ROUNDABOUT
GEOMETRIC DESIGN GUIDANCE

Federal Report # F/CA/RI-2006/13

FINAL REPORT

Prepared for
California Department of Transportation
Division of Research & Innovation

June 2007

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for the California Department of Transportation

Research Project #65A0229

California Department of Transportation
Division of Research and Innovation

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1. Report No. F/CA/RI-2006/13	2. Government Accession No.	3. Recipient's Catalog No.

3. Title and Subtitle Roundabout Geometric Design Guidance	5. Report Date June 2007
	6. Performing Organization Code
7. Author(s) Zong Z. Tian, Feng Xu, Lee A. Rodegerdts, Wade E. Scarbrough, Brian L. Ray, William E. Bishop, Thomas C. Ferrara, Sannow Mam	8. Performing Organization Report No. 1
9. Performing Organization Name and Address University of Nevada, Reno Department of Civil & Environmental Engineering Reno, NV 89557	10. Work Unit no. (TRAIS)
	11. Contract or Grant No. 65A0229
12. Sponsoring Agency Name and Address California Department of Transportation Division of Research & Innovation 1227 O St. Sacramento, CA 95814	13. Type of Report and Period Covered Final Report January 2006 – June 2007
	14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

This research report is intended to examine the geometric standards, guidelines, and practices used nationally and by other states to develop recommendations on roundabout design guidance for California. This research serves as a guidance tool in support of Caltrans' policy and standards within the Highway Design Manual and other statewide documents. Recommendations made from this research will guide Caltrans and other agencies in California in designing and operating roundabouts.

Several major areas were examined through this project, including assessing the operational performance of California roundabouts and developing calibrated capacity models consistent with recent national research (NCHRP 3-65); developing a calibrated intersection sight distance model; examining pedestrian and bicycle behavior at existing California roundabouts and comparing their performance to national observations; and developing a range of recommendations on geometric design parameters, including vehicle speeds, design vehicle, inscribed circle diameter, and issues related to roundabouts with more than four legs, roundabouts at freeway interchange terminals, and roundabouts in high-speed environments. The research resulted in a number of recommendations regarding the fundamental principles behind these elements, illustrated by tables and figures.

17. Key Words Roundabouts, Geometric Design, Operations, Pedestrians, Bicycles	18. Distribution Statement No restrictions.

19. Security Classify. (of this report) (None)	20. Security Classify. (of this page) (None)	21. No. of pages 81	22. Price

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ACKNOWLEDGEMENTS

This report is prepared in cooperation with the State of California Department of Transportation. The authors appreciated the review and comments provided by Caltrans staff members, including JD Bamfield, Kevin Hanley, Roya Hassas, Kevin Herritt, Rebecca Mowry, Maggie O'Mara, and Fred Yazdan, as well as Jeff Holm of FHWA.

The report is the result of a collaborative effort among three organizations. The University of Nevada Reno served as principal investigator and led the operational analysis components of this project. California State University, Chico, led the pedestrian and bicycle components. Kittelson & Associates, Inc., led the design components and assembled and edited the final report.

The authors would also like to acknowledge Eric Waltman of Kittelson & Associates, Inc., who contributed to the early stages of the design components of this report. In addition, the authors acknowledge the contributions of the members of and advisors to the Roundabout Task Force of the National Committee on Uniform Traffic Control Devices, through which the figures for the upcoming Manual on Uniform Traffic Control Devices were developed.

EXECUTIVE SUMMARY

Roundabouts have emerged as an increasingly popular tool to improve safety and operational efficiency at intersections throughout the United States, including California. Several research efforts have been underway to enhance U.S. practitioners' limited knowledge of and experience with designing and operating modern roundabouts, including FHWA's *Roundabouts: An Informational Guide* (FHWA Guide), and a number of subsequent state supplements. Such supplemental guidelines sometimes deviate from the guidance published in the FHWA Guide, which has created some concern about the best practice to recommend in California. This research project examined literature and relevant field data from roundabouts in California and elsewhere to specifically address the issues related to roundabout design and operation in California.

Several major areas were examined through this project:

- *Operational performance of California roundabouts*. The research team collected and analyzed operational performance data at nine existing California roundabouts to determine the gap acceptance behavior of California drivers. The resulting measurements, critical headway and follow-up headway, can be used to calibrate the capacity models developed by the recent national research project, NCHRP 3-65, as published in NCHRP Report 572, *Roundabouts in the United States*, and to calibrate the intersection sight distance model given in the FHWA Roundabout Guide.

- *Pedestrian and bicycle behavior*. The behavior of pedestrians and bicyclists at roundabouts was examined in a number of ways. First, pedestrian and bicyclist demand data was collected at intersections that are anticipated for conversion to roundabouts to facilitate a future study on the effects roundabouts have on pedestrian and bicyclist use. Second, the behaviors of pedestrians and bicyclists were examined at existing roundabouts in California using a methodology similar to that used on a national scale for NCHRP 3-65. Third, crash reports involving pedestrians and bicyclists at roundabouts were examined to identify any patterns that may be corrected through design.

- *Geometric design*. A variety of geometric design elements of interest to Caltrans were examined through this research, including vehicle speeds, design vehicle, inscribed circle diameter, and issues related to roundabouts with more than four legs, roundabouts at freeway interchange terminals, and roundabouts in high-speed environments. The research resulted in a number of recommendations regarding the fundamental principles behind these elements. These are illustrated by tables and figures.

Key specific findings from the research include the following:

- Attention to the overall layout of a roundabout is often more critical than the dimensions of individual components. In effect, roundabout design is performance-based; that is, success is measured from its output (operational and safety

performance, accommodation of design vehicle, pedestrian and bicycle usability, etc.) rather than its input (individual design dimensions).

- The following California-specific values for critical headway and follow-up headway should be used to calibrate capacity models to determine appropriate lane numbers and arrangements:
  - Single-lane roundabouts: critical headway = 4.8 s, follow-up headway = 2.5 s.
  - Multilane roundabouts, left lane: critical headway = 4.7 s, follow-up headway = 2.2 s.
  - Multilane roundabouts, right lane: critical headway = 4.4 s, follow-up headway = 2.2 s.
- Using the above calibrated values, the following capacity models can be used in a manner consistent with the recommendations from NCHRP 572, with c equal to capacity (passenger car equivalents per hour) and v_c equal to the conflicting flow rate (passenger car equivalents per hour):
  - Single-lane: $c = 1440 \cdot \exp(-0.0010 \cdot v_c)$
  - Multilane right lane: $c = 1640 \cdot \exp(-0.0009 \cdot v_c)$
  - Multilane left lane: $c = 1640 \cdot \exp(-0.0010 \cdot v_c)$
- The current methodology presented in the FHWA Guide for estimating vehicular speeds throughout the roundabout should be modified to account for acceleration and deceleration effects.
- While speed prediction for the various movements through a roundabout is reasonably accurate, the data show a trend between increased speeds and increased crash experience. However, this trend is not necessarily one that is statistically conclusive. Many sites in the NCHRP 3-65 database experienced few to zero crashes, and the site-to-site variation for the sites with nonzero crash experience is often significant.
- The NCHRP 3-65 data generally support the use of a 25 mph threshold for an entry speed adjusted for the effects of deceleration. However, the resulting crash experience can vary significantly among sites.
- Speed differentials of more than 10 mph between adjusted entry speeds (accounting for deceleration) and left-turn circulating speeds appear to correspond to an increase in entry-circulating crashes. Therefore, the FHWA Guide’s recommendation for a maximum speed differential of 12 mph appears to be supported if one adjusts entry speeds for deceleration effects.

- The report has suggested the appropriate design vehicles and side-by-side accommodation through single-lane and multilane roundabouts for various types of roadways.

- Care must be taken with the design of roundabouts to minimize exit-circulating conflicts through the appropriate spacing of entries and following exits. Examples have been provided.

- Care must be taken with the design of roundabouts to ensure appropriate visibility angles to the left. This need occurs most commonly in roundabouts with consecutive entries, such as at freeway interchange terminals. Examples have been provided.

- Typical ranges of inscribed circle diameter have been provided; however, inscribed circle diameter is a product of other factors and not a critical input parameter by itself.

- For intersection sight distance calculations, a California-specific critical headway of 5.9 seconds is recommended instead of the 6.5 seconds presented in the FHWA Guide. This methodology should be considered interim until a study on roundabout intersection sight distance is completed.

- The effect of roundabouts on pedestrian and bicyclist demand remains an open question. Data collected from sites anticipated to be converted to roundabouts will support a future research effort to address this question.

- Current U.S. design methods to accommodate pedestrians appear to be appropriate, although further research is needed to develop appropriate treatments to accommodate pedestrians with vision disabilities. The uncontrolled crosswalk treatments appear to operate well for the majority of users (pedestrians and conflicting vehicles). The use of a setback of one to two vehicles from the roundabout appears to be effective. Stopping sight distance needs to be provided so that motorists have the proper time to react after observing a pedestrian using the roundabout crosswalk; the same sight distance requirement helps pedestrian determine the appropriate time to enter the crosswalk. The pedestrian crossing treatments and methodology for selecting treatments as suggested in TCRP Report 112/NCHRP Report 562 should be considered.

- For pedestrians with visual impairments, recent and ongoing research suggests that a simple, uncontrolled crosswalk may be insufficient to provide access at some roundabouts, particularly at multilane roundabouts. The Access Board has made the draft recommendation that all pedestrian crossings that span two or more entry or exit lanes be provided with some form of signalization. Research on this treatment and other less restrictive treatments is being conducted as part of NCHRP 3-78 and other studies. The authors recommend caution in establishing a California-wide policy until that research is complete.

- Current U.S. design methods to accommodate bicyclists of a range of abilities—allowing cyclists to circulate as vehicles or as pedestrians—appear to be appropriate.

This includes the provision of a wider sidewalk or shared path around the perimeter of the roundabout and ramps to connect the sidewalk or path to the bicycle facilities on each leg as appropriate. The current U.S. recommendations to not stripe bike lanes within a roundabout help to address the exit-circulating conflict found in European experience. At multilane roundabouts, the evidence from this study suggests that it may be appropriate to use yield signs on a shared path around the roundabout, as many cyclists are riding rather than walking their bicycles.

1. INTRODUCTION

1.1. Background

Roundabouts have been used worldwide as an efficient intersection control type to improve safety and operational efficiency. However, application of modern roundabouts in the U.S. is more recent, with the first modern roundabout constructed in 1990 and the majority opened within the past few years. As evidence emerges for its effectiveness in reducing the number and severity of accidents, it is anticipated that more and more roundabouts will be built on U.S. streets and highways, including those in the State of California.

Several research efforts have been underway to enhance U.S. practitioners' limited knowledge of and experience with designing and operating modern roundabouts. In 2000, the FHWA developed a guide titled, *Roundabouts: An Informational Guide* (*1*), to pull together both national and international guidance into a single document. Since that time, some states, such as Kansas (*2*), have developed supplemental guidelines to further address their design needs specific to their state or to reflect more current thinking within the profession. Such supplemental guidelines sometimes deviate from the guidance published in the FHWA guide, which resulted in inconsistencies among state practices while designing and operating a roundabout. An effort is underway (initiated in February 2007, with completion expected in 2009) to update and produce a Second Edition of the FHWA guide as part of NCHRP Project 3-65A.

Compared to some other states in the U.S., California has implemented a limited number of roundabouts, with the majority being urban single-lane roundabouts located off the State highway system. Because of evidence supporting the significant safety benefits of roundabouts, it is anticipated that a growing number of roundabouts will be built on California's highways over the coming years. As a result, Caltrans has developed preliminary guidance for roundabouts in Design Information Bulletin (DIB) Number 80-01 (*3*) and is in the process of updating its Highway Design Manual (HDM) (*4*) to reflect state-of-the-art practices. This research project is designed to specifically address the issues related to roundabout design and operation for Caltrans. It is critical to examine different state practices before developing guidelines to suit California's local traffic and environment conditions.

