiting lane. For those who waited, the average wait time before crossing entering lanes was 3.9 seconds, while the average wait time before crossing exiting lanes was 4.1 seconds. This difference was statistically significant for some of the roundabout legs only. At the Delaware roundabout, of 53 pedestrians, 43% waited to cross entering lanes of the roundabout and 57% waited to cross exiting lanes of the roundabout. For those who waited, the average wait time to cross entering lanes of the roundabout was 4.7 seconds, while the average wait time to cross exiting lanes of the roundabout was 6.5 seconds. At the Michigan roundabout, of 288 pedestrians observed, 98% waited when crossing entering lanes and all pedestrians waited when crossing exiting lanes. These wait times were in the range of 0.1 to 17.7 seconds. For those who waited, the average wait time for crossing entering lanes of the roundabout was 3.6 seconds, while the average wait time for crossing exiting lanes of the roundabout was 5.6 seconds.

While the average wait times for both entering and exiting lanes at the Maryland roundabout were relatively consistent, pedestrians at the Delaware and Michigan roundabouts experienced wait times 2 seconds longer when crossing exiting lanes than when crossing entering lanes.

Overall, pedestrians experienced longer wait times when crossing exiting lanes than when crossing entering lanes.

Yielding Behavior

Overall, most drivers who could yield to pedestrians at crosswalks did so, however some drivers did not yield. The percentage of drivers who did not yield to pedestrians varied depending on location and lane and ranged from 0-100%. Lower driver yielding percentages tended to occur at roundabouts with lower pedestrian and bicycle traffic volumes. This indicates a proportional relationship between vehicle yielding and pedestrian demand at roundabouts. It also suggests that drivers pay more attention to pedestrians and bicyclists when there is higher pedestrian and bicyclist volume.

Risk-Taking Behavior

Using the pedestrian assertiveness parameters as defined during the video analysis, it is difficult to pinpoint factors that impact pedestrian risk- taking behaviors. However, not surprisingly, our observations of pedestrian level of assertion and crossing pace suggest that pedestrians' level of comfort may be related to traffic volumes. For bicyclists, their level of assertiveness was measured by identifying the cyclist's chosen position in the lane, i.e., whether they rode in the center or edge of the lane. Results of the video analysis suggest that bicyclists prefer to negotiate a roundabout on a separated bicycle path when such a path is available. The analysis also shows that 76% of bicyclists did not ride in the center of the lane when travelling on the road, choosing to ride at the outer edge of the lane instead.

3.3.2. Intercept Surveys

The results from the intercept surveys seem to be in agreement with those of the video documentation and focus group portions of this project. Since these were intercept surveys, the pedestrians and bicyclists interviewed were ones who were willing to use a multi-lane roundabout. Overall, 53 percent of pedestrians reported being comfortable traveling through roundabouts and 60 percent of bicyclists reported being comfortable traveling through roundabouts. On average, 30 percent of bicyclists biked on the roadway with vehicles through the roundabout (8% in East Lansing; 54% in Rehoboth Beach; 0% in Annapolis).

3.3.3. Focus Group Analysis

As mentioned in the literature review, the presence of roundabouts in general is among the factors that increase perceptions of risk for non-motorized travelers. (Moller and Hels 2007), and this study's focus group results generally confirm this idea. Members of the focus group walked and biked through roundabouts, but they said they find them risky and "scary." Bicyclists are concerned about conflicts with motorists in the roundabouts while pedestrians are concerned about crossing the entry and exit lanes. Separation of motor vehicle traffic and bicyclist and pedestrian traffic using a cycle track or shared use pathway was seen as the best solution to bicyclist-vehicle conflicts, as expressed by both bicyclists and pedestrians. This finding is echoed in the video documentation, which shows the majority of bicyclists using a side path when one is available, and most bicyclists using the roadway when a side path is not available. Enhanced crossing treatments were seen by focus group participants as potentially helpful to pedestrians.

Pedestrians in the focus group reported that they mostly navigate roundabouts assuming that drivers will not yield to them, like at other intersections. Most wait until all vehicle traffic has cleared from the roundabout before traveling across the entrance or exit of a roundabout leg. Many use the splitter island refuge to perform a two-stage crossing. A few participants noted that they had changed their route to deliberately avoid a roundabout.

Data gathered during this study show that non-motorized users-- particularly bicyclists-- are uncomfortable using multi-lane roundabouts. Yet people are still using roundabouts, despite this discomfort. Whether this discomfort relates to actual increased risk or just perception of increased risk is unclear from the focus group comments. Bicyclists' assertiveness as measured in the video analysis portion of this project shows that many bicyclists are cautious when using multi-lane roundabouts. The majority of observed bicyclists rode on the edge of the lane as opposed to the center of the lane, indicating a higher level of caution, discomfort, or lack of understanding of the proper way to navigate a roundabout.

3.4. Summary of Findings

Findings from this study raise several important issues that should be considered when designing multi-lane roundabouts:

Avoidance

- While 14% of pedestrians and 25% of bicyclists intercepted in the field stated that they would change their route to avoid multi-lane roundabouts, in-field comparison counts did not show a significant difference in pedestrian or bicyclist activity at roundabouts compared to traditional intersections

- Level of comfort with multi-lane roundabouts differs by user mode. Bicyclists were more likely than pedestrians to report feeling uncomfortable traveling through the roundabout, with 32 percent of bicyclists feeling uncomfortable traveling through the roundabout, compared to 18 percent of pedestrians. Most respondents felt comfortable traveling through the roundabout (60 percent of bicyclists and 53 percent of pedestrians.)

- People's comfort level at a multi-lane roundabout appears to be affected by the age of the respondent, the motor vehicle, bicycle and pedestrian volumes at the roundabout, and also the geometric configuration of the roundabout. Of the three roundabout locations surveyed, respondents at the East Lansing roundabout were most comfortable walking and biking through the roundabout (62 percent). These respondents were generally young (69 percent between ages 18-25) and the roundabout has a shared-use path around the perimeter. In Rehoboth Beach, Delaware, 49% of people surveyed were comfortable using the roundabout. This roundabout has significant bicycle and pedestrian activity (88 bicyclists and 89 pedestrians per hour). The relationship between comfort at roundabouts and age should be explored further.

- When given the choice of stop controlled, signalized and roundabout intersections, pedestrians equally prefer signalized intersections and roundabouts, but bicyclists prefer signalized intersections and not roundabouts. Neither bicyclists nor pedestrians prefer four-way stop-controlled intersections. The preference for more typical intersection types is probably not related to familiarity with these types and unfamiliarity with multi-lane roundabouts; all focus group participants were familiar with multi-lane roundabouts, and in the case of Maryland, had to travel through one or more multi-lane roundabouts to access the focus group location.

Collisions

- While data is limited, some studies suggest that multi-lane roundabouts have little effect on pedestrian crash numbers—either positively or negatively.

- While there are no U.S. studies on the subject, non-U.S. studies have shown that circulating bicyclist-entering vehicle collisions are the most common bicyclist collision type in multi-lane roundabouts.

- Bicyclist and pedestrian crash rates, measured by crashes per million bicyclists/pedestrians, vary at different roundabouts in different locations (e.g., 1.09 per million at East Lansing and 0.49 per million at Santa Barbara.)

- European studies have found that pedestrian and bicyclist crashes account for only 1 percent each of the total crashes at roundabouts. By contrast, bicyclist and pedestrian crashes in the case study roundabouts accounted for a much larger percentage of total crashes (12 percent at Santa Barbara, 55 percent at East Lansing). This suggests that European roundabout design, bicycle and pedestrian facility design, or driving, walking and biking behavior (cultural acceptance, training, laws, and familiarity) may have a role in reducing the number of bike and pedestrian collisions.

- European studies have shown that the four factors with the strongest effect on total crash rates in roundabouts are total traffic volume, proportion of vehicles entering from the minor road, speed limit, and number of legs.

- Very few conflicts were observed in video analysis of case study multi-lane roundabouts.

Behavior

- Based on video observations at case study multi-lane roundabouts, pedestrians overwhelmingly chose to cross at a crosswalk, and many did not have to wait for a gap in traffic.

- Between 33 and 100 percent of pedestrians observed in the video analysis had to wait to cross a roundabout leg, depending on the location. The wait times averaged 3.6 seconds for crossing entering lanes and 5.6 seconds for crossing exiting lanes.

- Multi-lane roundabouts with higher bicyclist and pedestrian volumes see less wait time for pedestrians and higher yielding rates by motorists.
- The majority of bicyclists observed riding in the circulating lane of a roundabout rode on the outer edge of the lane, as opposed to controlling the lane, indicating discomfort, caution, or lack of understanding of the proper way to navigate.
- When a shared-use path is provided around a roundabout, the majority of bicyclists choose to use the path, rather than travel through the roundabout on the roadway.
- Bicyclists would prefer multi-lane roundabouts with vehicle speeds that are close to bicycling speed (12 to 15 mph).

3.5. Limitations of Research

There are limitations to the conclusions that can be drawn from this study, due to both the scope of the research effort and the nature of the subject.

Lack of relevant data is the greatest obstacle to better understanding pedestrian and bicyclist safety at multi-lane roundabouts in the U.S. Multi-lane roundabouts remain uncommon in this country and many are relatively new, with little crash history. Where crash history is available, pedestrian and bicyclist volumes are generally not collected, making it difficult to calculate a crash rate that accounts for pedestrian or bicyclist exposure to motor-vehicle traffic. Because of limitations in police collision report forms, official crash reports from pedestrian and/or bicyclist-involved collisions at roundabouts may not be sufficient to conduct a detailed analysis. For example, the CHP 555 form used in California does not contain fields that specifically apply to roundabouts and it may be difficult for an officer to accurately describe a roundabout collision. The form is also limited in terms of the number of fields that apply to pedestrians and/or bicyclists, and efforts have been underway for years to improve reporting of pedestrian and bicyclist-involved collisions. In addition, because crashes, and especially crashes involving pedestrians, are rare, a long observation period is required to observe enough crashes to conduct a meaningful analysis. As more multi-lane roundabouts are constructed in the U.S., there will likely be more pedestrian and/or bicyclist-involved crashes at roundabouts. While unfortunate, these crashes will provide more data for future studies.

For this study, we referenced the literature on the European multi-lane roundabout experience, although it must be noted that roadway design features will not necessarily translate well from one country to another. The public's lack of familiarity with roundabout operation, as noted in the focus groups, suggests that Americans are still generally confused by roundabouts, especially multi-lane roundabouts. Attitudes toward walking and bicycling also vary considerably between the U.S. and various European countries--factors which may affect the safety performance of a roundabout.

This analysis relies on both observational and self-reported data. As with any research that involves self-reporting, including surveys and focus groups, self-reporting bias may affect the validity of findings. The topic of this study is not sensitive or controversial enough to suggest that respondents might avoid truthful responses. The survey questions were designed and written to minimize bias, and focus groups were conducted in an informal atmosphere, with participants assured of the purpose of the meeting.