1.2. Scope and Objectives

This research project's major outcome is a comprehensive document that addresses the key roundabout design elements based on current practices and research. This document is anticipated to serve as a primary resource for updating the HDM and DIB 80. These documents will help ensure that future roundabouts in California follow best practices and achieve maximum benefits.

This report has the following major components:

- An assessment of vehicle operational performance by drivers at California roundabouts.

- An assessment of pedestrian and bicycle behavior at California roundabouts and other roundabouts around the United States.

- An assessment of key geometric design parameters of interest to Caltrans.

- Conclusions and recommendations.

2. VEHICLE OPERATIONS ASSESSMENT

Roundabouts have been used worldwide as an efficient intersection control type to improve safety and operational efficiency. Two major operational parameters are often used to perform the operational analysis and geometric design of roundabouts: critical headway and follow-up headway. These are generally defined in the *Highway Capacity Manual* (HCM) as follows (*5*):

- *Critical headway*. This is the minimum time between successive major-stream vehicles in which a minor-street vehicle can make a maneuver. Critical headway has been historically referred to as critical gap (including the HCM 2000).

- *Follow-up headway*. The time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same gap under a condition of continuous queuing.

These two parameters reflect driver's behavior at roundabouts and are the main factors used to estimate capacity at roundabouts through analytical techniques. Critical headway is also one of the major parameters used to calculate intersection sight distance in roundabout design. Adequate intersection sight distance assists in providing safe operations, but excessive intersection sight distance at roundabouts may result in high vehicle entry speeds that could lead to higher crash frequencies (*1*, *6*).

This chapter discusses how to measure these two operational parameters for use in the operational analysis and design of roundabouts in California. The chapter first discusses the current values for critical headway and follow-up headway at roundabouts (found in the literature), then discusses the measurement and analysis of those parameters on roundabouts in California.

2.1. Literature Review

This section presents an overview of the use of operational parameters in capacity estimation and design, followed by a discussion of the current use of those parameters for roundabout analysis and design. Finally, the section discusses recent national research on these parameters.

2.1.1. Background

Generally, there are two basic methods to evaluate the capacity for each roundabout category: analytical and regression. Recent national research in the U.S. has determined that a simple empirical regression model best fits the latest U.S. operational performance data (*7*). The research also found that an equivalent gap-acceptance model using critical headway and follow-up headway can be used to develop capacity estimates that can be calibrated to local conditions.

The other major use of critical headway is in design, specifically to calculate intersection sight distance. In general, the critical headway at roundabouts represents the minimum time interval in the circulating flow during which a vehicle can safely enter a roundabout. Specifically, according to FHWA Guide (*1*), critical headway for sight distance purposes is the amount of time required for a vehicle to enter a roundabout while requiring the conflicting stream vehicles to slow their initial speed by no more than 70 percent. A driver rejects any headway that is less than his/her personal critical headway and accepts any headway that is equal to or greater than the critical headway. Longer headways in the circulating/conflicting traffic stream provide the entering vehicles with an opportunity for multiple entries. The number of such entries is determined by the follow-up headway. The follow-up headway is the minimum time interval between two successive vehicles in a queue entering the roundabout using the same gap (headway) in the conflicting/circulating traffic stream.

2.1.2. Critical Headway and Follow-Up Headway Values in Use

The FHWA Guide identifies the critical gap value as 6.5 seconds based on the critical gap required for passenger cars, which are assumed to be the most critical design vehicle for intersection sight distance. This assumption holds true for single-unit and combination truck speeds that are at least 10 km/h (6 mph) and 15 to 20 km/h (9 to 12 mph) slower than passenger cars, respectively.

Most of the state DOTs who have developed guidelines for roundabout design and operations adopt the critical headway recommended by the FHWA Guide. However, some variations exist. The current Caltrans Design Information Bulletin (DIB) 80-01 (*3*) states that designers shall use the critical headway value of 6.5 seconds recommended by the FHWA Guide as an initial design parameter for the purpose of determining intersection sight distance. If the design speed or speed consistency cannot be obtained, DIB 80-01 states that the geometries should be modified to meet the target design speed through the circulatory roadway. If the target speed cannot be met in this fashion, the value for the critical headway may be reduced until the target design speed is achieved, or until the minimum critical headway value of 5.0 second is reached.

In their supplement to the FHWA Guide, the Kansas Department of Transportation adopts the FHWA Guide's 6.5-second critical headway, but notes that the critical headway may be reduced to 4.6 seconds in locations where sight distance may be constrained by adjacent topography features or buildings (*2*). This value is based on the more conservative critical headway given for single-lane roundabouts in the *Highway Capacity Manual 2000* (*5*). The state of Arizona has adopted similar discussions (*8*).

The Wisconsin Department of Transportation's roundabout guidance in their *Facilities Design Manual* (*9*) recommends a critical headway of 4.5 seconds. The source for this lower value is undocumented.

Based on a recent study (*10*), the Utah Department of Transportation adopted the critical headway values from SIDRA (a computer software program for roundabouts developed in Australia), where the minimum critical headway is 2.0 seconds and the maximum critical headway is 8.0 seconds, and the two boundary critical headway values from the HCM (4.1 seconds and 4.6 seconds) (*5*). These critical headway values are mainly used for the purpose of conducting operational analyses.

In summary, most state DOTs who have developed roundabout guidelines have adopted the critical headway recommended by the FHWA Guide, except Wisconsin and Utah where significant deviations are noticed. Some states such as California and Kansas recognize that critical headway should be adjusted to meet the ultimate design objectives, such as the target design speed. The recently completed NCHRP 3-65 report includes a new set of critical headway and follow-up headway values based on data from more than 500 hours of video at various roundabout locations throughout the U.S. However, the data did not include any sites in California. As a result, it is unclear whether the critical headway and follow-up headway from NCHRP 3-65 may or may not be representative of California's conditions. As one of the major research tasks, data need to be collected at roundabout sites in California and the critical headway and follow-up headway need to be measured at these sites to better reflect California's conditions.

2.1.3. Recent National Research

Critical headway is affected by local conditions such as geometric layout, driver behavior, vehicle characteristics, and traffic conditions (*11*). The recently completed NCHRP Report 572 (*7*), which documents the results of NCHRP 3-65, highly recommends that practitioners calibrate the critical headway and follow-up headway based on local conditions in order to provide accurate capacity estimates. This report provides the critical headway results measured at 14 sites using the Maximum Likelihood Technique (*12*). The study reveals that the critical headway at single-lane roundabouts varies between 4.2 and 5.9 seconds, and the critical headway at multilane roundabouts varies between 3.4 and 4.9 seconds in the right-lane, and 4.2 and 5.5 seconds in the left-lane. For purposes of calculating intersection sight distance, NCHRP Report 572 identifies a critical headway value of 6.2 seconds for determining intersection sight distance, derived from the mean critical headway (5.1 seconds) plus one standard deviation (1.1 seconds).

NCHRP Report 572 also includes a new set of follow-up headway values based on data collected from six states: Washington, Maryland, Maine, Michigan, Oregon, and Vermont. The report recommends follow-up headways of 3.2 seconds at single-lane roundabouts, 3.4 seconds for the left lane at multilane roundabouts, and 3.1 seconds for the right lane at multilane roundabouts.

2.2. Data Collection and Analysis

This section presents the details of data collection, data extraction, and critical and follow-up headway measurement results and analyses. First, field data collection efforts (e.g., video taping) are described, followed by discussions on the data extraction process from the videos. Based on the time events extracted from the videos, measurements of the critical headway and the follow-up headway are conducted. The results are then compared with those from other studies. The results of an analysis of the factors affecting critical headway and follow-up headway are also provided.

2.2.1. Field Data Collection

Roundabout operations were videotaped in the field, along with geometry, vehicle speed, and any abnormal site conditions. The data from the recorded videos were extracted in the lab, and the other field-recorded data was used to analyze the factors that may affect critical headway and follow-up headway.

In June 2006, field data was collected at ten roundabout sites located in six California cities: Truckee, Modesto, Calabasas, Santa Barbara, Long Beach and Davis. Typically, the videos were recorded during the weekday peak periods when high traffic volumes could be observed. To increase the sample size, two additional hours of video were taken at the sites in Truckee and Davis. Only the approach with the highest traffic volume was video-taped, using a single camera mounted on a tripod. Table 1 contains a summary of the ten roundabout sites.

Of the ten sites, seven were single-lane roundabouts and three were multilane. Because the Bowen Avenue/Fremont Avenue roundabout in Modesto had very low traffic volumes and the number of data samples would not be sufficient for critical headway and follow-up headway measurements, an additional two hours of data was collected at the James Street/G Street roundabout, also in Modesto, during the midday peak hours.

In the field, circulating vehicle speeds were recorded using a radar gun. The vehicle speeds were recorded to analyze whether vehicle speed affects driver's critical headway and follow-up headway. Figure 1 shows the zone where the speeds were measured. In this case, the study approach is the eastbound approach, i.e., the eastbound approach was video taped and studied for critical headway and follow-up headway.

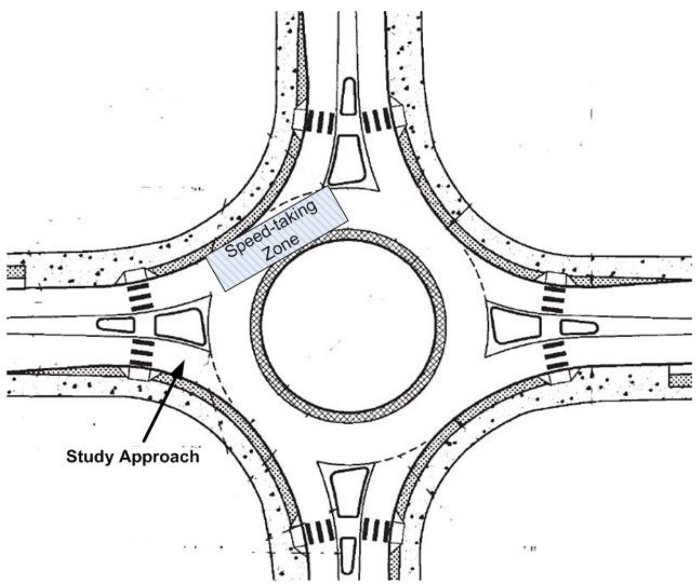


Figure 1. Circulating Speed Measurement Zone

Field observations revealed that most single-lane roundabouts were located in residential areas and were mainly used as traffic calming devices. Therefore, these traffic volumes were generally low. Much higher traffic volumes were observed at the three multilane roundabouts.

Pedestrian and bicycle use at roundabouts was also low. Moderate pedestrian and bicycle volumes were observed only at two sites: James Street/G Street in Modesto, and Anderson Road/Alvarado Avenue in Davis. The pedestrian and bicycle activity at these two sites is further documented in Chapter 3 of this report.

Table 1. Ten Roundabout Sites Observed in California

City	Site ID	Site Name	Date and Time Period of Data Collection (all dates 2006)	Duration of Extracted Video	Number of Circulating Lanes
Calabasas	CA01	#14: Parkway Calabasas/Camino Portal	Thursday, June 15, 7:00 a.m. to 9:00 a.m.	2 hours	1
Davis	DA01	#6: Anderson Rd./Alvarado Ave	Sunday, June 18, 11:30 a.m. to 1:30 p.m.	2 hours	1
			Tuesday, June 20, 4:00 p.m. to 6:00 p.m.	2 hours	1
Long Beach	LB01	#10: Los Alamitos Circle	Friday, June 16, 4:00 p.m. to 6:00 p.m.	2 hours	3
Modesto	MO01	#11: Bowen Ave./Fremont Ave.	—	No Traffic	1
	MO02	#12: Bowen Ave./Phelps Ave.	Monday, June 12, 4:00 p.m. to 6:00 p.m.	2 hours	1
	MO03	#15: La Loma/James St./G St.	Tuesday, June 13, 7:00 a.m. to 9:00 a.m.	2 hours	1
			Tuesday, June 13, 11:30 a.m. to 1:30 p.m.	2 hours	1
Santa Barbara	SB01	#20: Milpas St./US 101 NB Ramps	Thursday, June 15, 4:00 p.m. to 6:00 p.m.	2 hours	2
	SB02	#19: Alameda Padre Serra/Salinas	Friday, June 16, 7:00 a.m. to 9:00 a.m.	2 hours	1
Truckee	TR01-W	#21: Donner Pass Rd.	Saturday, May 20, 11:30 a.m. to 1:30 p.m.	2 hours	1
			Tuesday, May 30, 11:30 a.m. to 1:30 p.m.	2 hours	1
	TR02-S	#22: I-80 EB Ramps/Hwy 89	Saturday, May 20, 4:00 p.m. to 6:00 p.m.	2 hours	2
			Tuesday, May 30, 4:00 p.m. to 6:00 p.m.	2 hours	2
Total				26 hours	

Two field observations that may reflect inadequate roundabout designs are worth mentioning. The first is inadequate entry deflection observed at the Bowen Avenue/Phelps Avenue roundabout in Modesto, a three-leg, single-lane roundabout. As shown in Figure 2, in the westbound direction there was a lack of entry deflection to reduce vehicle speed. This appears to have contributed to some collisions between vehicles and the curb, causing some damage to the curb.

Figure 2. Inadequate Entry Deflection and Curb Damage at the Bowen Avenue/Phelps Avenue Roundabout in Modesto

The second is vehicles running over the apron when traveling at higher speeds at the Anderson Road/Alvarado Avenue roundabout in Davis. According to the FHWA Guide, the truck apron is a mountable portion of the central island adjacent to the circulatory roadway. The purpose of a truck apron is to accommodate the wheel path of large vehicles at smaller roundabouts; passenger vehicles are discouraged from using it. The FHWA Guide recommends that the outer edge of an apron should be raised a minimum of 30 mm (1.2 inch) above the circulatory roadway surface. However, this roundabout in Davis does not have a raised apron; therefore, a number of vehicles were observed running over the apron and traveling through the roundabout at higher speeds. As shown in Figure 3, the apron is in disrepair, which may make it difficult for the drivers to see at night.

Figure 3. Inadequate Apron Design and Use at
Anderson Road/Alvarado Avenue Roundabout in Davis

2.2.2. Data Extraction

Necessary time events were tracked from the data to derive the various headway events needed to calculate the critical and follow-up headways. Three time events involving an entering vehicle were recorded: the time when an entering vehicle stopped at the entrance line, the passage times of circulatory vehicles that directly conflicted with the entering vehicle, and the time at which the stopped vehicle passed the entrance line. The passage times of circulating vehicles defined the start and end of major stream headways that were either accepted or rejected by the entering vehicles.

The procedure of extracting video data and measuring critical headway and follow-up headway included the following steps:

- *Step 1*. The time events (defined above) were recorded using *TDIP (Traffic Data Input Program)* computer software. TDIP was developed at the University of Idaho and has been used in research projects (NCHRP 3-46, NCHRP 3-65) to extract data events from videos.

- *Step 2*. The accepted headways, the maximum rejected headways, and the follow-up headways were extracted using a Microsoft Excel macro program developed by the research team. The accepted headways and the maximum rejected headways were used to estimate the critical headway using the Maximum Likelihood Methodology (*12*). In this study, the passage times of circulating vehicles were recorded when the front bumpers passed the conflicting point. The recorded passage times were used to calculate the headways between successive circulating vehicles. The follow-up headways were directly obtained from the time events using the macro program. The raw time event data was validated, and any unrealistic time events were removed. For example, some unusual driver behavior was observed such as a stalled vehicle, which resulted in very large rejected headways. Such data was removed to minimize the errors from the headway measurements. In this study, a headway of 8 seconds was considered as the upper threshold for driver's acceptable headways. Therefore, any accepted headways greater than 8 seconds were reduced to 8 seconds.

- *Step 3*. Based on the results of Step 2, the Maximum Likelihood Methodology was used to derive driver's critical headway. Two headway-acceptance cases were identified. Case 1 was when a driver rejected at least one headway before entering the roundabout (the driver waited for at least one conflicting vehicle to pass), and Case 2 was when a driver accepted the first headway (referred to as a lag) without rejecting any headway (the driver entered before a conflicting vehicle passed). Table 2 and Table 3 illustrate the number of headways observed in the two headway-acceptance cases at single-lane and multilane sites, respectively. These headway data only included vehicles that stopped at the roundabout entry. As can be seen, the majority of vehicles were classified as Case 1.

Table 2. Accepted/Rejected Headway Cases at Single-Lane Sites

Site	Total No. of Headways	Case 1*	% of Total	Case 2**	% of Total
CA01-S	237	177	75%	60	25%
DA01-E	98	77	79%	21	21%
MO02-S	40	34	85%	6	15%
MO03-S	117	91	78%	26	22%
MO03-S	217	137	63%	80	37%
SB02-NW	321	237	74%	84	26%
TR01-W	136	113	83%	23	17%
Total	1166	866	77%	300	23%

* Case 1: Driver rejected one or more headways
** Case 2: Driver accepted the first available headway

Table 3. Accepted/Rejected Headway Cases at Multilane Sites

Site	Lane	Total No. of Headways	Case 1*	% of Total	Case 2**	% of Total
LB01-W	left	374	241	64%	133	36%
LB01-W	right	263	184	70%	79	30%
SB01-S	left	456	324	71%	132	29%
SB01-S	right	539	408	76%	131	24%
TR02-S	left	160	126	79%	34	21%
TR02-S	right	214	153	71%	61	29%
Total		2006	1436	72%	570	28%

* Case 1: Driver rejected one or more headways
** Case 2: Driver accepted the first available headway

2.3. Critical Headway Measurements

As discussed previously, the Maximum Likelihood Methodology was used to estimate the critical headway. It should be noted that critical headway cannot be obtained directly from the recorded time events. However, the Maximum Likelihood Methodology estimates the average critical headway of all the drivers based on the fact that a driver's critical headway is between two observeable values: the driver's largest rejected headway, and the driver's accepted headway.

2.3.1. Single-Lane Roundabouts

Table 4 provides a summary of the results of the critical headways measured at the single-lane sites. It can be seen that the critical headway varied between 4.5 and 5.3 seconds, with a mean value of 4.8 seconds. These critical headway values are in a range similar to those reported by NCHRP 3-65; a detailed comparison is provided later in this paper.

Table 4. Critical Headway Results at Single-Lane Roundabout Sites

Site	**Critical Headway**	
	Mean (seconds)	**Standard Deviation (seconds)**
CA01-S	4.7	1.1
DA01-E	4.7	1.0
MO02-S	5.3	1.0
MO03-S, A.M.	4.8	1.3
MO03-S, Midday	5.0	1.1
TR01-W	5.0	1.1
SB02-NW	4.5	0.9
Average	4.8	1.1

2.3.2. Multilane Roundabouts

Headway events are defined differently for multilane roundabouts. For a two-lane entry, the vehicles in the right entry lane are assumed to only yield to the conflicting vehicles in the right-most circulatory lane, but the vehicles in the left entry lane are assumed to yield to the vehicles in all the circulatory lanes (*13*). Therefore, the headway events are extracted only based on pertinent conflicting vehicles.

Table 5 provides a summary of the critical headway results for the three multilane sites. As can be seen, the critical headway for the left lane varied between 4.4 and 5.1 seconds with a mean value of 4.7 seconds, and the critical headway for the right lane varied between 4.0 and 4.8 seconds with a mean value of 4.4 seconds. The critical headway was slightly higher in the left lane than that in the right lane, which is consistent with NCHRP 3-65.

Table 5. Critical Headways at Multilane Roundabouts

Site		**Critical Headway**	
		Mean (seconds)	**Standard Deviation (seconds)**
LB01-W	Left lane	4.4	0.9
	Right lane	4.0	1.1
SB01-NW	Left lane	4.8	1.1
	Right lane	4.5	1.0
TR02-S	Left lane	5.1	1.1
	Right lane	4.8	0.9
Average	Left lane	4.7	1.0
	Right lane	4.4	1.0

2.4. Follow-up Headway Measurements

Unlike critical headway estimation, follow-up headways were obtained directly from the recorded time events. By definition, follow-up headway is the minimum headway between two entering vehicles accepting the same gap, which is calculated by the difference between the passage times of two entering vehicles that accept the same mainstream headway under a queued condition. Once the individual follow-up headway is obtained, the average and the standard deviation can be calculated.

2.4.1. Single-Lane Roundabouts

Table 6 presents follow-up headways recorded at the single-lane roundabout sites, where the mean value, the standard deviation, and the sample size are listed for each site. It can be seen, the follow-up headway ranged between 2.3 and 2.8 seconds. The average for all the sites was 2.5 seconds. The largest follow-up headway, 2.8 seconds, was observed at Site DA01 in Davis, which is a compact roundabout in a residential area. The smallest follow-up headway, 2.3 seconds, was observed at Site MO03 in Modesto, which is located in the downtown area.

The average follow-up headway from this study was smaller than that of NCHRP 3-65.

Table 6. Follow-up Headway Results at Single-Lane Roundabouts

Site	Mean of Follow-up Headways seconds)	Standard Deviation of Follow-up Headways (seconds)	Sample Size
CA01-S	2.4	0.6	55
DA01-E	2.8	0.7	15
MO02-S	2.4	0.3	5
MO03-S,AM	2.3	0.7	14
MO03-S,Midday	2.6	1.0	58
SB02-NW	2.3	0.7	63
TR01-W	2.5	0.8	20
Average	2.5	0.7	Total = 230

2.4.2. Multilane Roundabouts

Table 7 shows the average follow-up headway at the three multilane roundabouts. The follow-up headways in the left-lane varied between 1.8 and 2.7 seconds, and the follow-up headways in the right-lane ranged between 2.1 and 2.3 seconds. The mean follow-up headways for both lanes were the same, both of which were 2.2 seconds. These values are smaller than that reported in NCHRP 3-65.

It should be noted that the results are based on a limited number of sites (three sites); however, the follow-up headway values from the three sites are rather consistent.

Table 7. Follow-up Headway at Multilane Roundabouts

Site		Average Follow-up Headway (seconds)	SD of Follow-up Headway (seconds)	Sample Size
LB01-W, left lane		2.2	0.6	125
LB01-W, right lane		2.1	0.7	75
TR02-S, left lane		1.8	0.7	27
TR03-S, right lane		2.1	0.9	59
SB01-NW, left lane		2.7	0.9	109
SB01-NW, right lane		2.3	1.0	117
Average	left lane	2.2	0.7	Total = 261
	right lane	2.2	0.8	Total = 251

2.5. Comparison with Other Studies

Comparisons were made between the results of this study (the California data) and the data from other sources including NCHRP 3-65, which reported data from sites in the U.S., Germany, and France, and data from the HCM. Table 8 summarizes the critical headway and follow-up headway values from these different sources.

Table 8. Critical Headway and Follow-up Headway
from Different Sources

Model		Critical Headway (seconds)		Follow-up Headway (seconds)	
		One lane	Two lane	One lane	Two lane
HCM		4.1 to 4.6	N/A	2.6 to 3.1	N/A
Germany[1]		4.4	4.4	3.2	3.2
France[1]		N/A	N/A	2.1	2.1
NCHRP 3-65	Left lane	4.2 to 5.9 (5.1)[2]	4.2 - 5.5 (4.5)	2.6 - 4.3 (3.2)	3.1 - 4.7 (3.4)
	Right lane		3.4 - 4.9 (4.2)		2.7 - 4.4 (3.1)
California	Left lane	4.5 - 5.3 (4.8)	4.4 - 5.1 (4.7)	2.3 - 2.8 (2.5)	1.8 - 2.7 (2.2)
	Right lane		4.0 - 4.8 (4.4)		2.1 -2.3 (2.2)

Notes: 1. Results obtained from NCHRP Report 572 (*7*)
2. Numbers in ( ) indicate the average value

Based on the results shown in Table 8, the following observations were made. The statistical analyses will follow below:

- The critical headway based on California's sites was similar to the U.S. sites discussed in the NCHRP 3-65 study.