Through the comparison counts, the Milpas corridor analysis, surveys, and focus groups, we sought to ascertain whether pedestrians and/or bicyclists actively avoid traveling through multi-lane roundabouts. The focus groups confirmed that these users sometimes avoid roundabouts, but their route choice is also greatly influenced by factors of directness, land use, the existence of attractors, and of alternative route choices. In the extreme case pedestrians and bicyclists will avoid a roundabout with the consequence of not walking or biking. This would result in zero pedestrian or bicyclist-involved crashes but it is difficult to quantify the true impact on these users. Above all, land use factors seem to be the most influential variable in pedestrian's and bicyclists' choice of route, relative to multi-lane roundabouts.

4. Recommendations

4.1. Introduction

This chapter presents recommendations for installing multi-lane roundabouts and recommends design features to accommodate bicyclists and pedestrians at multi-lane roundabouts. The design recommendations are based on several existing design resources:

- FHWA's *Roundabouts: An Informational Guide FHWA-RD-00-067*
- Caltrans Design Information Bulletin (DIB) 80-01
- AASHTO *Guide for the Planning, Design, and Operation of Pedestrian Facilities*
- AASHTO *Guide for the Development of Bicycle Facilities*
- California Manual on Uniform Traffic Control Devices
- Proposed Amendments to Federal MUTCD
- Draft Public Rights-of-Way Accessibility Guidelines (2005)
- FHWA memo on Public-Rights-of-Way (2006)

We have used insights gathered from our research to clarify and supplement recommendations presented in the documents above and in emerging international and domestic research. Engineers should use professional judgment when applying these recommendations to multi-lane roundabouts. Most treatments are already accepted for use at other locations, but have not yet been applied or studied for multi-lane roundabouts specifically.

This chapter is divided into the following sections:

Section 4.2. A comparison of conflict points, capacity and other elements of multi-lane roundabouts to signalized intersections

Section 4.3. A summary of operational problems faced by bicyclists and pedestrians when navigating multi-lane roundabouts

Section 5.4. Considerations for meeting the safety, comfort and mobility needs of bicyclists and pedestrians when planning and designing multi-lane roundabouts, including locations where roundabouts may not be appropriate.

Section 4.5. Recommended designs for accommodating bicyclists and pedestrians at multi-lane roundabouts

Section 4.6. A summary of recommended designs and illustrations of example roundabout designs

4.1.1. Documents Governing the Design of Multi-Lane Roundabouts in California

Roundabout design in California shall follow Federal Highway Administration's technical publication, *Roundabouts: An Informal Guide* (Guide), published in June 2001, and the Caltrans Design Information Bulletin (DIB) 80-01 and its Attachment A, both of which specify guidelines and considerations for roundabout design. The text provided in DIB 80-01 Attachment A shall govern in every instance where conflicts arise or ambiguities exist between the Guide and the Highway Design Manual (HDM) or the Traffic Manual.

As stated in Caltrans DIB 80-01, "roundabouts need to be evaluated and designed on a case-by-case basis, taking into consideration the physical characteristics of the location, the orientation of the approaches to the circular intersection, the existing and proposed intersection operating conditions, plus the safety and mobility needs of all motorists, bicyclists, and pedestrians that will be using the facility.

Deputy Directive 64, R-1, issued October 2008, requires the safety and mobility needs of bicyclists and pedestrians to be addressed in all projects on the State Highway system, regardless of funding. As stated in DD 64-R1, "The intent of this directive is to ensure that travelers of all ages and abilities can move safety and efficiently along and across a network of 'complete streets.'" DD-64 R1 defines a complete street as "A transportation facility that is planned, designed, operated, and maintained to provide safe mobility for all users, including bicyclists, pedestrians, transit riders, and motorists appropriate to the function and the context of the facility." In compliance with DD 64 R-1, all roundabouts located on state highways must address the needs of bicyclists and pedestrians in the planning, design, operation and maintenance stages.

In addition, several other design guides are applicable to the planning and design of roundabouts, including the American Association of State Highway and Transportation Officials (AASHTO) Guide for the Planning, Design, and Operation of Pedestrian Facilities (AASHTO Ped.), published in July 2004, the AASHTO Guide for the Development of Bicycle Facilities (AASHTO Bike), published in 1999, U.S. Access Board in Draft PROWAG, and the California Manual on Uniform Traffic Control Devices (CA MUTCD), published in September 2006.

The FHWA has a Notice of Proposed Amendment regarding changes to the next edition of the MUTCD which went out for comment in July 2008 and a Final Rule for the next edition of the MUTCD is anticipated in 2009. Proposed amendments for the next edition of the MUTCD include recommendations for roundabouts signing and striping.

4.2. Comparison of Bicyclist and Pedestrian Experience at Multi-Lane Roundabouts and Signalized Intersections

The user experience for bicyclists and pedestrians greatly varies between multi-lane roundabouts and traditional intersections. Three primary factors that contribute to bicyclists' and pedestrians' discomfort at roundabouts are: (1) the fact that crossings are uncontrolled, (2) the higher number of conflict points for bicyclists at multi-lane roundabouts and (3) the longer distance required to travel through these intersections.

Table 12: Matrix Comparing Multi-Lane Roundabouts to Traditional Intersections

	Multi-Lane Roundabout	Signalized Intersection of two four-lane roads*	Signalized Intersection of two four-lane roads with right-slip turn*
Bicyclist distance to traverse	Generally longer than signalized intersections	Shorter than roundabouts	Shorter than roundabouts
Pedestrian distance to traverse	Generally longer than signalized intersections	Generally shorter than roundabout	Can be the same as roundabout
Bicyclist delay	Function of motor vehicle volumes and yielding behavior, but can be shorter than signalized intersections	Function of signal timing	Function of signal timing
Pedestrian delay	Function of motor vehicle volumes and yielding behavior, but can be shorter than signalized intersections	Function of signal timing	Function of signal timing
Motor vehicle conflict points	Fewer, fewer T and head-on conflicts	More, T and head on conflicts are possible	More than a roundabout, T and head on conflicts as well as conflicts associated with right slip turn
Bicycle conflict points	More, many merging/weaving conflicts	Fewer merging/weaving conflicts than a roundabout	More than a roundabout, some crossings are uncontrolled
Pedestrian conflict points	Same number, crossings are uncontrolled	Same number as a roundabout, crossings are controlled	More than a roundabout, some crossings may be uncontrolled
*These intersection types are lower capacity than multi-lane roundabouts.			

As referenced earlier in this report, a reduction of conflict points in comparison to a traditional intersection is a commonly-cited benefit of roundabouts. This is not true of multi-lane roundabouts. Bicyclists experience more conflict points at multi-lane roundabouts than at traditional four-way intersections, and pedestrians face an equal number or slightly fewer collision points See Section 3.2.2. for more details.

4.3. Operational Issues for Pedestrians and Bicyclists at Multi-Lane Roundabouts

Several design challenges must be addressed when designing multi-lane roundabouts to address the safety and mobility needs of bicyclists and pedestrians. The challenges for each mode of travel are discussed separately to clarify the issues unique to each mode, as follows:

4.3.1. Issues for Pedestrians

Multi-lane roundabouts pose the following challenges for pedestrians:

- Pedestrians crossing the exit lane must be able to correctly judge whether a circulating motorist is going to exit, to correctly judge the speed of that motorist and judge whether the driver is going to yield.
- At multi-lane roundabouts, pedestrians often have to make judgments about more than one vehicle when crossing.

- Every crossing represents a potential "multiple threat" scenario, in which a motorist in the lane nearest the pedestrian yields and blocks the view of the pedestrian, while the motorist in the second lane does not yield.[12]

- Pedestrians traveling counterclockwise around the roundabout must look behind them to check for circulating vehicles that may exit.

- Motorists approaching the roundabout are looking to the left for a gap in traffic and are less likely to notice pedestrians trying to cross from their right.

- A pedestrian's path of travel is longer at multi-lane roundabouts than at a signalized intersection.

- Pedestrians who are blind or who have low vision may have greater difficulty discerning appropriate crossing times, resulting in more risk and delay, because the sound of other vehicles traveling around the roundabout, or a vehicle yielding in one lane, may mask the sound of a vehicle approaching the crosswalk.

- Bicyclists using shared side paths or sidewalks to travel around a roundabout can cause conflicts with pedestrians, in particular pedestrians with disabilities.

- Pedestrians crossing the entry lanes must be able to correctly judge the speed of approaching vehicles and judge whether the drivers are going to yield.

4.3.2. Issues for Bicyclists

Bicyclists can travel through a multi-lane roundabout three ways: (1) riding on the sidewalk or separated shared use path, (2) like a motorist, controlling the lane and circulating on the roundabout within a traffic lane, or (3) dismounting and walking through the roundabout as a pedestrian.

Bicyclists who ride on a separated path around a roundabout have similar challenges to pedestrians, with three key differences:

- Bicyclists travel several times faster than pedestrians. Motorists are not expecting to see a person travel so quickly into a crosswalk, and may not be able to yield in time.

- Unlike pedestrians, bicyclists cannot easily stop or jump out of the way if they notice a motorist that is not going to yield.

- The California Vehicle Code does not specifically protect bicyclists riding on sidewalks and in crosswalks. Bicyclists riding crosswalks are not given the same legal rights and responsibilities as pedestrians and, as such, may be found liable if they are involved a collision while riding in a crosswalk.

Multi-lane roundabouts pose the following challenges to bicyclists who control the lane:

[12] Passing a vehicle that is stopped for a pedestrian in a crosswalk is a violation of CVC Section 21951, which states, "Whenever any vehicle has stopped at a marked crosswalk or at any unmarked crosswalk at an intersection to permit a pedestrian to cross the roadway the driver of any other vehicle approaching from the rear shall not overtake and pass the stopped vehicle."

- Bicyclists must control the lane before they enter the roundabout to avoid becoming caught in a "right hook," a situation in which a motorist turns right, across the path of a bicyclist traveling straight. Entry leg speeds must be slow enough for bicyclists to be able to control the lane safely.

- Theoretically, once motor vehicle volumes reach a certain magnitude, there are no gaps in traffic large enough to accommodate a bicyclist.

- Bicyclists must be able to correctly judge the speed of circulating motorists to find a gap that is large enough for them to safely enter the roundabout. This task is particularly difficult if the circulating motorists are traveling at a much higher speed than the bicyclists. In addition, if circulating speeds in a roundabout are much higher than 20 mph, drivers behind a bicyclist may become impatient, and may pass the bicyclist and turn in front of him, creating more risks for the bicyclist.

- As a circulating bicyclist approaches an entry lane, a driver waiting to enter must notice the bicyclist, properly judge the bicyclist's speed, and yield to him/her if necessary. In a location where there are few bicyclists, motorists may not even register that there is a bicyclist approaching. If a bicyclist is hugging the curb, s/he may be outside the motorist's cone of vision.

4.4. Considerations When Planning Multi-Lane Roundabouts

Planners and designers should consider the safety, comfort and mobility of bicyclists and pedestrians when determining if a multi-lane roundabout is appropriate, and should design multi-lane roundabouts that balance the needs of drivers with the needs of bicyclists and pedestrians. In some cases, a multi-lane roundabout may not be the best option for bicyclists and pedestrians, and alternative designs should be considered.