- The critical headways and follow-up headways used in the HCM and in Germany had similar values, but were generally smaller than those obtained from this California data and elsewhere.

- The follow-up headways from this research were very similar to that used in France; however, they were generally smaller than those reported in the NCHRP 3-65 report.

Statistical analyses were conducted to determine whether California drivers have critical headways and follow-up headways that are statistically different from those reported for other states in the U.S. in the NCHRP 3-65 study. Figure 4 shows the comparison and statistics of critical headways at the single-lane sites. There were 16 data points from the NCHRP 3-65 study, representing the critical headways from 16 different sites (ten from Washington, three from Maryland, two from Maine, and one from Oregon). The 95% confidence intervals were also plotted. Using confidence intervals for different populations is one of the means of conducting hypothesis tests in statistics. If the confidence intervals overlap each other, it means there is no significant statistical difference between the mean values of the two populations. As shown in Figure 4, the 95% confidence interval of the California sites is (4.64, 5.05) and the 95% confidence interval of other states is (4.81, 5.29). Because the 95% confidence intervals of two parameters overlap, this indicates that the two parameters are not statistically different at the 5% significance level. However, the conclusions drawn from statistical analysis must be carefully interpreted in practical applications. In this case, the statistical analysis indicates that there is no significant statistical difference between the critical headways of California and other states. Practically speaking, the mean critical headway values of California and other states seem to be nearly identical.

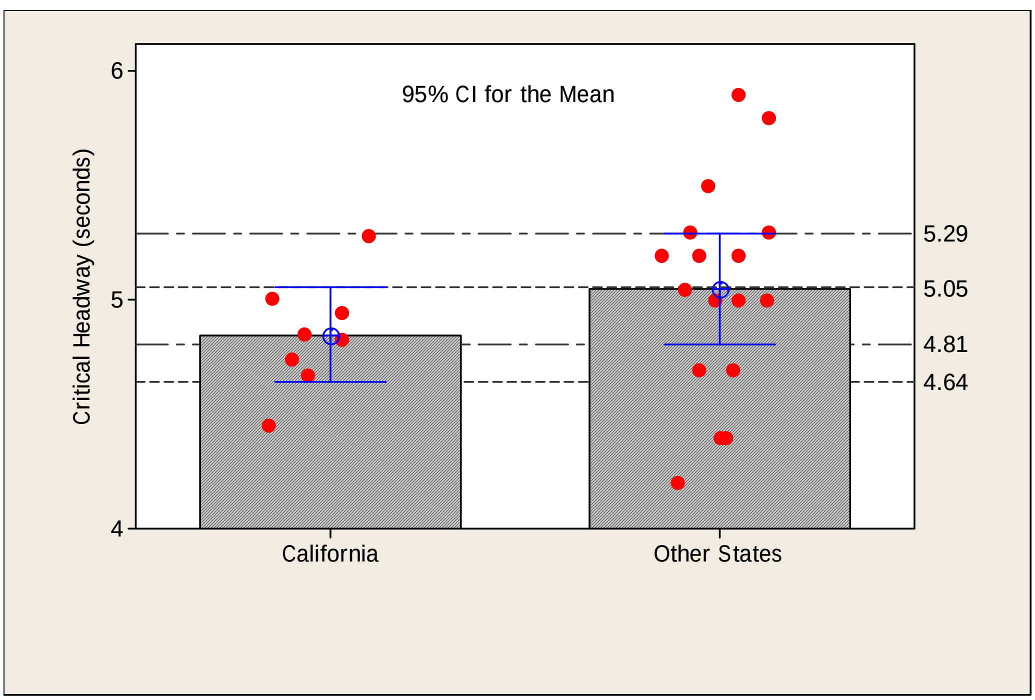


Figure 4. Comparison of Critical Headway, California and Other States: Single-Lane Sites

Figure 5 shows the comparisons of critical headways at the multilane sites, listed separately for the left turn and the right lane. There were seven data points from the NCHRP 3-65 report, representing the critical headways from seven different sites (three from Maryland, three from Vermont, and one from Washington). Although slightly different mean critical headway values were noticed, there was no significant statistical difference between the left lanes and the right lanes in California compared with other states, again indicated by the overlapping 95% confidence intervals. However, the number of multilane sites is very limited for both California and other states and does not support definitive conclusions. This is also shown by the wide range of the 95% confidence intervals, indicating that the estimate of the true mean is not precise. Further research on multilane roundabout sites is necessary.

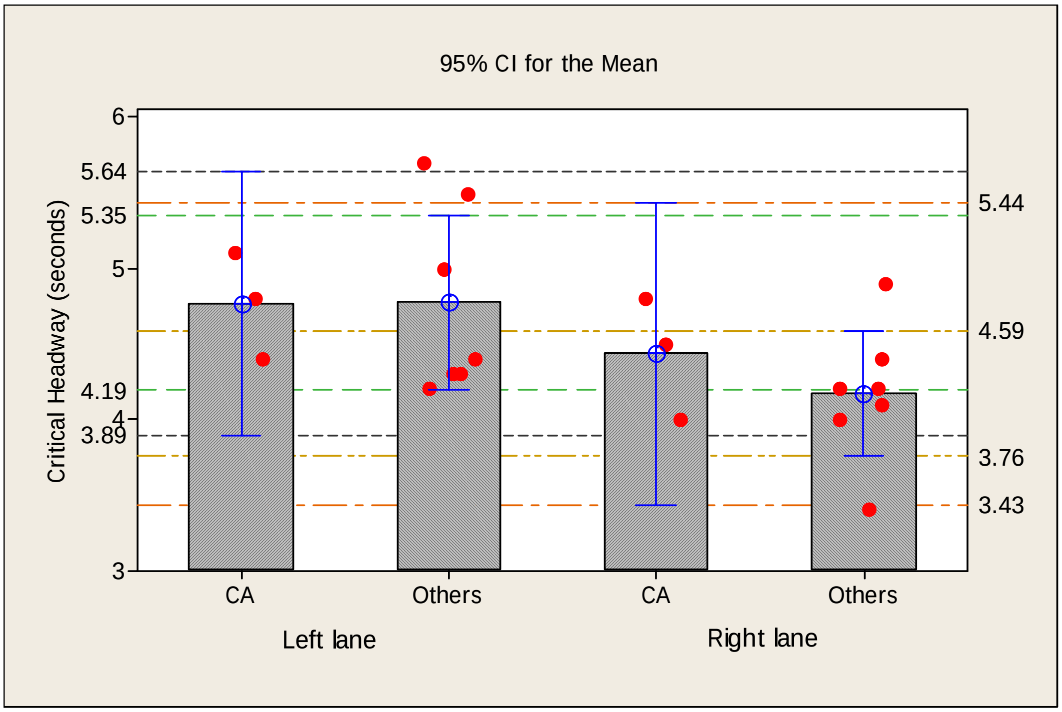


Figure 5. Comparison of Critical Headway, California and Other States: Multilane Sites

Figure 6 compares the follow-up headways at the single-lane sites. There were eighteen data points from the NCHRP 3-65 study, representing the average follow-up headways from eighteen different sites (eleven from Washington, three from Maryland, two from Maine, one from Michigan, and one from Oregon). As indicated by the 95% confidence intervals in the figure, California's follow-up headway was statistically significantly lower than that of other states. The mean follow-up headway in California was 2.4 seconds, whereas the mean follow-up headway in other states was 3.3 seconds.

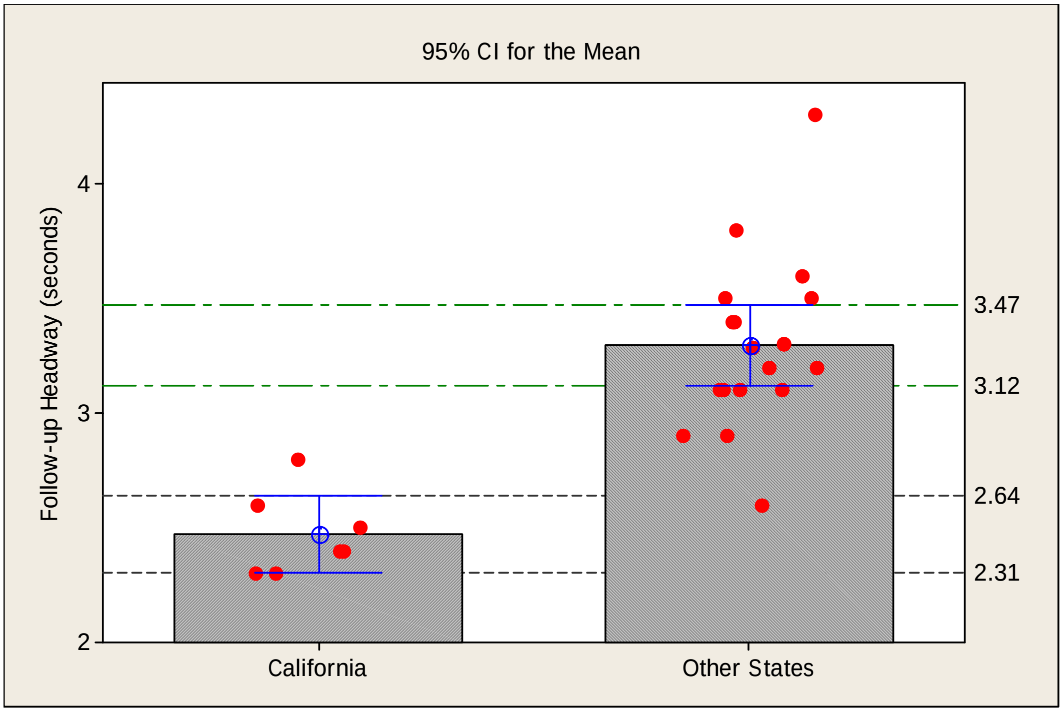


Figure 6. Comparison of Follow-up Headway between California and Other States: Single-lane Sites

Figure 7 compares the follow-up headways at the multilane sites, listed by the left lane and the right lane. There were seven data points from the NCHRP 3-65 study, representing the average follow-up headways from seven different sites (three from Maryland, three from Vermont, and one from Washington). As indicated by the 95% confidence intervals shown in the figure, California had a significantly lower follow-up headway than that of other states. Although the follow-up headway in the left lane did not show a statistically significant difference from other states, the smaller number of samples in California produced the high variance. From practical point of view, the difference is considered significant.

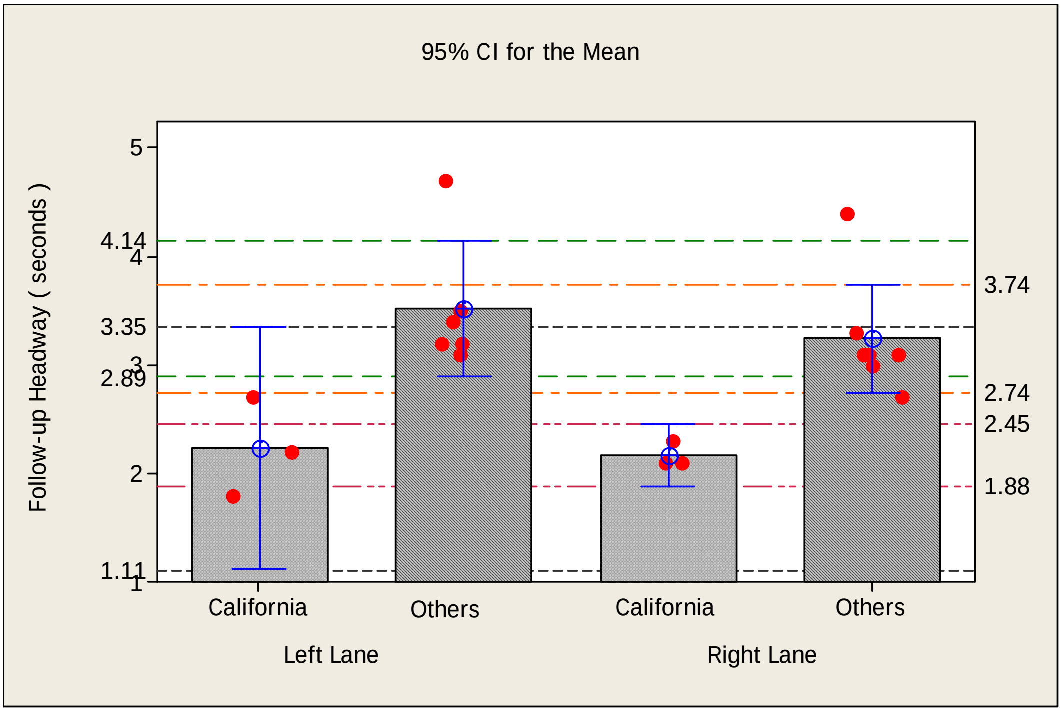


Figure 7. Comparison of Follow-up Headway between California and Other States: Multilane Sites

2.6. Analysis of Factors Affecting Critical Headway and Follow-up Headway

An investigation was conducted on the factors that may affect critical headway and follow-up headway. The factors investigated include the number of exiting vehicles in the circulatory traffic, the conflicting volume, and the speed of the circulating vehicles.

2.6.1. Impact of Exiting Vehicles on Critical Headway and Follow-up Headway

Similar to the major-street right-turn vehicles at two-way stop-controlled intersections, it was expected that exiting vehicles in the circulatory traffic at roundabouts might also influence the behavior of entering vehicles. Such an impact was clearly seen during field observations, especially at compact and small roundabouts. For example, at the MO03-S site in Modesto shown in Figure 8, the entering vehicles in the westbound La Loma Avenue always tended to stop when facing exiting vehicles. With a higher percentage of exiting vehicles, a larger critical headway was expected, especially with the tight geometric layout, high circulating speed, and limited intersection sight distance. However, this assumption is based only on the field observations. At this time, no data is available yet to support this assumption.

Figure 8. Impact of Exiting Vehicles at Modesto Roundabout MO03-S

2.6.2. Impact of Circulating Traffic on Critical Headway and Follow-up Headway

Previous studies indicate that the conflicting volume and vehicle speeds might affect the behavior of drivers in the minor traffic stream. For example, based on the data from Australia (*14*), the follow-up headway at single-lane roundabouts was related to both roundabout size (inscribed circle diameter) and circulating flow rate. Higher circulating flow rates resulted in much smaller follow-up headways. Where circulating flow rates are low, the follow-up headway varied between 2.27 to 2.99 seconds when the inscribed circle diameter was between 60 and 240 feet. The follow-up headway was as low as 1.7 seconds when the circulating flow approached 1,500 vehicles per hour (vph). At two-lane roundabouts with a circulating flow rate of 2,500 vph, the follow-up headway was as low as 1.3 seconds. NCHRP 3-65 reported moderate inverse correlation between critical headway and conflicting flow rate, suggesting that the critical headway tended to decrease with an increase in conflicting flow rate.

A simple correlation analysis was applied to the California data to investigate whether the conflicting flow and vehicle speeds have any impact on critical headway and follow-up headway. The correlation analysis provided two measures: linear correlation coefficient and P-value. The correlation coefficient is a measure of the linear relationship between two attributes or columns of data. The correlation value can range from –1 to +1 and is independent of the units of measurement. A value near 0 indicates poor correlation between attributes; a value near +1 or –1 indicates a high level of correlation. When two attributes have a positive correlation coefficient, an increase in the value of one attribute indicates a likely increase in the value of the second attribute. A negative coefficient indicates that one attribute tends to show an increase when the other one show a decrease. The P-value is used for hypothesis test of the correlation coefficient being zero. Table 9 presents the correlation analysis results.

Table 9. Results of Correlation Analysis

Parameter		Critical Headway	Follow-up Headway
Conflicting Flow	Pearson Correlation	–0.522	–0.037
	P-value	0.067	0.905
Circulating Speed	Pearson Correlation	–0.447	–0.684
	P-value	0.126	0.01

From Table 9, the critical headway and conflicting flow had moderate negative correlation (–0.522), with a P-value of 6.7%, which is slightly above the normally acceptable 5% significance level. This may be characterized as marginally significant statistically. The moderate negative correlation means that critical headway and conflicting flow had a weak inverse linear relationship, where the increase in conflicting flow might result in a decrease in the critical headway. This relationship is illustrated in Figure 9.

Table 9 also indicates that the correlation between follow-up headway and conflicting flow was weak (correlation coefficient of –0.037 and P-value of 0.905). This is indicated in Figure 9, where the follow-up headway was not sensitive to the conflicting flow.

The speed of the circulating traffic had a negative correlation (–0.447) with the critical headway, indicating the circulating speed did affect critical headway, but a linear correlation between the two parameters is weak (P-value of 0.126). As shown in Figure 10, an increase in speed may result in a decrease in critical headway.

The speed of the circulating vehicles had a negative correlation to follow-up headway (–0.684) and the linear correlation was strong (P-value of 0.01). As shown in Figure 10, the follow-up headway decreases as the conflicting speed increases.

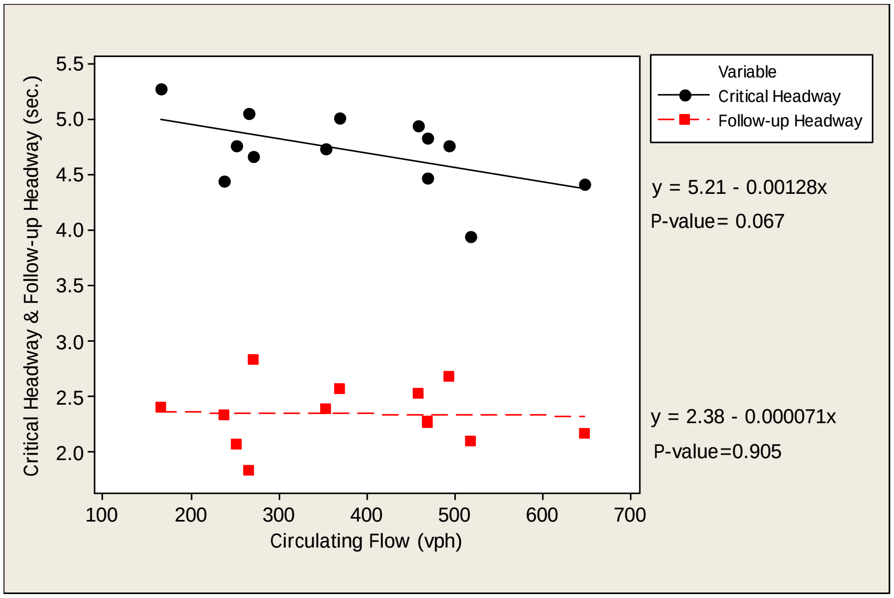


Figure 9. Critical Headway and Follow-up Headway as a Function of Circulating Flow

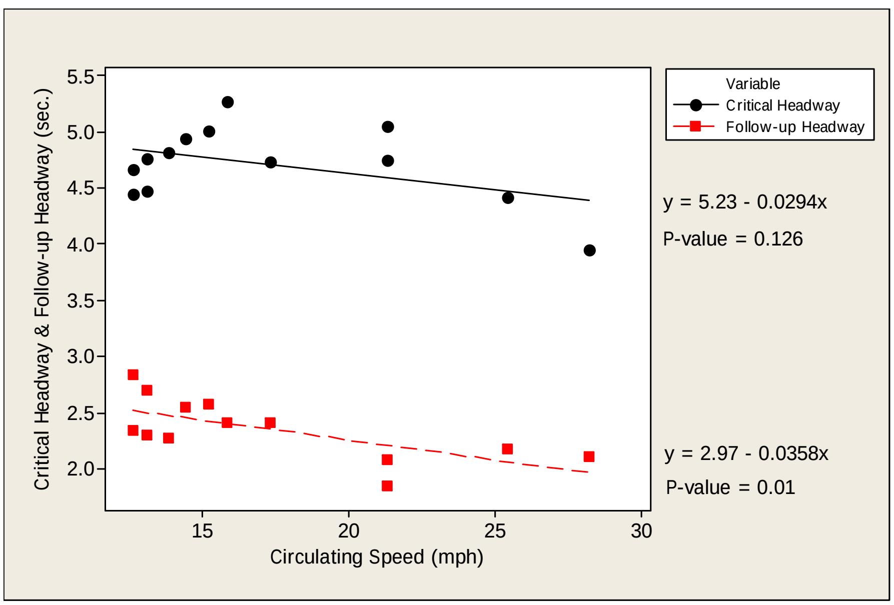


Figure 10. Critical Headway and Follow-up Headway as a Function of Circulating Speed

2.7. Summary and Conclusions

A summary of the major findings and conclusions from this research task is presented below. Please note that conclusions regarding multilane roundabouts may be considered preliminary due to the limited number of sites (three).

- Critical headway at the single-lane roundabouts (seven sites) in California was found to vary between 4.5 and 5.3 seconds, with a mean of 4.8 seconds. At multilane roundabouts (three sites), critical headway ranged between 4.4 and 5.1 seconds in the left-lane, and 4.0 and 4.8 seconds in the right-lane. The average critical headways for the two lanes were 4.7 and 4.4 seconds, respectively. These critical headway values were within the range reported in NCHRP Report 572. Statistical analyses did not show a significant difference between the critical headway values in California and other states in the U.S.

- A total of 742 individual follow-up headways were collected at the ten roundabout sites; 230 were from single-lane sites, and 512 were from multilane sites. The mean follow-up headway was 2.5 seconds at the single-lane sites. For multilane sites, the mean follow-up headway was 2.2 seconds for both the left and right lanes. These follow-up headways were statistically different from those obtained from other states as reported in NCHRP Report 572.

- The conflicting flow rate and speed were found to have moderate to low negative correlation with both critical headway and follow-up headway, which means that with an increase in conflicting flow and/or speed, the critical headway and follow-up headway tend to decrease. However, the results from the correlation analyses indicate that the correlation between speed and follow-up headway is the strongest, and the correlation between conflicting flow and follow-up headway is the weakest. Field observations also revealed that exiting vehicles were another factor with the potential to affect critical headway and follow-up headway; however, data was not available yet to support any quantitative conclusions.

3. PEDESTRIAN AND BICYCLE CONSIDERATIONS

Pedestrians and bicycles are important users of the transportation system. This chapter presents four major elements:

- Discussion of key literature related to pedestrian and bicycle use of roundabouts;
- Collection of pedestrian and bicycle usage at sites that are anticipated to be converted to roundabouts to allow for a future before-after study of roundabout use by pedestrians and bicycles;
- Review of pedestrian and bicycle use at California roundabouts; and
- Review of reported pedestrian and bicycle collisions at roundabouts across the United States.

Chapter 4 includes design recommendations based on this research.

3.1. Pedestrian Literature

This section provides a review of the literature related to pedestrian safety and accessibility at roundabouts in the United States and other countries.