Designers and planners should consider alternatives to multi-lane roundabouts in the following situations:

- As noted in the *Guide*, "heavy pedestrian or bicycle movements in conflict with high traffic volumes" may preclude a roundabout at a specific location. (Section 3.3.2) The *Guide* also lists general ways in which issues can be resolved, including design features, operational changes, and in some cases, specific mitigation actions. The *Guide* does not go into further detail.

- Planners should consider alternatives to multi-lane roundabouts located within the walkshed or bikeshed of schools serving younger students. If multi-lane roundabouts are placed within the walkshed or bikeshed of school serving younger students, designers should consider signalizing the roundabout.[13]

- Planners should consider alternatives to multi-lane roundabouts located within walking vicinity of a senior center, nursing home, or other facility that serves the elderly. If multi-lane roundabouts are placed within walking vicinity of a facility that serves the elderly, designers should consider signalizing the roundabout. [14]

[13] While there is little specific information on the safety of children navigating roundabouts, this demographic crash involvement rates are highest among males aged 5 to 9 years old (PedSafe), and elementary school-aged children have a narrower field of vision than adults and often over-estimate their physical abilities (uwhealth.org)..

[14] While there is little specific information on the safety of seniors navigating roundabouts, collisions involving seniors are much more likely to include severe injuries and fatalities than collisions involving younger pedestrians. Pedestrian collisions resulting in death are greater than 20 percent for adults over 75 years of age as compared to less than 8 percent for pedestrians under age 14 (Pedsafe).

Designers and planners should provide enhanced pedestrian and bicycle facilities at the following locations:

- Multi-lane roundabouts within a quarter mile walking distance of pedestrian generators, (e.g. transit stops, shopping districts, universities, etc…) should be designed with best practice pedestrian and bicycle treatments, including treatments identified in this document.

- If pedestrian generators are developed within a quarter mile walking distance of an existing multi-lane roundabout, the existing roundabout should be evaluated for accommodation of pedestrians and necessary treatments should be installed.

In general, all roundabouts should be designed to meet the following recommendations:

- Multi-lane roundabouts should be designed to accommodate bicyclists of all abilities, through the use of lowest practical design speeds and best practice bicycle treatments, including treatments described in this document.

- Multi-lane roundabouts should be designed to accommodate pedestrians of all abilities, through the use of lower design speeds, signage, striping and traffic control devices to increase yielding at crosswalks, and best practice pedestrian treatments including treatments described in this document.

- Particular attention should be given to accommodating pedestrians with disabilities at multi-lane roundabouts. In particular, engineers and designers are urged to follow the progress of NCHRP 3-78, which is conducting a very large-scale in-field test of various roundabout treatments to enhance the experience of visually impaired pedestrians. Findings from the study are expected in December 2009.

4.5. Designing Multi-Lane Roundabouts to Meet the Needs of Bicyclists and Pedestrians

This section of the report is intended to help engineers and planners better understand ways in which multi-lane roundabouts can be designed to accommodate pedestrians and bicyclists. The recommendations presented in this chapter are a compilation of emerging best practices from across the United States and from other countries, as well as recommendations based on results of our research gathered through focus groups, surveys and field observations.

4.5.1. General Design Goals

The design recommendations in this section are based on the following design goals.

1. Design roundabouts to accommodate on-street bicyclists by reducing the speed differential between circulating motorists and bicyclists. We recommend a 25 mph maximum circulating design speed.[15]

2. Design approaches and exits to the lowest speeds possible, in order to reduce the severity of potential collisions with pedestrians.

[15] A 2004 FHWA study that collected field data in 21 locations around the United States measured the 85th percentile speed of bicyclists at 14 mph. http://www.tfhrc.gov/safety/pubs/04103/index.htm

3. Design roundabout approaches, circulating lanes and exits to encourage bicyclists navigating the roundabout like motor vehicles to control the lane. This approach reduces the chances of a bicyclist being cut off by a "right hook."

4. Utilize the most practicable and effective tools to maximize yielding rate of motorists to pedestrians and bicyclists at crosswalks.

5. Provide separated facilities for bicyclists who prefer not to navigate the roundabout on the roadway.[16]

6. Use appropriate signing, roadway markings and geometric design to clearly indicate to drivers, bicyclists and pedestrians, the right-of-way rules and correct navigation at a multi-lane roundabout.

4.5.2. Geometric Design of Multi-Lane Roundabouts

Through literature reviews, observations, and surveys, three key components of geometric design have been identified that affect safety and perceived safety of pedestrians and bicyclists at multi-lane roundabouts:

- Vehicle design speed (on entry, circulating, and on exit)
- Visibility of pedestrians and bicyclists (both to see vehicles and to be seen by drivers)
- Width of roundabout lanes

These components are addressed in the following three sections.

4.5.3. Design Speed

Vehicle speeds on approach to, into, through, and on exit of a roundabout are influenced by the various radii chosen by the roundabout designer. The FHWA guidance document specifies five specific path radii to be selected by the designer to meet the overall objectives of roundabout performance. These are identified in Figure 6.

R1 – entry path radius

R2 – circulating path radius

R3 – exit path radius

R4 – left turn path circulating radius

R5 – right turn path radius

[16] Even though a separated path may be provided, some bicyclists may choose to travel through the roundabout with motor vehicles, and are legally allowed to do so. Roundabouts should, whenever possible, be designed to accommodate bicyclists on the approaches and circulating roadway.

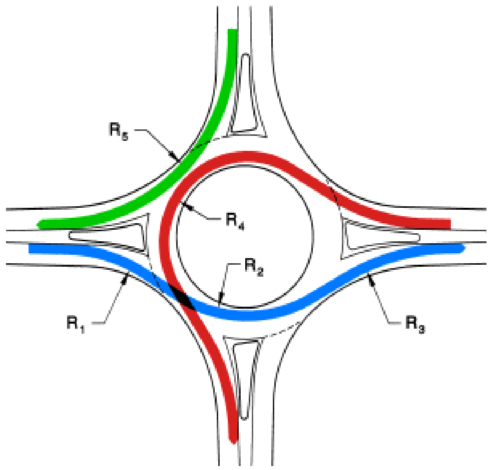

Figure 6: Five Key Radii that Affect Design Speed

Source: FHWA Roundabouts: An Informational Guide

Information from NCHRP Report 572 has further refined the speed prediction models which were previously based on AASHTO *Policy on Geometric Design of Streets and Highways.*

$V = 15R(e + f)$ *Equation 1*

where
V = speed (mph),
R= radius (ft),
e= superelevation (ft/ft), and
f= side friction factor.

NCHRP Report 572 further simplified the relationship between speed, radius, superelevation and side friction factor by assuming the use of common superelevation factors of +0.02 and -0.02:

$V = 3.4415R0.3861$, *for* $e = +0.02$ *Equation 2*
$V = 3.4614R0.3673$, *for* $e = -0.02$ *Equation 3*

where V = *predicted speed (mph), and*
R = *radius of curve (ft).*

Speed data collected at several study locations helped researchers of NCHRP Report 572 to determine the variations that exist between basic horizontal speed estimates and driver selected speeds through roundabouts. Two additional suggested changes were made to the exit and entry speed prediction models, in which the AASHTO relationship was found to over-estimate these speeds at roundabouts.

Selection of design speed is typically related to factors in the environment in which the roundabout is to be placed, posted speed limits on the approaches, capacity requirements, and available sight distance for entering drivers. Current guidance from the *FHWA Roundabout Guide* recommends higher entry speeds for locations in rural areas and for urban double- lane roundabouts (30 and 25 mph, respectively) (FHWA Guide).

Recommendations

1. **When designing roundabout radii, use AASHTO relationship between radius, superelevation, and friction to estimate speeds (see Equation 1, above) rather than relationships from NCHRP Report 572.**

   Rationale: The AASHTO equation provides higher predicted speeds than the equation in NCHRP Report 572. Given the relationship between bicyclist and pedestrian injury severity and speed, we recommend using the more conservative AASHTO equation.

2. **Design roundabout entries that slow motor vehicles to speeds of 25 mph or less.**

   Rationale: Research shows that survival rates of pedestrians struck by vehicles is highly correlated to the speed at which the vehicle was traveling when the pedestrian was struck. Fatality rates grow from 5 percent to 45 percent to 85 percent when impact speeds increase from 32km/hour (20 mph); 48km/hour (30 mph); and 64 km/hour (40 mph) respectively (Tian, UK Dept of Transport, 1997).

   Analysis of the data collected through NCHRP 3-65 revealed a positive relationship between the differential speed between the predicted entry speed, V_1 and the predicted left turning circulating speed around the center island, V_4 and the 'entering-circulating' vehicle crash rate (Tian). As the difference in predicted entering and circulating speeds increases, "entering-circulating" vehicle crash rates were also found to increase. Optimum roundabouts will have left turning circulating speed (V_4) of 25 mph or less.

3. **Use speed reduction features upstream to gradually reduce driver speed in high speed environments.** When higher speed entries are used in suburban/rural locations, it may be necessary to use a series of reverse curves on the approach to reduce driver speeds to 25 mph within the circulating roadway.

   Rationale: Research has shown that drivers perform better in environments that do not demand sudden speed changes but instead reduce the change in speed between successive geometric elements of no more than 12 mph (Krammes).

4. **Design circulating speeds of 25 mph or less.**

   Rationale: Surveys of bicyclists in New Zealand and focus groups held in the United States as part of this research effort both revealed a preference among bicyclists for roundabouts with circulating speeds of 18 mph (New Zealand findings) or 15-20 mph (U.S. findings).

4.5.4. Sight Distance

Driver sight distance, which affects driver speed, should be considered when designing roundabouts to accommodate bicyclists and pedestrians.

As noted in FHWA *Roundabouts: An Informational Guide*, when excessive intersection approach sight distance is available, driver-selected speeds tend to be higher. Observational studies reveal that drivers begin to scan the upstream legs of the roundabout and increase or decrease their speed to fill a gap that may be created before the vehicle entering on the upstream leg is able to reach the roundabout.

Figure 7 shows a roundabout approach taken at a multi-lane roundabout in Summerlin, Nevada, that has nearly unlimited sight distance for entering drivers. When observing this roundabout in the late 1990s, one could actually hear and see drivers decelerate as they scanned the upstream legs for approaching vehicles, then rapidly accelerate to "beat" upstream entering drivers into the roundabout. This type of design is not recommended for multi-lane roundabouts that are open to pedestrians and bicyclists.

Figure 7: Roundabout with unlimited sight distance

Source: Google Maps

To reduce driver distraction, it is recommended that the roundabout be designed to separate the driver actions of scanning the pedestrian crosswalk and scanning the circulating traffic for gaps.