3.1.1. Current Pedestrian Design Guidance

Most state guidelines in the U.S. include recommendations and policy considerations related to pedestrians at roundabouts. The FHWA Guide presents design guidelines related to pedestrian facilities at roundabouts, including pedestrian crossing locations and sidewalk treatments. The FHWA Guide suggests that the location of the pedestrian crossing needs to balance pedestrian convenience, pedestrian safety, and roundabout operation. Similar to the FHWA Guide, most state guidelines recommend that a crosswalk be 1 or 2 car lengths from a yield line. This reduces concurrent decision-making for drivers and minimizes the impact of vehicle queues on roundabout operation. Sidewalks are recommended to be set 5 feet (with a minimum set back of 2 feet) from the edge of the circulatory roadway.

3.1.2. National and International Pedestrian Research

European experiences have generally, if not universally, indicated that roundabouts are safer for pedestrians than other traditional types of intersections (*15*). Limited studies in the U.S. have shown a similar trend (*16*, *17*).

As part of NCHRP 3-65, Harkey and Carter (*18*, also *7*) conducted one of the most comprehensive studies to date of pedestrian safety at roundabouts in the U.S. They carefully tabulated 769 pedestrian crossing events at seven roundabouts. The majority of the roundabouts observed in the study showed few safety problems for crossing pedestrians, with very few recorded pedestrian crashes and few observed conflicts. However, the limited number of pedestrian movements in the behavior videos was not sufficient to make statistical analyses or draw any definitive conclusions. Major findings from their study include:

- The percentage of drivers who do not yield to pedestrians is higher than stop controlled and signalized intersections, but lower than uncontrolled pedestrian crossings.

- Drivers yield to pedestrians less frequently on exit legs than on entry legs and on two-lane crossings than on one-lane crossings. For single-lane crossing sites, 29 percent of the motorists did not yield to the pedestrians on the exit leg; 10 percent did not yield on the entry leg. For two-lane crossing sites, 62 percent of the motorists did not yield to the pedestrians on the exit leg; 33 percent did not yield on the entry leg.

- Drivers yield to pedestrians less frequently on two-lane approaches than on one-lane approaches: 43% did not yield on two-lane approaches, whereas 17% did not yield on one-lane approaches.

- In the 769 pedestrians crossing events observed, four conflicts were identified in which interaction occurred where either the pedestrian or the motorist had to react to avoid a collision. All four conflicts occurred in one-lane roundabouts approaches. The overall conflict rate was established as 2.3 conflicts per 1,000 opportunities, with one-lane approaches having a higher rate than two-lane approaches.

- An emphasis needs to be placed on designing exit legs to improve upon the interaction between motorists and pedestrians. Harkey and Carter suggest that modifications could include design changes (e.g., reductions in exit radius and/or lane width), operational changes (e.g., static warning signs, real-time devices that warn when a pedestrian is present), and enforcement and education (e.g., improving user compliance with existing rules of the road).

- Multilane roundabouts may require additional traffic control measures to ensure safe access for pedestrians. Harkey and Carter do not elaborate further on these measures.

Harkey and Carter also compared the results of the observational analysis at roundabouts with observational analysis at conventional intersections. The behavior characteristics categorized for conventional intersections were different from categories used for the roundabouts. Still, they observed that behaviors of motorists and pedestrians were similar to behaviors observed at conventional intersection with no traffic control and those observed at crossings with signal or stopped control.

Harkey and Carter state that the "overwhelming majority of the roundabouts in this observational study showed very few problems for pedestrians and bicyclists." In terms of pedestrian safety, the roundabouts under study had only four observed conflicts and no reported collisions. The paper concludes that an emphasis needs to be placed on designing exit legs to improve behaviors of both motorists and pedestrians. They commented that multilane roundabouts may require additional measures. Design changes could range from reductions in the exit radius to decreases in lane widths. They made no suggestions relating to the setback distance between the pedestrian crosswalk and the roundabout.

A recent TCRP/NCHRP report, *TCRP Report 112/NCHRP Report 562: Improving Pedestrian Safety at Unsignalized Crossings* (*19*) provides a methodology for crossing treatments. It recommends that an uncontrolled crossing, with critical vehicle speed below 35 miles per hour, be carefully analyzed when pedestrian volumes exceed 20 in a peak hour. A crossing treatment can then be selected based upon pedestrian delay and expected motorist compliance. One treatment the NCHRP report highlights as being very effective is the median refuge islands, a treatment that is part of any roundabout installation and should not be omitted. Treatments that may well be applicable to crosswalks at roundabouts include: in roadway warning lights, flashing beacons, and nighttime lighting.

3.1.3. California Vehicle Code

The California Vehicle Code requires that motorists yield to pedestrians that are in a crosswalk. Further, the pedestrian is not allowed to step into a crosswalk when a vehicle is so close that the vehicle may constitute a hazard. The text of the relevant sections (21950 and 21952) are as follows: (*20*)

> “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.
>
> “21952. The driver of any motor vehicle, prior to driving over or upon any sidewalk, shall yield the right-of-way to any pedestrian approaching thereon.”

3.1.4. Pedestrians with Vision Disabilities

Pedestrians with vision disabilities face many challenges when navigating a street network. Roundabouts present particular challenges in navigation, gap detection, and yield detection. These challenges are not necessarily unique to roundabouts (they are common to most unsignalized intersections), but some of the characteristics of the roundabout tend to exacerbate these challenges. These challenges are described further as follows:

- *Navigation.* One of the challenges facing pedestrians with vision disabilities is the task of navigating a roundabout. While the crosswalk distance is shorter, the total walk distance is longer because the crosswalks are set back from the roundabout.

- *Gap Detection.* Pedestrians with vision disabilities may also find it more difficult to identify gaps in roundabout traffic through observing sounds at roundabouts.

- *Yield Detection.* Pedestrians with vision disabilities often find it difficult to detect when a driver has yielded for them.

Clearly the provisions to deal with pedestrians with vision disabilities are issues that need attention (*21*).

The U. S. Access Board has made a number of draft recommendations regarding the accommodation of pedestrians with vision disabilities at roundabouts and other intersections (*21*). Planters are recommended to indicate crosswalk locations, and audible and accessible pedestrian signals of some type are recommended to help guide pedestrians with vision disabilities across the intersection. To address the issue of gap detection and yield detection at roundabouts, the U. S. Access Board indicates that the only practical solution at this time is to install some type of signalization to stop vehicles and allow pedestrians to cross. Water features should be avoided near roundabouts because they mask the sounds of cars. In addition, a raised crosswalk, with or without a raised guide strip at the centerline, may help pedestrians with vision disabilities remain aligned on the crosswalk.

Two major research efforts on the usability of roundabouts by pedestrians with vision impairments have been recently completed or are underway. In the first study, *Pedestrian Access to Roundabouts: Assessment of Motorists' Yielding to Visually Impaired Pedestrians and Potential Treatments to Improve Access*, Inman et al. described two studies intended to addresses two-lane roundabout accessibility issues for visually impaired pedestrians (*22*). The first study was conducted on a closed course to evaluate a pavement treatment designed to alert blind pedestrians when vehicles yielded to them. The second study examined drivers' yielding behaviors at a two-lane roundabout. The following is from the report abstract:

> In the first study, there were two experimental conditions: a control condition and a treatment condition in which rumble strip-like devices were placed on the roadway surface. Seven individuals who have severe visual impairments participated. Participants stood at a crosswalk and used hand signals to indicate when they detected vehicles stopping or departing after a stop. Compared to the control condition, the sound strips treatment increased the probability of detecting stopped vehicles, and decreased by more than a second the amount of time needed to make a detection; however, the treatment did not reduce the number of false detections. False detections could result in the pedestrian crossing when moving vehicles are approaching the crosswalk.

> The second study was an experiment conducted at an operating roundabout. In that environment the rumble strip-like treatment was not effective, probably because the majority of vehicles stopped in the circular roadway before crossing over the rumble strips. A Yield to Pedestrians, State Law sign that was placed in the roundabout exit between the two travel lanes resulted in an increase in drivers' yielding from 11 percent of vehicles in the control condition to 16 percent in the experimental condition.
>
> It was concluded that the treatments explored in these studies do not appear promising for double-lane roundabouts, but should be explored further to see if they might work at single-lane crossings.

No clear conclusions leading to design recommendations resulted from the studies done by Inman et al. The "yield to pedestrians" sign on a roundabout exit does hold some very modest opportunity to improve motorists' behavior.

The other major study, NCHRP Project 3-78, *Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities*, is currently underway and is expected to be complete in 2009. The project is using modeling and field studies to quantify and identify practical field solutions that can measurably improve accessibility of roundabouts and channelized turn lanes for pedestrians with vision disabilities. It is anticipated that these treatments may also impart benefits to sighted pedestrians.

In other research, Hughes (*23*) notes that automated yield detection can help meet the access goal for roundabout crosswalks. For automated yield detection, inductive loops detect the presence of vehicles blocking the crosswalk and vehicles yielding to pedestrians. Then accessible pedestrian signals with locator tones and audible messages are placed at a pedestrian-actuated, marked crosswalk upstream from the roundabout. The technology would help pedestrians with vision disabilities in the case of quiet cars. Yield detection or not, the likelihood of blind pedestrians accepting risky gaps points to a potential safety problem. From the perspective of the United States Access Board and the Americans with Disabilities Act, no pedestrians should experience access difficulties or be at risk (*21*). Automated yield detection is only theoretical at this point, and significant practical considerations need to be addressed prior to implementation.

3.1.5. Summary of Pedestrian Literature

This literature review indicates that pedestrians will generally receive a safety benefit when roundabouts are installed, although questions remain regarding usability in certain circumstances. For pedestrians, the risk of being involved in a severe collision is lower at roundabouts than at other forms of intersections due to the slower vehicle speeds, the lower number of conflict points, and the separation of entry and exit lanes by the splitter islands (*24*). On the other hand, roundabouts also bring challenges to users such as pedestrians with vision disabilities who may find it difficult to locate the crosswalks or determine vehicle gaps. The critical safety issues for pedestrians include pedestrian crossing position and treatments, splitter island design, sidewalk treatment, signing, and illumination. These issues need to be studied further, especially for pedestrians with vision disabilities.

3.2. Bicycle Literature

European experiences, reported over a decade ago, have indicated that single-lane and mini roundabouts do not appear to be particularly dangerous for bicyclists (*25*, *26*). Limited studies in the U.S. have shown a similar trend (*16*). However, the literature on bicycle safety at roundabouts is not totally consistent. Some European studies (specifically those conducted in the United Kingdom) indicated bicyclists are the most vulnerable at large roundabouts, especially multilane roundabouts. Bicyclists are involved in much higher rate of accidents at roundabouts as compared to conventional intersections (*27*, *28*, *29*). In addition, a study by Maycock and Hall (*6*) in the U.K. reported that a bicyclist is 14 to 16 times more likely than a car to be involved in a crash when using a roundabout. The study also indicated that large roundabouts (up to 70 m in diameter) are the most feared by bicyclists, although no statistical evidence is available to support the hypothesis. Peel collected a 3-year accident history at 35 roundabouts and 38 comparable signalized intersections in a British urban area and found out that the number of accidents per site involving bicycles is significantly higher at roundabouts than at signalized intersections (*30*). Other European countries identify similar mixed findings (*15*, *31*).

The most common (more than 50 percent) bicycle accidents at roundabouts involve conflicts between circulating bicyclists and entering vehicles (*32*, *33*). The primary cause of such accidents is drivers who fail to detect the bicycles mixed with the circulating traffic (*34*). Studies have shown that there is a strong correlation between collision speed and the risk of fatality. Lower vehicle speeds will improve driver's recognition of bicyclists and can also assist bicyclists to undertake their maneuvers within a roundabout, which can potentially reduce both numbers and severity of all user crashes (*35*). The lower vehicle speed also allows bicyclists to travel at or near the same speed as the motor vehicles. However, the smaller radii needed to produce lower speeds are often compromised to accommodate trucks.

Efforts have been taken to achieve lower speeds through innovative roundabout designs. Campbell and Dunn of New Zealand developed a conceptual "C" type multilane roundabout which aims at achieving speed of 30 km/h (*36*). The key design element is to narrow entry width to encourage bicyclists to travel in the center of the lane. The narrowed entry also prevents larger vehicles from attempting to enter the roundabouts alongside other vehicles. Fortuijn of the Netherlands proposed a turbo-roundabout design which aims to provide a compromised solution of accommodating large vehicles while reducing speed and conflicts at multilane roundabouts (*37*).

All the European countries identify that a more careful design is necessary to enhance the bicyclists' safety. In Europe, there are generally three alternatives to accommodate bicyclists at roundabouts: no designated bicycle facility, a bicycle lane within the circulatory roadway, or a bike path outside the roundabout. Studies have shown that a bicycle lane within the circulatory roadway results in the highest number of accidents (*16*, *26*). Providing a separate bicycle path has shown to be the safest for bicyclists; however, a bicycle path may not be used extensively when motorized vehicle traffic volume is low, as bicyclists traveling through are less likely to divert from the main roadway due to the number of stops and increased delay (*35*).

The current national Manual on Uniform Traffic Control Devices prohibits bicycle lane markings on the circulatory roadway of a roundabout (*38*, Section 3B-24). When no bicycle lane is provided, bicyclists should be advised to ride in the center of the lane as if they were driving a motorized vehicle. The FHWA Roundabout Guide advises that because bicyclists have a range of abilities, designers should strive to accommodate that range by designing the roundabout so that bicyclists can circulate as either motorized vehicles (by sharing the lane) or as pedestrians (by sharing a sidewalk or multiuse path) (*1*). Note that the California Vehicle Code does not prohibit bicycle use on sidewalks, although it allows local agencies to regulate the operation of bicycles on sidewalks (CVC Section 21206).

With regard to roundabout design, one can refer to the *AASHTO Guide for Development of Bicycle Facilities* (*39*) for detailed design requirements for bicycle and shared-use path design. There is also a list of Australian guidelines (*25*) with recommendations for roundabout design for bicyclists. One guideline is that the line of sight should not be obstructed by landscaping, traffic signs, or poles that could even momentarily obscure a cyclist. More accidents associated with right-of-way conflicts involving cyclists occur when vehicle volume is 8,000 to 12,000 vehicles per day. The Netherlands introduced physical separators called "hedgehogs" to counteract the wide turning movements of trucks or swerving that caused cyclists to be hit. A hedgehog is a partition that consists of a narrow raised divided curb; they are built at the entry and exit and are properly spaced within the roundabout (*23*). These types of raised devices are currently prohibited in California due to concern over bicyclists hitting them and losing control (*4*, Section 1000).

As for the most recent U.S. experience, Harkey and Carter studied bicycle behavior as part of NCHRP 3-65 (*40*, also *7*). The key observations and findings include the following:

- Fourteen roadway approaches to roundabouts were observed, allowing researchers to observe 690 bicycle events. Only two of the approaches were multilane. The majority of bicyclists entering or exiting the roundabouts were positioned on the edge of the roadway. Circulating bicyclists often possessed the lane. Bicyclists' behaviors upon entering the roundabout posed virtually no safety problems in 238 observations.

- Only four conflicts were observed during the 690 bicycle event observations; these all occurred at single-lane roundabouts. No comparisons were made to any observed bicyclist and motorist interactions at conventionally controlled intersections.

- Harkey and Carter made two comments related to roundabout design. It was pointed out that European countries no longer design roundabouts with bicycle lanes on the outer edge of the circulatory roadway; with high motor vehicle speeds and bicycle volumes, separate cycling paths outside the perimeter of the roundabout may be required. They also commented that additional care to ensure bicyclist safety could be taken at the junction of the exit lanes and the circulatory lanes, which was identified as the location posing the greatest risks to bicyclists. They did not specify what type of "care" should be taken, other than to suggest that at higher volumes of vehicles and bicyclists it may be necessary to provide separate bicycle facilities outside the perimeter of the roundabout. This is already part of the current FHWA guidance to design a roundabout to allow cyclists to circulate as either vehicles or pedestrians (*1*).

3.3. Pedestrian and Bicyclist Demand at California Roundabouts

One of the questions of interest to Caltrans is whether the presence of a roundabout affects pedestrian and bicyclist demand at the intersection. The effect of roundabouts on pedestrian and bicyclist demand (i.e., does the roundabout cause pedestrians and bicyclists to change routes to avoid the intersection?) is not well documented in the literature, largely due to a lack of pedestrian and bicyclist volume count information in the period before conversion. The data presented in this section is intended to support a future research effort that would involve a before-and-after study of pedestrian and bicycle use at recently converted roundabouts in California.

Detailed pedestrian and bicyclist counts were conducted in May and June of 2006 at ten conventional intersections throughout California where conversions to a roundabout were likely to happen in the near future. The locations were selected because there is a definite likelihood that the conventional intersection will be reconstructed into a roundabout in the near future. The pedestrian and bicyclist numbers varied at each location. Several other characteristics of the intersections, such as the size and lane width, also varied by location. Efforts were made to find locations near state highways that have a large volume of pedestrian and bicyclist activities, although such locations are very scarce. When choosing a location, satellite pictures were used to determine the setting and nature of land developments in the area. Locations were selected that might be attractive to pedestrian and bicycle traffic. Table 10 lists the selected intersections.

Table 10. Pedestrian and Bicyclist Counts at Proposed Future Roundabouts

City	Intersection	# Of Pedestrians	# Of Bicycles	Total
Oroville	Washington Avenue/Montgomery Street	64	23	87
Modesto	Sylvan Avenue/Roselle Avenue	2	5	7
Fresno	Fresno Street/North Fresno Street/Divisadero Street	172	18	190
Watsonville	Main Street/Freedom Boulevard	96	26	122
Santa Cruz	Beach Street/Pacific Avenue	1009	342	1351
Palmdale	47th Street East/State Route 138	0	1	1
Paso Robles	Highway 46 West/Route 101	2	0	2
Berkeley	Gilman Street/I-80	98	37	135
Truckee	Alder Drive/Prosser Dam Road	1	17	18
Kings Beach	Bear Street/State Route 28	270	64	334
	Total	**1714**	**533**	**2247**

The counts were set up to record 16 different movements—12 bicycle movements and four pedestrian movements. For the bicycle movements, it was noted what direction the bicyclist was traveling and if the bicyclist was turning left, right, or proceeding straight. The pedestrian movements identified the crosswalk the pedestrian used. The counts took place between the hours of 2:30 p.m. and 6:00 p.m., and were conducted on days when schools were in session.

For sites where the intersection is reconstructed into a roundabout, another count needs to be conducted to determine whether pedestrian and bicyclist demand changes with the presence of a roundabout. When conducting the counts, it is important that the population growth in the area be examined so that proper adjustments can be made.

3.4. Pedestrian and Bicycle Behavior at California Roundabouts

Pedestrian and bicyclist characteristics in these roundabouts were examined from videos of roundabouts in California collected as part of this project. Pedestrian and motorist behaviors were examined where pedestrians encountered motorists while crossing an intersection. Bicyclist behaviors when encountering a motorist were also recorded. The intersection characteristics were recorded as the bicyclist entered and circulated the roundabout.

3.4.1. Method for Video Data Analysis

Tables were created from the video analysis to characterize how pedestrians and bicyclists interact with motorists in roundabouts. The recordings of existing roundabouts in California were provided by this project and the NCHRP 3-65 project. The locations where roundabouts were examined were exclusively in California: Davis, Modesto, and Santa Barbara. The roundabouts in Davis and Modesto are single-lane roundabouts, whereas the roundabout in Santa Barbara is a multilane roundabout. The guidelines for the tables used in this study were taken from the studies prepared under NCHRP 3-65 by Harkey and Carter (*18*, *40*).

Data analysis sheets for the bicyclists and pedestrians were created from the videos. The data sheets contain all of the data that are provided in the report and emphasized events where the pedestrian or bicyclist had an interaction with a motorist. An event occurs when the roundabout is being used by either a pedestrian or a bicyclist. Table 11 and Table 12 provide summaries of the bicycle and pedestrian observations, respectively. Roundabout characteristics for the sites observed are included in the two tables.

Table 11. Roundabout Bicycle Observations

City	Intersection	Observation Period (min)	Bicycle Events	Average Daily Traffic	Circulatory Lanes	Approach Lanes	Crossing Distance (ft)	Splitter Island Width (ft)
Davis, CA	Anderson Rd./Alvarado Ave.	99	420	8900	1	1	50	15
		120	99		1	1	50	15
Santa Barbara, CA	Milpas St./ US 101 NB Ramps/ Carpinteria St.	120	573	No Data	2	2	48	12
Modesto, CA	La Loma St./James St.	90	26	No Data	1	1	No Data	No Data

Table 12. Roundabout Pedestrian Observations

City	Intersection	Observation Period (min)	Pedestrian Events	Average Daily Traffic	Circulatory Lanes	Approach Lanes	Crossing Distance (ft)	Splitter Island Width (ft)	Install Date
Davis, CA	Anderson Rd./Alvarado Ave.	99	272	8900	1	1	50	15	1997
		120	25		1	1	50	15	
Santa Barbara, CA	Milpas St./ US 101 NB Ramps/ Carpinteria St.	120	643	No Data	2	2	48	12	2000
Modesto, CA	La Loma St./James St.	90	10	No Data	1	1	No Data	No Data	1997

3.4.2. Distribution of Bicyclists by Lane Position

Table 13 depicts the position that the bicyclist was in as he/she entered, circulated, and exited the roundabout. The majority of bicyclists traveled on the edge of the lanes when traveling in the roundabout. For a bicyclist to possess the lane, they needed to travel in the middle of the lane in such a way that motorists could not safely pass them. At the multilane roundabout in Santa Barbara, at the multilane roundabout, more bicyclists chose to circulate using the sidewalk and the crosswalk.

Table 13. Numbers of Bicyclist by Position at the Roundabouts

Position of Bicyclist of Event Type or Maneuver at the Roundabout									
	Entering Roundabout			Exiting Roundabout			Circulating		
Location	Bicyclists on Edge of Lane	Bicyclists Possessing Lane	Bicyclists on Sidewalk	Bicyclists on Edge of Lane	Bicyclists Possessing Lane	Bicyclists on Sidewalk	Bicyclists on Edge of Lane	Bicyclists Possessing Lane	Bicyclists on Sidewalk
Davis, CA	147	10	6	135	7	11	125	54	14
Santa Barbara, CA	53	5	3	133	4	1	78	19	229
Modesto, CA	7	0	0	6	0	0	3	2	8

Table 14 further elaborates the distribution of bicyclists by lane position, breaking down the percentage of how often the bicyclist rode on the edge of the lane, possessed the lane, or used the sidewalk while entering, circulating, and exiting the roundabout.

Table 14. Percentages of Bicyclists by Position at the Roundabouts

Distribution of Bicyclists by Lane Position			
Location	**Edge of Lane**	**Possessing Lane**	**Sidewalk**
Davis, CA	80.0%	13.9%	6.1%
Santa Barbara, CA	50.3%	5.3%	44.4%
Modesto, CA	61.5%	7.7%	30.8%
Total	64.8%	9.5%	25.7%

3.4.3. Distribution of Bicyclist Positions by Vehicle Presence

Table 15 provides the bicyclist position relative to the motorists when both were traveling in the roundabout. The types of motorists present were classified where a bicyclist was either leading or trailing a motor vehicle, if the bicyclist was within two car lengths. Most of the bicyclists were not affected by a motorist's presence. Few bicyclists possessed the lane when motorists were present. According to these data, 17 (22.7%) out of 75 bicyclists in roundabouts in California possessed the lane.