To accomplish a two-stage successful entry into a multi-lane roundabout, it is recommended that landscaping be used to restrict driver sight lines in order to limit their ability to search for gaps created by entering vehicles from the upstream approach until after crossing the pedestrian crosswalk. Figure 8 demonstrates the use of landscaping on the splitter island and outer diameter of the circulating roadway to restrict sight lines of entering drivers.

It is recommended that the approach leg of the triangle sight distance be limited to 50 feet (FHWA). If the available sight distance on the approach leg of the sight distance triangle is greater than 50 feet, it is recommended that landscaping be used to restrict sight distance. The distance of 50 feet is based on British research which found that excessive sight distance resulted in higher crash frequencies. This length of the approach leg sight distance triangle also allows drivers to focus on the pedestrian crosswalk before changing focus and beginning their search for an acceptable gap in traffic for entering the roundabout (FHWA Guide).

Figure 8: Landscaped Splitter Island on Roundabout Approach Henrico County, VA

The required stopping sight distance for vehicles can be estimated using the AASHTO recommended stopping sight distance equation as follows:

$$d = 1.468(t)(V) + 1.087(\frac{V^2}{a}) \quad \text{Equation 4}$$

Where
d = stopping sight distance, ft;
t = perception-brake reaction time, assumed to be 2.5 s;
V = initial speed, mph; and
a = driver deceleration, assumed to be 11.2 ft/s^2.

Stopping sight distance should be maintained for every point within the roundabout -- on approach, and on exit from the circulating roadway. (AASHTO)

- Entering stream, comprised of vehicles from the immediate upstream entry. (Figure 9) The speed for this movement can be approximated by taking the average of the entry path speed (path with radius R1 from Figure 6) and the circulating path speed (path with radius R2 from Figure 6).

- Circulating stream, comprised of vehicles that entered the roundabout prior to the immediate upstream entry. (Figure 9) This speed can be approximated by taking the speed of left-turning vehicles (path with radius R4 from Figure 6) (FHWA).

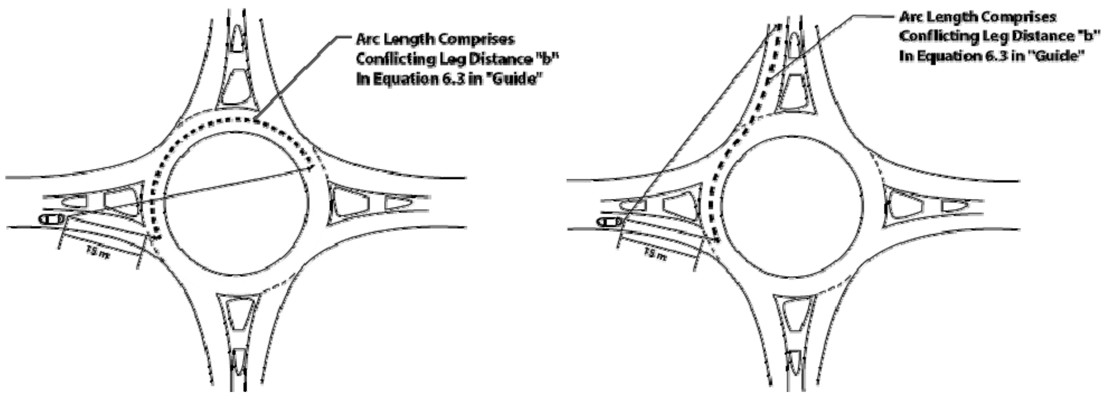

Figure 9: Circulating Stream (left) and Entering Stream (right) from DIB 80-01

The required sight distance can be calculated using Equation 5:

$$b = 1.468(V_{major})(t_c) \qquad \text{Equation 5}$$

Where:

b = length of conflicting leg of sight triangle, ft
V_{major} = design speed of conflicting movement, mph,
t_c = critical gap for entering the major road, s, equal to 6.5 s

DIB 80-01 states that if design speed or speed consistency cannot be obtained with the above sight distance equation, and if modifications to the geometrics cannot be made to meet the target speed, then the value for the critical gap may be reduced until the target speed is achieved, or until a critical gap of 5.0 seconds is reached. This recommendation in DIB 80-01 is in line with a recently completed study for Caltrans by Tian, which suggests that California drivers have adjusted to roundabouts and have shorter critical gap requirements, on the order of 4.7 seconds for multi-lane roundabouts.

Again, if the available sight distance exceeds the required sight distance, it is recommended that landscaping be used to restrict sight distance to help reduce driver-selected speeds on approach and entry to the roundabout.

Engineers and designers are also required to check adequate stopping sight distance for three key locations at a minimum:

- Approach sight distance (Figure 10).
- Sight distance on circulatory roadway (Figure 11).
- Sight distance to crosswalk on exit (Figure 12).

These sight distances must be equal to or greater than the required stopping sight distance as per AASHTO's requirements given in Equation 4 (FHWA).

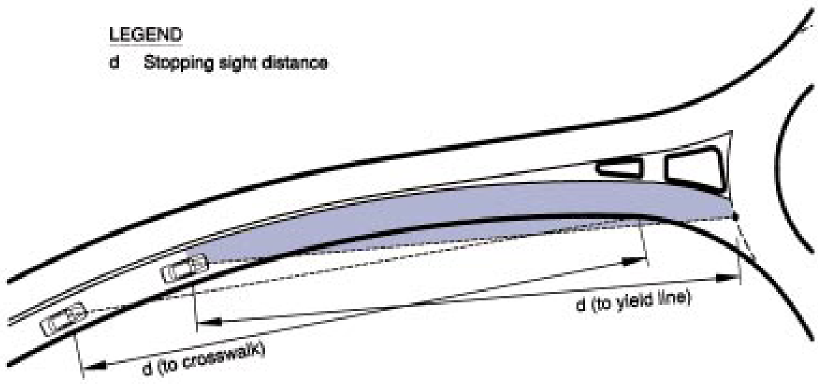

Figure 10: Approach Sight Distance (Source: FHWA Roundabouts: An Informational Guide)

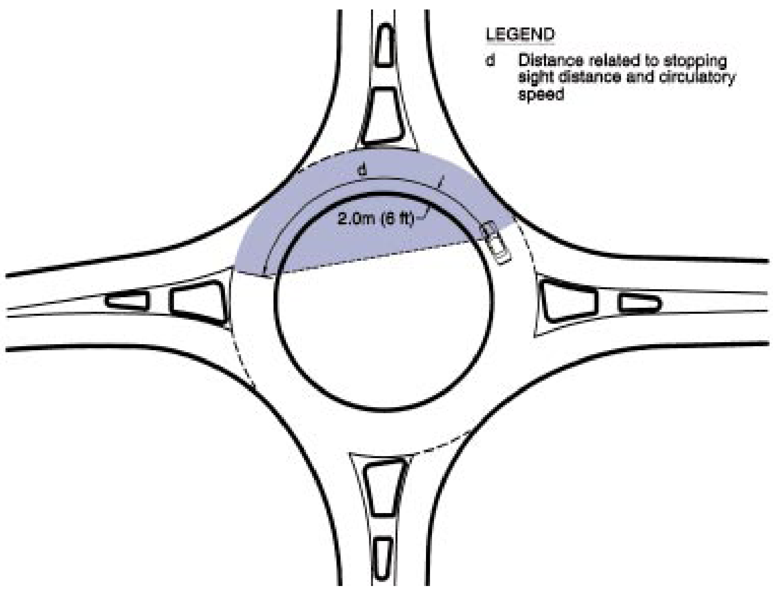

Figure 11: Circulating Roadway Sight Distance (Source: FHWA Roundabouts: An Informational Guide)

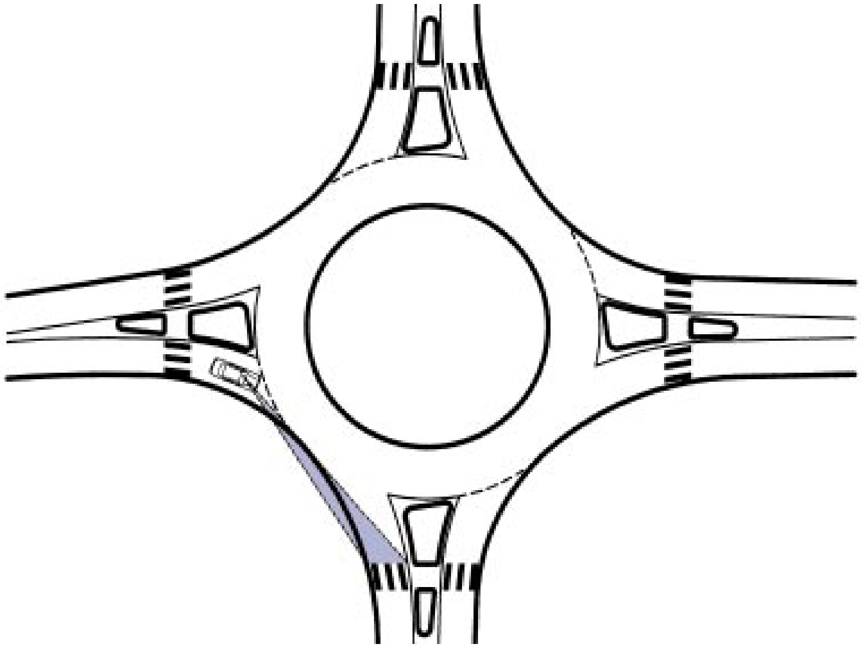

Figure 12: Sight Distance to Crosswalk on Immediate Downstream Exit (Source: FHWA Roundabouts: An Informational Guide)

Recommendations

1. **To reduce driver distraction, it is recommended that roundabouts be designed to separate the driver actions of scanning the pedestrian crosswalk and scanning the circulating traffic for gaps.** This can be achieved by locating the crosswalk back from the circulating roadway (50 feet), and by limiting the approach sight distance triangle to 50feet from the circulating roadway.

   Rationale: With separation of the two actions of scanning pedestrian crosswalk and scanning for gaps, drivers will be less distracted with either task and are more likely to make safe decisions.

2. **Restrict the ability of drivers to scan upstream legs for entering traffic by limiting the approach leg sight distance triangle length to 50 feet. If length of the approach leg sight distance triangle is longer than 50 feet, reduce distance to 50 feet using landscaping.**

   Rationale: This recommendation is intended to reduce driver approach speeds. As noted in FHWA *Roundabouts: An Informational Guide*, when excessive intersection approach sight distance is available, driver-selected speeds tend to be higher. Observational studies reveal that drivers begin to scan the upstream legs of the roundabout and increase or decrease their speed to fill a gap that may be created before the vehicle entering on the upstream leg is able to reach the roundabout. At the same time, they tend to ignore the pedestrian crosswalk.

3. **When calculating required sight distance for conflicting entering and circulating traffic streams, use the critical gap time of 4.5 seconds.**

   Rationale: California drivers have adjusted well to roundabout operations as per a field study conducted in 2006 (Tian). The findings of the California driver study also do not differ significantly from NCHRP Report 572, which contains data from many locations nationwide.

4. **When calculating deceleration distance, use the deceleration rate of -4.2 ft/sec^2 (NCHRP Report 572).**

   Rationale: Field research from NCHRP 3-26 suggests that the deceleration rate of drivers entering a multi-lane roundabout is slower than AASHTO-recommended deceleration rates for stopping sight distance (-11.2 ft/sec^2) and clearance intervals for signalized intersections (-10 ft/sec^2).

4.5.5. Width of Lanes

Width of lanes affects roundabout capacity, with wider lanes increasing capacity at a roundabout. FHWA guide suggests a width of 13-16 feet per lane at entry and exit and 26-30 feet for double circulating lanes.

Bicyclists are more likely to control the lane if the lane is narrower. By controlling the lane, bicyclists are visible to drivers, and at less risk of being sideswiped or turned into by a driver. If a lane is wide, motorists are more likely to try to share the lane with the bicyclist, increasing the chances of a collision. We therefore recommend narrower entry and circulating lanes, so that bicyclists will feel more comfortable controlling the lane. Narrower lanes also mean a shorter crossing distance for pedestrians.

Narrower lanes can also reduce speeds, benefiting bicyclists and pedestrians. However, at roundabouts, reducing radii may be a better way to control speeds than narrowing lanes. NCHRP Report 572showed a potential correlation between narrower entry/circulating lanes on multi-lane roundabouts and higher numbers of motor vehicle crashes.

Recommendations

1. **Design entry lanes and circulating roadway to be narrow (12 feet at the crosswalk and 24 feet or less for the circulating roadway) to encourage bicyclists to control the lane when traveling through the roundabout as motorists.**

   Rationale: Narrower lanes discourage sharing and encourage bicyclists to control the lane and reduce the chances that a motorist will attempt to pass a bicyclist and reduce motor vehicle speeds.

Figure 13: Bicyclist Controlling the Lane in Rehoboth Beach, DE

4.5.6. Single-lane vs. Multi-lane

The decision to install a single-lane or a multi-lane roundabout is primarily based on motor vehicle capacity. Roundabouts are designed to provide 15 percent over the predicted capacity of an intersection, and in California, are designed to provide enough capacity for predicted vehicle volumes 20 years down the road.

However, consideration should be given to bicycle and pedestrian use at that intersection. Single-lane roundabouts are preferred by bicyclists and pedestrians compared to multi-lane roundabouts.

Recommendations

1. **Use a single-lane roundabout in place of a multi-lane roundabout when possible.**

   Rationale: Single-lane roundabouts have fewer conflict points for bicyclists and pedestrians, slower speeds and shorter crossing distances, and require pedestrians to travel a shorter distance when navigating around the roundabout.

2. **Use the minimum number of entry, circulating, and exit lanes, as directed by required capacity. If traffic volumes allow, design the roundabout to accommodate the high-volume roadway with two lanes and the low-volume roadway with one lane.**

   Rationale: Restricting the through and left-turn movements to one lane reduces conflict points for bicyclists who are traveling in the roadway as motorists. The Rehoboth Beach roundabout was designed in this manner, and we observed many bicyclists riding through the roundabout comfortably. Figure 13 is a photo of this roundabout.

Figure 14: Aerial View of Rehoboth Beach Roundabout

4.5.7. Signage and Pavement Markings for Directional Guidance

Navigating roundabouts requires active decision-making by both drivers and bicyclists on the approach, while circulating, and on exit. On the approach to a roundabout, drivers and bicyclists begin to scan the upstream approach, the circulating roadway and the exit of the approach from which they are attempting to enter the roundabout, as illustrated in Figure 15. Unlike traditional intersections where there are traffic signals, roundabouts require drivers and bicyclists to actively seek and determine acceptable gaps in the circulating and entering traffic streams from upstream legs of the roundabout and merge with traffic in the roundabout circulating stream. After successful entry into the roundabout, drivers and bicyclists in multi-lane roundabouts must also successfully negotiate and merge with circulating, entering, and exiting traffic in order to exit the roundabout.

Driver's reaction times increase as a function of decision complexity and the amount of information to be processed. According to AASHTO, drivers making an expected, complex decision with several alternatives take an average of 2.5 to 3.5 second to respond, with some drivers taking up to 5 seconds to respond. When an event is unexpected, driver reaction times increase, sometimes by several seconds.[17] When navigating a roundabout, drivers may be so distracted that they may not react quickly enough to avoid bicyclists and pedestrians, particularly if bicyclists and pedestrians are unexpected. These conditions point to a need to design roundabouts with fewer driver distractions, specifically, as stated in AASHTO, "Needed information should be in the driver's field of view, available when and where needed, available in a useable form, and capable of capturing the driver's attention."[18] Driver decisions should be simplified and spaced farther apart to decrease information-processing demands.

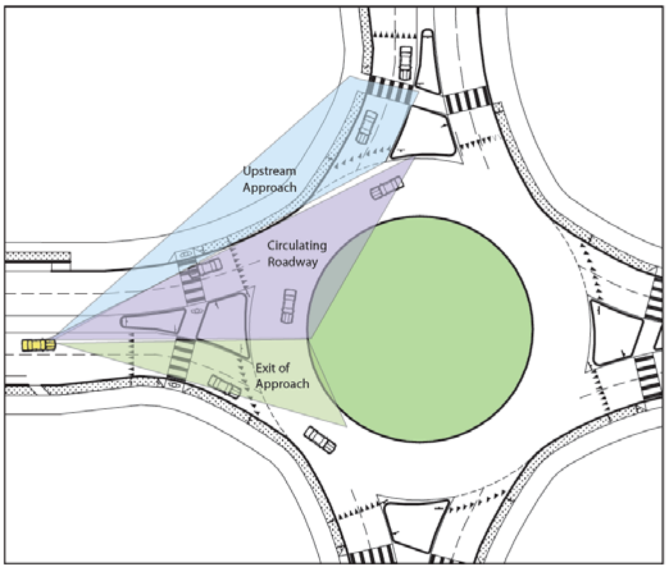

Figure 15: Driver, Pedestrian, and Bicyclist Scanning on Approach to Roundabout

Source: AASHTO 2004

Guide Signs

The MUTCD has recommended the use of new guide signs for roundabouts as shown in Figure 16 and Figure 17 (FHWA Notice of Proposed Amendment Presentation, January 2008). These exit signs can be mounted on the splitter island of each approach to help drivers and bicyclists exiting the circulating roadway determine their desired exit points.

[17] AASHTO Geometric Design of Highways and Streets, 2004. Chapter 1, pp 46-56.

[18] AASHTO Geometric Design of Highways and Streets, 2004. Chapter 1, page 50.

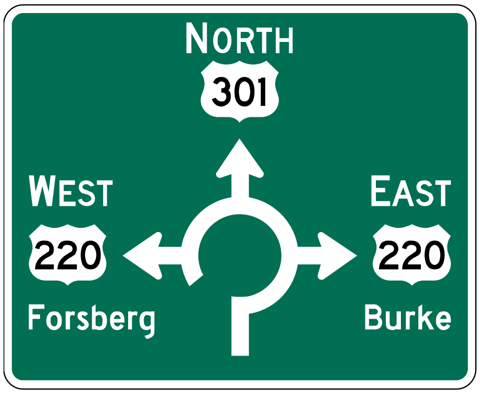

Figure 16: MUTCD Recommended Guide Signs for Roundabouts (FHWA, 2008)

Figure 17: MUTCD Recommended Exit Sign for Roundabouts (FHWA, 2008)

Fish-Hook Pavement Markings and Signs

FHWA recommends the use of the optional fish-hook pavement marking to help drivers and bicyclists place themselves in the correct lane prior to entry into the roundabout. As with the additional guide signs in the 2007 proposed changes to the Federal MUTCD, the optional fish-hook pavement marking should help improve driver and bicyclist placement and negotiation of a multi-lane roundabout.

Figure 18: Recommended Optional Fish-Hook Arrows on Lane Use Control Signs at Multi-Lane Roundabouts (FHWA, 2008)

Figure 19: Optional Fish-Hook Lane-Use Arrows (FHWA, 2008)

Lane Lines within the Circulatory Roadway

Caltrans DIB 80-01 states that "lane lines within the circulatory roadway of two-lane roundabouts are not marked. However, special delineation treatments may be considered at specific locations to facilitate or enhance operations that otherwise may be inhibited by non-conforming design features."

The forthcoming revisions to the Federal MUTCD state that: "Multi-lane roundabouts should have lane line markings within the circulatory roadway to channelize traffic to the appropriate exit." Also: "Continuous concentric lane lines shall not be used within the circulatory roadway of roundabouts."[19]

Recommendations

1. **Multi-lane roundabouts should have lane lines within the circulating roadway to channelize traffic to the appropriate exit. Concentric lane markings are not recommended.**

   Rationale: CA DIB 80-01 permits markings within the circulatory roadway of two-lane roundabouts to facilitate or enhance operations and the 2007 Notice of Proposed Amendment to the Federal MUTCD recommends lane lines in the circulatory roadway of multi-lane roundabouts. By delineating lanes in the circulating roadway, it may simplify driver and bicyclist decision-making, and permit drivers and bicyclists to react more quickly. Bicyclists may benefit from lane markings by allowing them to more easily "control" a lane. Focus group participants noted that often they feel drivers are distracted by the lane selection and exit selection process, and as a result, participants felt vulnerable as bicyclists and pedestrians at multi-lane roundabouts. Many participants felt that improved navigational devices such as additional signage and pavement markings would help drivers negotiate multi-lane roundabouts better and thus improve the sense of safety for pedestrians and bicyclists.

2. **Where turning movements are high, install a fish-hook sign on approach to a roundabout. This sign is optional in the Federal MUTCD. Paint fish-hook pavement markings in**

[19] 2007 Notice of Proposed Amendments for the Manual on Uniform Traffic Control Devices, December 2007

roundabout approach lanes to improve driver and bicyclist understanding, placement, and negotiation of the roundabout.

Rationale: Findings from the focus groups held as part of this study show support for the use of directional signs to help drivers better negotiate multi-lane roundabouts. Many participants in the focus groups reporting thinking that drivers had a difficult time determining when to exit the roundabout. They postulated that by including very clear directional signs on the approach to a multi-lane roundabout, drivers would perform better and be better able to process information regarding pedestrian presence and movements.

With improved guidance on the approach to the roundabout, drivers should be more comfortable and less distracted with the entry task and more aware of pedestrian and bicycle presence and movements. Drivers would be able to choose the appropriate entry and circulating lane, reducing unexpected and prohibited lane changes within the roundabout. This will also improve navigation of the roundabout for bicyclists.

3. **Paint arrow pavement markings in roundabout circulating lanes to improve driver understanding, placement, and negotiation of the roundabout.**

   Rationale: Same as #1

4. **Install directional guide signs on the approach to the roundabout and exit guide signs on splitter islands, but only if the benefits outweigh the costs of decreased driver awareness due to sign clutter.**

   Rationale: Focus group participants noted that the addition of signs highlighting where drivers should exit made them feel safer as pedestrians. They believed drivers would be more aware of their presence if they had better guidance as to where to exit the roundabout.

4.5.8. Bicycle Facilities at Roundabouts

Bicyclists can be accommodated through roundabouts either in mixed flow with vehicular traffic or on separate facilities. All roundabouts should strive to accommodate bicyclists in mixed traffic through the use of low speeds, narrow lanes, and other design factors described above. However, the authors recognize that 1) in some instances, the choice is made to design a roundabout that does not easily accommodate all bicyclists in the roadway and 2) even the best-designed multi-lane roundabout may not accommodate all levels of bicyclists on the roadway. When designing roundabouts, one must consider the skill level of the bicyclist that is expected to use the facility, the skill level needed to navigate the planned roundabout on a bicycle in mixed-flow traffic, and design bicycle facilities that accommodate the skill level of the expected bicyclist. Among the possible solutions are separate bikeways, shared use of the pedestrian facility, separate bike routing through other intersections, or grade separation for the vulnerable modes (AASHTO Bike).

The FHWA Guide recommends the following designs for bicycle accommodation:

- Raised pavement markings are not to be used in bicyclist's path of travel.
- On existing or proposed bicycle routes, bicycle lanes should be used on the approach to roundabouts, with the lanes dropped in advance of the crosswalk.
- Bike lanes should be terminated 100 feet in advance of the inscribed circle to encourage bicycles to mix with vehicle traffic. The Guide notes that this is most successful at smaller roundabouts with speeds below 20 mph, where bicycle speeds can more closely match motor vehicle speeds.
- Bike lane markings are not recommended within the circulatory roadway.

- To accommodate bicyclists who prefer not to use the circulatory roadway, a widened sidewalk or shared-use path may be provided.

The California DIB 80-01 recommends the following additional designs for bicycle accommodation:

- To accommodate bicyclists on the State highway system who prefer not to use the circulatory roadway, ramps up to enter the shared-use path are to be provided as shown below :

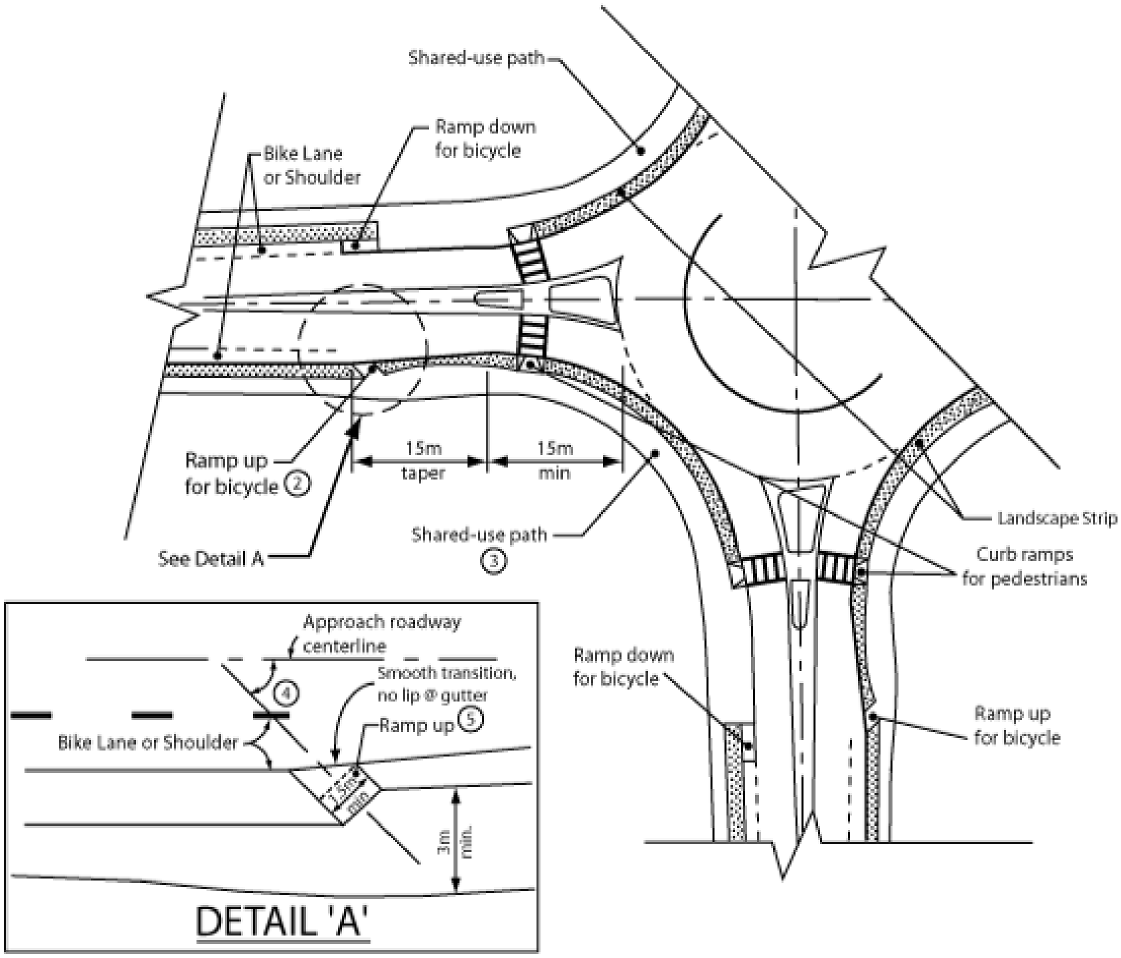

Figure 20: Bike Facility Design from Caltrans DIB 80-01

Recommendations

In addition to all the above guidance, we recommend:

1. **Provide a paved bike path around the roundabout, designed similar to Class I requirements, for bicyclists who are not comfortable traveling through the roundabout on the circulatory roadway. Minimum path width should be eight feet paved with two feet clearance on either side, for a minimum total width of 12 feet. Ten-foot paved width is recommended whenever bicyclist or pedestrian volumes are high.**

Rationale: Video analysis showed that when available, the majority of bicyclists used separated bike paths rather than traveling through the roundabout on the circulatory roadway, suggesting that most bicyclists prefer using paths to travel through roundabouts.

2. **Use colored pavement, striping or pavement markings to designate a separate area for pedestrians on the separated path.**

   Rationale: Separating bicyclist and pedestrian use will reduce pedestrian-bicyclist conflicts and further indicate to bicyclists that they are permitted to travel on the side path. Research suggests that site design and signage greatly affects road users' roadway placement (Svensson, Jonsson, & Hyden, 2007).

3. **Provide signage on approach informing bicyclists of ramp to shared-use pathway.**
   Rationale: Signage will indicate to bicyclists that they are permitted to travel on the side path.

4. **Design entry lanes and circulating roadway to be narrow (12 feet at the crosswalk and 24 feet or less for the circulating roadway) to encourage bicyclists to control the lane when traveling through the roundabout as motorists.**
   Rationale: By controlling the lane, bicyclists will reduce the chances that a motorist will overtake them and turn in front of them.

5. **Install "Bicyclists Allowed Full Use of Lane" signs in advance of the roundabout.**
   Rationale: "Bicyclists Allowed Full Use of Lane" signs, which have been used experimentally in San Francisco and Berkeley, indicate to bicyclists and motorists that bicyclists are allowed to ride in the middle of the lane. This also reinforces the California Vehicle Code, which allows bicyclists to travel in the middle of the lane under certain circumstances.

6. **Avoid right-turn bypass lanes, particularly those designed with acceleration lanes for turning traffic to merge with main traffic flow. If these are used, install bicycle warning signage, and blue bike lanes or other treatments, to guide bicyclists across right-turn bypass lanes.**

   Rationale: Right-turn bypass lanes are not recommended in urban areas where bicyclists and pedestrians are expected (Guide Section 6.3.15).

   There are two options for constructing right-turn bypass lanes. The first is a right-turn bypass lane with an acceleration lane. This configuration is more difficult for bicyclists to navigate, since through bicyclists are required to merge across motor vehicle traffic traveling at much higher speeds.

The second option is a right-turn bypass lane with a yield at the exit leg. This configuration is preferable, since motorists will be driving more slowly than in the first option and will be prepared to yield. Also, the visibility of approaching bicyclists is greater than in the first option.

Figure 21: Example of a Right-Turn Bypass Lane with a Yield at Exit Leg (FHWA Guide)

4.5.9. Pedestrian Facilities at Roundabouts

The FHWA Guide recommends the following pedestrian treatments at roundabouts:

- Crosswalks should be set back from the roundabout to reduce the crossing distance, to separate vehicle-vehicle and pedestrian-vehicle conflicts, and to allow drivers to focus attention on the pedestrian crossing before having to focus on entering the roundabout.

- Parking should be restricted 20 feet or more upstream of the pedestrian crossing. (Section 2.4.6, Section 6.3.14).

- Potential treatments listed but not further described include: raised speed tables with detectable warnings, treatments for visually impaired pedestrians to locate crosswalks, raised pavement markers with yellow flashing lights to alert drivers of crossing pedestrians, and pedestrian crossings with actuated signals set sufficiently upstream of the yield line to minimize the possibility of exiting vehicle queues spilling back into the circulatory roadway.

- The Guide does not require pedestrian crossing signs at roundabout pedestrian crossings, (Section 7.1.3.5). However, California MUTCD recommends Pedestrian Crossing (W11-2) sign and a diagonal downward pointing arrow (W16-7P) plaque at pedestrian crossings at roundabouts.

- Ramps are required at the end of crosswalks to connect the crosswalks to the sidewalks.

- Speed tables may be considered for crosswalks in urban areas where the approach speed has been reduced to 12 mph near the pedestrian crossing.

- Recommended sidewalk set back distance should be 5 feet from the roadway, with a minimum set back distance of 2 feet from the roadway.

- A ten-foot wide sidewalk is recommended to accommodate bicyclists and pedestrians.
- In areas with expected speeds of 50 mph or greater, additional treatments can be used to reduce speeds in advance of the roundabout. Two treatments applicable to pedestrian crossings are pavement markings across pavement and speed warning signs. The Guide also suggests rumble strips, which are not advisable.
- Crosswalk markings should be installed across both the entrance and exit of each leg and across any right-turn bypass lanes. The crosswalk should be aligned with the ramps and pedestrian refuge in the splitter island and have markings that are generally perpendicular to the flow of vehicular traffic. Pedestrian crosswalk markings should not be used at roundabouts without illumination (Guide).
- Pedestrian refuges should be designed at street level, rather than elevated to the height of the splitter island (Guide).

The Caltrans Design Information Bulletin 80-01 recommends the following pedestrian treatments at roundabouts:

- A pedestrian crossing at a multi-lane roundabout should be located two car lengths (50 feet/15 meters) away from the inscribed circle, and no closer than 20 feet (6 meters).
- Crosswalks must be marked at roundabouts, including rural roundabouts, on "all legs where pedestrians will be crossing."
- Crosswalks marked at roundabouts should be "ladder" type to improve clarification of crossing for pedestrians, including those who are visually impaired.
- Install detectable warning surfaces at all pedestrian crossings to aid visually impaired pedestrians.

Recommendations

We recommend the following new and modified guidelines:

1. **Treat crosswalks at roundabouts as uncontrolled mid-block crossings, rather than as crosswalks at intersections.**

   Rationale: Roundabout crosswalks, particularly when set back two car lengths from the intersection as required by DIB 80-01, essentially function as uncontrolled mid-block crossings and should be signed and striped as such.

2. **Parking, if provided, should be restricted to 20 feet or more upstream of the crosswalk.**

   Rationale: Parking restrictions increase sight distance from the approaching lane and the edge of the crosswalk where pedestrians are waiting to cross. Twenty feet is recommended by AASHTO.

3. **The crosswalks and pedestrian refuge should provide a straight path across the roadway.**

   Rationale: A straight path is easier for visually- impaired pedestrians to navigate.

4. **A speed table for the crosswalk should be considered as a design option for urban multi-lane roundabouts.**

Rationale: Speed tables are acknowledged in the Guide as potential treatments.

5. **Consider installation of pedestrian-actuated flashing warning lights.** Actuation devices should be ADA accessible and accessible to bicyclists who are using the side path.

   Rationale: A high-intensity activated crosswalk (HAWK) treatment, overhead beacons or rapid rectangular flashers are preferred to in-pavement flashing lights. While in-pavement flashers are suggested in the Guide, they are not as visible as overhead beacons; only the driver of the first car in line is able to see them. Flashing warning lights, HAWK and rapid rectangular flashing beacons are not part of the current MUTCD and thus must be treated as experimental traffic control devices (Guide).

6. **Stripe yield lines** (a row of solid white isosceles triangles pointing toward approaching vehicles) **across approach lanes to indicate the point at which the yield is intended or required.** Also install "Yield Here to Pedestrian" signs.

   Rationale: Yield triangles and "yield here to pedestrians" signs are permissible under CAMUTCD and may encourage higher yielding rates.

7. **In-street pedestrian crossing signs (R1-6) should be considered at crossing locations on roundabout exits.**

   Rationale: In-street pedestrian crossing signs are permissible under CAMUTCD and may encourage higher yielding rates.

8. **Focus treatments to increase motorist yielding at exits more than at entries.**

   Rationale: Pedestrians had more difficulty crossing exit lanes than entry lanes. Video analysis showed longer pedestrian delays at exit lanes. This is not to imply that treatments at entries are not important, but rather that exits are a higher priority.

4.5.10. Splitter Island/ Pedestrian Refuge

The following design details are provided in the FHWA Guide:

- Splitter islands should be provided on all multi-lane roundabouts.

- The total length of the island should generally be at least 50 feet to provide sufficient protection for pedestrians and to alert approaching drivers to the roundabout geometry. Additionally, the splitter island should extend beyond the end of the exit curve to prevent exiting traffic from accidentally crossing into the path of approaching traffic.

- Standard AASHTO guidelines for island design should be followed for the splitter island. This includes using larger nose radii at approach corners to maximize island visibility and offsetting curb lines at the approach ends to create a funneling effect.

- The width of the pedestrian refuge area should be ten feet and the minimum depth is six feet. Detectable warning surfaces are required at entry and exits to refuge-type splitter islands, and should be two feet wide minimum (three feet where possible) and extend the length of the refuge area.

- The total splitter island length should be 50 feet, 200 feet for extended splitter islands at rural multi-lane roundabouts.

Recommendations

No additional recommendations.

4.5.11. Grade-Separated Crossings

Consideration should be given to the use of grade-separated facilities when motor vehicle volumes are high and there are significant bicycle or pedestrian volumes. The use of grade separated facilities at roundabouts has not yet been studied in the U.S. or widely used. However, it is expected that such facilities may provide an alternative means of access for bicyclists uncomfortable traveling through multi-lane roundabouts on the roadway. The FHWA Guide and the Caltrans DIB 80-01 do not provide specific guidance for grade-separated facilities.

Figure 22: Bicycle and Pedestrian Roundabout Undercrossing at Western Michigan University

Source: Premarc

Figure 23: Undercrossing Detail (Western Michigan University)

Source: Premarc

4.5.12. Operational Recommendations

The FHWA Guide mentions using pedestrian crossings with actuated signals, but does not go into detail other than recommending that these be set sufficiently upstream of the yield line to minimize the possibility of exiting vehicle queues spilling back into the circulatory roadway.

High-intensity activated crosswalk (HAWK) signals show promise for improving roundabout operations for pedestrians. HAWK signals allow pedestrians to actuate overhead signals, which will first flash yellow, then steady yellow, then steady red. The signal is dark when it is not activated.

HAWK signals are currently being tested at a high-volume three-lane roundabout in Oakland County, Michigan. If the results of the study are finalized before this research ends, we will incorporate these findings into this paper.

4.5.13. Accommodating Visually Impaired Pedestrians

The reader is urged to follow the findings of NCHRP 3-78 "Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities," which is investigating various technologies to assist drivers and visually-impaired pedestrians in crossing roundabouts. This research involves field studies with visually impaired participants and was expected to be completed in December of 2008.[20]

[20] Additional information on this study can be found at the Transportation Research Board website and through this link: http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=834

4.5.14. Innovative Designs

Multi-lane roundabouts are common in Europe, where motorists succeed in coexisting with bicyclists and pedestrians. The Dutch multi-lane roundabout design, for example, uses a cycletrack around the perimeter of the circulating roadway. Pedestrians and bicyclists have the right of way at the entry and exit points. Dutch motorist behavior is strongly cyclist-aware, and motorists are trained to expect and yield to cyclists when exiting the roundabout.

Research outside the U.S. has led to some innovative treatments for multi-lane roundabouts. Two are described here.

Figure 24: Netherlands Roundabout

C-Roundabout

The c-roundabout, or cycle roundabout, is a multi-lane roundabout designed to be more amenable to bicyclists. It was designed by researchers in New Zealand but has yet to be constructed and tested (Campbell, Jurisich and Dunn). Based on crash analysis and bicyclist surveys, the researchers determined that the best solution to accommodating bicyclists was to reduce the circulating speed of the roundabout to approximately 18 mph (30 km/hr). This would allow bicyclists to control the lane and comfortably circulate in the roundabout with motor vehicles.

The design solution requires large vehicles to straddle two lanes. A roundabout in Auckland, New Zealand, has demonstrated that this design can be successful, even with large motor vehicle volumes. The c-roundabout's entry width is narrowed to 18 feet to produce lower vehicle speeds, which are anticipated to improve bicyclist safety. Typical multi-lane roundabout designs call for the use of a wider circulating lane width to accommodate large motor vehicles circulating alongside smaller motor vehicles. The c-roundabout has been designed to allow large motor vehicles to navigate the roundabout by straddling the lane line in the entry and circulating lanes. This design is currently under review in New Zealand (Campbell, Jurisich and Dunn). Reducing the entry width also allows the central island to be designed with a diameter of 66 feet (20 meters). A traversable apron is not necessary.

A diagram of the c-roundabout showing a large tractor trailer navigating the intersection is shown in Figure 25. Note that motor vehicles circulate clockwise in New Zealand.

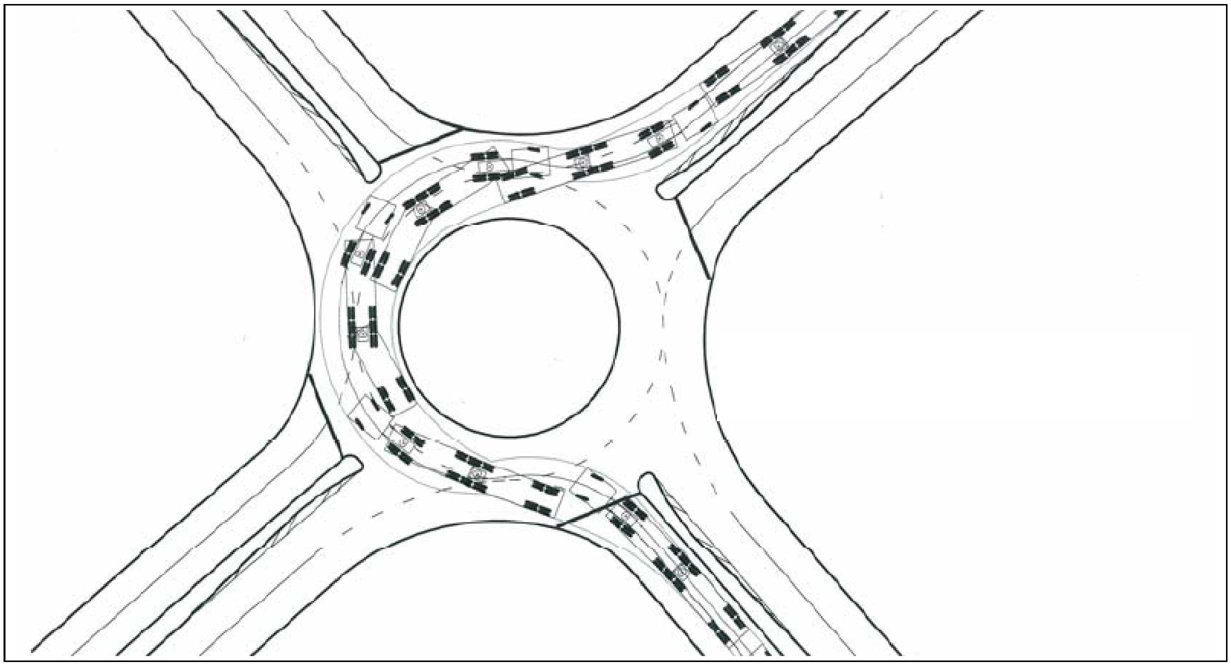

Figure 25: Tractor trailer circulating through C-Roundabout

Source: Campbell, Jurisich and Dunn

Turbo Roundabout

In the Netherlands, turbo roundabouts are one step in a series of roundabout intersection designs that provide increasingly higher capacity. The series of Dutch roundabout intersection designs are listed below.

- Low volume intersections are normally single-lane roundabouts; if a single-lane roundabout does not provide sufficient capacity, then a turbo-roundabout is considered.
- If a turbo-roundabout does not provide sufficient capacity then a signalized intersection is considered.
- If a signalized intersection will not provide sufficient capacity, then a signalized roundabout is considered (Inman and Davis).

Turbo roundabouts provide additional capacity for multi-lane roundabouts, but are designed very differently than typical multi-lane roundabouts. Barriers are used on the roundabout approach to force drivers to select the correct lane. Within the roundabout, mountable curbs are used between lanes to prevent drivers from veering out of their lane (path overlap). A portion of the central island is used for left turns. Bicyclists and pedestrians crossing turbo roundabout entries and exits must yield to traffic entering and exiting the roundabout, unlike single-lane roundabouts in the Netherlands, in which bicyclists and pedestrians have the right-of-way.

Pedestrian and bicyclist crossings can be at-grade or grade separated. Grade separated crossings are used where bicycle and/or pedestrian volumes are high, to reduce motor vehicle conflicts and improve motor vehicle flow. Bicyclist crossings have a "jog" in the splitter island to encourage bicyclists to slow down and yield to oncoming traffic.

Figure 26 shows a typical design for a Dutch turbo roundabout.

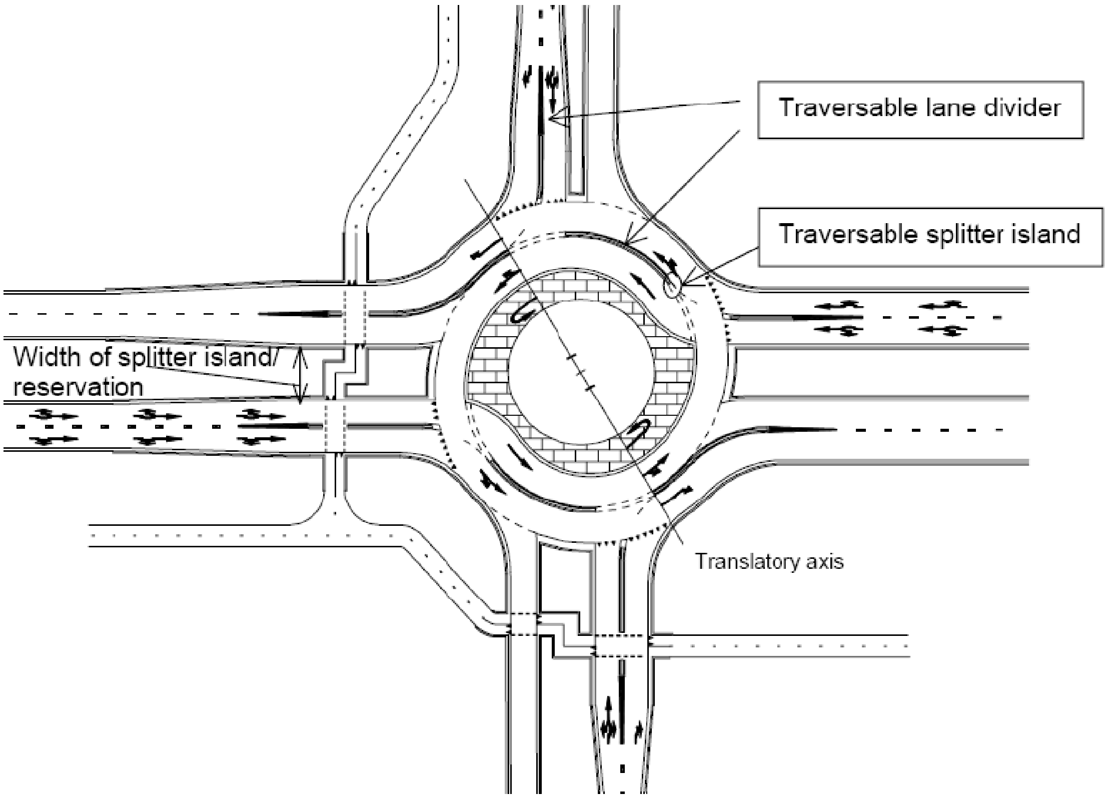

Figure 26: Typical Dutch Design for a Turbo Roundabout

Source: Inman and Davis, 2007.

Figure 27: Jog in bicycle path on splitter island

Source: "Synthesis of Literature Relevant to Roundabout Signalization to Provide Pedestrian Access" 2007

Continental-Style Roundabouts

Recent guidance has been published by Transport for London (a local UK government agency created in 2000 which is responsible for most transport systems in the Greater London area), which recommends the use of "continental-style" roundabouts when roundabouts are used on bicycle routes with vehicle traffic greater than 2500 vehicles per hour. Continental-style roundabouts are designed to accommodate bicyclists through the use of designs that slow driver speeds. The guidance recommends single-lane roundabouts, but also provides design guidance for multi-lane roundabouts, including the following features:

- Legs that are perpendicular, rather than tangential to the roundabout.
- Minimal flare on entry.
- Reducing some entries to single lane entries if two lane capacity is not required.
- Strive to achieve vehicle speeds of 12 mph with a maximum of 20 mph.
- Consider introducing cycle tracks and Toucan crossings (see Figure 28) , i.e., those that accommodate pedestrians and cyclists in the same crosswalk, typically 13 feet or 4 meters wide.

When conditions do not allow for single lane roundabouts and traffic volumes are considered "high," it is recommended that signalization of the roundabout should be considered. Figure 29 shows a signalized roundabout in York, England.

Figure 28: Toucan Crossing at Roundabout in England

Source: Wikipedia 2009

Figure 29: Signalized Roundabout York, England

Source: Transport for London, Design Portfolio A.13 Roundabouts

Australia Guidelines for Bicyclists at Roundabouts

The *Austroads Guide to Traffic Engineering Practice, Part 14 – Bicycles,* presents a detailed approach to accommodating bicycles on streets and highways in Australia. Of particular interest is Chapter 5, which describes in detail the recommended design approach for accommodating bicyclists at intersections including roundabouts (Austroads).

The Austroads Guide recommends special bicycle provisions for roundabouts that have at least one of the following conditions:

- Traffic exceeds 10,000 vehicles per day.
- The central island diameter of the roundabout exceeds 82 feet (25 meters).
- Multi-lane roundabouts.
- Vehicle speeds exceeding 31 mph (50 kph).

Special treatments deemed appropriate to accommodate bicyclists when one of the above conditions exists include:

- Use of a separate cycle track around the roundabout as an alternative to using the circulating roadway of the roundabout.
- Full-time signalization on one or all of the entries to the roundabout, -depending on crash history and bicycle movements.
- Controlled crossing on critical approaches or the use of grade separation to physically separate vehicle and bicycle traffic.

The Austroads Guide notes that special considerations should be made when including a separate bicycle lane around the perimeter of the roundabout to avoid conflicts with pedestrian movements on shared use facilities.

4.6. Illustrations of Recommended Design Treatments

The Austroads guide authors have developed diagrams illustrating recommended design treatments to accommodate bicyclists and pedestrians at urban multi-lane roundabouts, rural multi-lane roundabouts, and multi-lane roundabouts at freeway interchanges. Table 13 describes the design goals for these roundabout types.

Table 13: Recommended Design Goals for Accommodating Bicyclists and Pedestrians at Multi-Lane Roundabouts in Urban, Rural and Freeway Interchange Environments

Roundabout Type	Key Design Goals for Meeting Bicyclist and Pedestrian Comfort, Safety and Mobility Needs
Urban Multi-Lane Roundabout **Constrained ROW**	Provide comfortable on-street shared use environment for adult bicyclists of all abilities by reducing entry and circulating speeds to less than 25 mph. Maximize driver yielding rates at crossings through signage, striping, and infrastructure. If motor vehicle volumes are high, consider pedestrian- and bicyclist- activated beacons or signals. Reduce bicyclist and pedestrian collision severity by slowing motor vehicles to 25 mph or less in advance of crosswalks.
Urban Multi-Lane Roundabout **Unconstrained ROW**	Provide comfortable on-street shared use environment for experienced adult bicyclists by reducing entry and circulating speeds to less than 25 mph. Provide off-street alternative for bicyclists through shared use path. Maximize driver yielding rates at crossings through signage, striping, and infrastructure or pedestrian- and bicyclist- activated signals. If motor vehicle volumes are high, consider pedestrian- and bicyclist-activated beacons or signals. If motor vehicle volumes are high, and speed reductions or interruption of motor vehicle flow is not acceptable, consider grade separated crossing for bicyclists and pedestrians.
Rural Double-Lane Roundabout	Slow motor vehicle approach and circulating speeds to 30-35 mph in advance of the pedestrian crossing through reverse curves or other design measures. Provide off-street alternative for bicyclists through shared use path. If traffic volumes are high and crossing gaps are short, maximize driver yielding rates at crossings through pedestrian- and bicyclist -activated signals.
Freeway Interchange	Use the most appropriate treatment above, with: Slow motor vehicle speeds on ramp in advance of crossing to 25 mph or less or provide a pedestrian- or bicyclist actuated signal.

Source: Austroads

5. Conclusions

5.1. Summary of Findings

Caltrans and local California agencies are considering installing multi-lane roundabouts, which have been demonstrated in the U.S. and elsewhere to decrease the number and severity of automobile collisions and improve traffic flow in both urban and rural environments. However, it remains unclear whether bicyclists and pedestrians in roundabouts garner the same level of benefit as motorists. Information regarding pedestrian and bicyclist collisions at roundabouts is often ambiguous or incomplete. In addition, pedestrian and bicyclist-involved collisions in general are not always reported, or in some cases are systematically excluded from crash databases, making it difficult to effectively analyze crashes and evaluate countermeasures. In addition, without information about the level of walking and bicycling at roundabouts and therefore exposure to crash risk, it is not possible to calculate the rates of pedestrian and/or bicyclist-involved collisions or compare relative risk.

This project sought to understand factors that influence bicycle and pedestrian demand and behavior at multi-lane roundabouts through literature review, case studies, in-field counts and surveys, focus groups, and video analysis. Among other factors, sight distance, longer travel distance, judgment of vehicle speeds, and overall lack of familiarity with multi-lane roundabout use were found to influence bicycle and pedestrian behavior at multi-lane roundabouts. Multi-lane roundabouts present significant comfort concerns for bicyclists and pedestrians, and may present greater safety issues for non-motorized users compared to traditional intersections.

As this study demonstrates, a number of design solutions can be employed to make roundabouts safer and more user-friendly for both bicyclists and pedestrians, and to help drivers effectively and safely share the road with these users. Recommendations have been provided for design guidelines for multi-lane roundabouts as well as for circumstances under which multi-lane roundabouts should or should not be installed.

5.2. Additional Avenues of Research

In the course of this study, several additional avenues of research were identified. While many of the treatments described in this document are known to be effective at standard intersections and roadways their efficacy at multi-lane roundabouts has not been explored. Additionally, Caltrans may wish to consider exploring the following research topics in the future:

- Before-and-after study of pedestrian and bicyclist volumes, collision rates and types at the ten locations scheduled for multi-lane roundabouts identified and surveyed by Tian.
- Cultural factors influencing motorist yielding behavior to pedestrians and bicyclists at multi-lane roundabouts, with a comparison between drivers in California, other parts of the United States, and Europe.
- Field trials of treatments identified in this document to understand their effectiveness of increasing motorist yielding behavior to pedestrians and bicyclists at multi-lane roundabouts.
- Field trials of HAWK and other signalization treatments at multi-lane roundabouts to understand their effectiveness in improving bicyclist and pedestrian comfort and safety at multi-lane roundabouts, and their effect on roundabout capacity and motor vehicle delay.

- Comparison of effects of in-road bicycle treatments and off-street bicycle treatments on bicyclist safety and comfort at multi-lane roundabouts.

- Summary of vehicle codes that clarify bicyclist, pedestrian and motorist right-of-way at multi-lane roundabouts, and recommended changes to the California Vehicle Code.

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