Table 15. Distribution of Bicyclist Positions within Roundabout by Vehicle Position

Motor Vehicle Presence	**Edge of Lane/ Shoulder/ Bike Lane**		**Possessing Lane**		**Total**	
	Count	**Percent**	**Count**	**Percent**	**Count**	**Percent**
None	629	88.3%	83	11.7%	712	100.0%
Leading	38	74.5%	13	25.5%	51	100.0%
Trailing	15	93.8%	1	6.3%	16	100.0%
Both Leading and Trailing	5	62.5%	3	37.5%	8	100.0%
Total	687	87.3%	100	12.7%	787	100.0%

3.4.4. Bicyclist Movements When Entering a Roundabout

Table 16 presents the type of movements bicyclists made when entering the roundabout, categorized by entering the roundabout without stopping, waiting before entering the roundabout, or entering using the sidewalk. As can be seen, most bicyclists were observed to enter the roundabout without stopping. The lower percentage observed at Modesto is largely influenced by the small sample size.

Table 16. Bicycle Movements When Entering the Roundabout

Location	**Entering Circulation Without Stopping**		**Waiting Before Entering Circulatory Lanes**		**Entering on Sidewalk**		**Total**	
	Count	**Percent**	**Count**	**Percent**	**Count**	**Percent**	**Count**	**Percent**
Davis, CA	135	82.8%	22	13.5%	6	3.7%	163	100.0%
Santa Barbara, CA	50	82.0%	11	18.0%	0	0.0%	61	100.0%
Modesto, CA	4	57.1%	3	42.9%	0	0.0%	7	100.0%
Total	189	81.8%	36	15.6%	6	2.6%	231	100.0%

3.4.5. Bicyclist and Motorist Behavior at Crosswalks by Entry Leg and Exit Leg

Many bicyclists entered the roundabout by crossing at the pedestrian crossing. Table 17 and Table 18 present bicyclists' and motorists' behaviors, respectively, when the bicyclist entered the roundabout at the crosswalk.

Table 17. Bicyclist Behavior at Crosswalk by Entry Leg and Exit Leg

Bicyclist's Behavior	**Entry Leg**		**Exit Leg**	
	Count	**Percent**	**Count**	**Percent**
Normal	174	90.6%	117	84.2%
Waits/ Hesitates before starting	17	8.9%	19	13.7%
Hesitates after starting	1	0.5%	3	2.2%
Total	192	100.0%	139	100.0%

Table 18. Motorist Behavior at Crosswalk by Entry Leg and Exit Leg

Motorist's Behavior	**Entry Leg**		**Exit Leg**	
	Count	**Percent**	**Count**	**Percent**
No Motor Vehicle Present	126	63.6%	123	90.4%
Slows or Stops for a waiting Bicycle	2	1.0%	2	1.5%
Slows or Stops for bicycle in Transit	27	13.6%	11	8.1%
Already Stopped	43	21.7%	0	0.0%
Total	198	100.0%	136	100.0%

Technically, any bicyclist entering the roundabout from the sidewalk is expected to yield the right-of-way to the motorist in the entry or exit leg. The situation is legally comparable to a motorist merging to a roadway from a driveway. If the bicyclist is dismounted, the motorist is expected to yield to the pedestrian guiding the bicycle. In this study, when a bicyclist entered the roundabout without having to stop or hesitate, the behavior was classified as “normal.” In most of the observed cases, the bicyclist exhibited normal behavior as he/she used an acceptable gap in motor vehicle traffic. If the bicyclist waited or hesitated to enter the roundabout, the action was classified as “waits/hesitates before starting.” If the bicyclist started to enter the roundabout then hesitated, the action was classified as “hesitates after starting.”

Most bicyclists were able to use the crosswalk without any conflict with motorists. One bicyclist/motorist conflict occurred when a bicyclist was cut off while trying to enter the roundabout, which forced the bicyclist to come to an abrupt stop. A second bicyclist/motorist conflict occurred when a bicyclist entered a crosswalk and the motorist had to swerve around the bicyclist to avoid collision. One borderline conflict occurred when the bicyclist entering the crosswalk and a conflicting motorist had to brake abruptly to avoid each other.

Table 17 shows the motorists’ behaviors when interacting with bicyclists. The results are broken down by interactions that occurred at the entry and exit legs. The biggest difference was that on the entry leg and at multilane roundabouts, there were more cars already stopped than at the exit lane and at single-lane roundabouts. There were four classifications used to categorize the motorists’ behavior: no motor vehicle present, motor vehicle slows or stops for waiting bike, motor vehicle slows or stops for bike in transit, and motor vehicle already stopped.

There is no requirement for the motorist to yield to the bicyclist. However, Table 18 indicates that many motorists did. The events of a motorist passing a waiting bicyclist were not tabulated.

3.4.6. Pedestrian Crossings with Vehicle Interaction

Table 19 compares where pedestrians encountered motorists when using a roundabout. The pedestrians had an interaction either at the entry or exit leg of the roundabout: each was recorded and depicted in the table. The third column of the table breaks down the percentage of interactions between pedestrians and motorists within each roundabout location. For example, in the roundabout located in Davis, 16.5% of the pedestrian’s crossing at the crosswalk had some sort of vehicle interaction. The remaining 83.5% did not. The fifth and seventh columns of the table break down the percentage of interactions on the entry and exit leg for each of the roundabouts. In Davis, of the 16.5% that had vehicle interaction, 69.4% of the interactions occurred on the entry leg and 30.6% of the interactions occurred on the exit leg.

Table 19. Pedestrian Motor Vehicle Interactions at Crosswalks

Location	**% of Pedestrian Crossings with Vehicle Interaction**		**% of Interactions on Entry Leg**		**% of Interactions on Exit Leg**	
	Count	**Percent**	**Count**	**Percent**	**Count**	**Percent**
Davis, CA	49	16.5%	34	69.4%	15	30.6%
Santa Barbara, CA	312	48.5%	240	76.9%	72	23.1%
Modesto, CA	3	30.0%	3	100.0%	0	0.0%

3.4.7. Pedestrian's Behavior when Crossing in Roundabout

As pedestrians used the crosswalk, their actions were broken down into four different categories: normal, hesitates, retreats, and runs. Normal behavior was defined as a person who used the crosswalk without hesitating, running, or retreating back to the sidewalk. The pedestrian behaviors are presented in Table 20.

For a pedestrian to hesitate when using a crosswalk, the pedestrian either had to have an unnecessary long pause before entering when no cars were present or have a pause after starting to enter the roundabout. The classification "runs" is when a pedestrian rushed across in a very fast manner that was unlike their approach to the roundabout. A jogger was counted as a pedestrain with normal behavior. "Other than normal" behavior occurred more frequently at the multilane roundabout crossings than at the single-lane roundabout crossings.

Table 20. Pedestrian Behavior when Crossing in Roundabout

Location	**Normal**		**Hesitates**		**Retreats**		**Runs**	
	Count	**Percentage**	**Count**	**Percentage**	**Count**	**Percentage**	**Count**	**Percentage**
Davis, CA	289	97.3%	4	1.3%	0	0.0%	4	1.3%
Santa Barbara, CA	600	93.3%	22	3.4%	2	0.3%	19	3.0%
Modesto, CA	9	90.0%	1	10.0%	0	0.0%	0	0.0%
Total	898	94.5%	27	2.8%	2	0.2%	23	2.4%

3.4.8. Crossing Location

Pedestrians do not always stay in the crosswalk. Table 21 classifies where the pedestrian crossed when traveling around the roundabout. A pedestrian could cross completely in the crosswalk, start in the crosswalk and then stray outside the crosswalk before reaching the other side, start off the crosswalk but then enter the crosswalk at mid-span, or cross off the crosswalk. It appears that in single-lane crossings, it is more likely that the pedestrians will not use the crosswalk at all. At the multilane crossings, pedestrians used part of the crosswalk more often than at the single-lane crossings.

Table 21. Pedestrian Crossing Location

Location	**Crosswalk**		**In-Entry/Out-Exit**		**Out-Entry/In-Exit**		**Off Crosswalk**	
	Count	**Percentage**	**Count**	**Percentage**	**Count**	**Percentage**	**Count**	**Percentage**
Davis, CA	152	51.2%	6	2.0%	20	6.7%	119	40.1%
Santa Barbara, CA	470	73.1%	111	17.3%	18	2.8%	44	6.8%
Modesto, CA	9	90.0%	0	0.0%	0	0.0%	1	10.0%
Total	631	66.4%	117	12.3%	38	4.0%	164	17.3%

3.4.9. Motorist's Yield Behavior

When a motorist had an interaction with a pedestrian, the motorist's actions were classified as an active yield, a passive yield, or did not yield. An active yield is where a motorist slows or stops for a pedestrian waiting to cross; the pedestrian is the reason that the motorist stops or slows. A passive yield is where a motorist yields to the pedestrian but is already stopped for another reason. This happened more in the multilane roundabout when motorists had to wait to enter. The last classification, did not yield, is when a pedestrian makes a motion to enter the roundabout but the motorist proceeds without yielding. As noted previously, the California Vehicle Code requires that motorists yield to pedestrians that are in a crosswalk.

Table 22 depicts driver behaviors when a pedestrian starts the crossing on the roundabout entry leg. Table 23 provides the same information for the case when the pedestrian begins the crossing on the roundabout exit leg. Table 24 provides the percentages for the combined entry legs and exit legs crossings.

Table 22. Motorist Yield Behavior, Pedestrian Start on Entry Side

Location	**Behavior on Entry Leg**			**Behavior on Exit Leg**		
	Active Yield	**Passive Yield**	**Did Not Yield**	**Active Yield**	**Passive Yield**	**Did Not Yield**
Davis, CA	7	0	0	15	0	1
Santa Barbara, CA	52	29	0	17	0	2
Modesto, CA	1	0	0	0	0	0
Total	60	29	0	32	0	3

Table 23. Motorist Yield Behavior, Pedestrian Start on Exit Side

Location	**Behavior on Entry Leg**			**Behavior on Exit Leg**		
	Active Yield	**Passive Yield**	**Did Not Yield**	**Active Yield**	**Passive Yield**	**Did Not Yield**
Davis, CA	25	0	3	2	0	0
Santa Barbara, CA	39	38	0	46	0	6
Modesto, CA	1	0	0	0	0	0
Total	65	38	3	48	0	6

Table 24. Motorist Yield Behavior Percentages

Location	Behavior on Entry Leg			Behavior on Exit Leg		
	Active Yield	**Passive Yield**	**Did Not Yield**	**Active Yield**	**Passive Yield**	**Did Not Yield**
Davis, CA	91.4%	0.0%	8.6%	94.4%	0.0%	5.6%
Santa Barbara, CA	57.6%	42.4%	0.0%	88.7%	0.0%	11.3%
Modesto, CA	100.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Total	64.1%	34.4%	1.5%	89.9%	0.0%	10.1%

3.4.10. California Compared to National Data

The data that was tabulated for California showed some similarities and some differences to studies by Harkey and Carter (*18*, *40*). As with Harkey and Carter, the research found no major safety problems that needed to be addressed for bicyclists and pedestrians at the roundabouts. However, there were differences in many of the numbers, which is to be expected with the data being taken at different roundabouts and times.

The bicyclists' position in roundabouts produced different results, but no statistical conclusion can be drawn from the differences given the limited amount of data available, nor is it possible to definitively draw separate conclusions for single-lane and multilane roundabouts. An example of the difference is that Harkey and Carter concluded that 54 percent of bicyclists rode on the edge of the roundabouts; the California data revealed that 65 percent of the bicyclists rode on the edge of the roundabouts. Harkey and Carter stated that 28 percent of bicyclists possessed the lane, whereas the California data revealed only 10 percent. While some of that difference probably came from the different roundabouts and times studied, additional differences may have come from the observer's discretion of what exactly was counted as possessing the lane. There were times when lane possession was very clear but at other times, a bicyclist would be riding in an area where it was hard to determine whether they possessed the lane or were on the edge of the lane. The data were all determined from video of the roundabouts, and there were times where the angles on the camera made it hard to clearly determine positions.

The major conclusions that can be drawn from the combined national and California video observation data of pedestrians and bicycles are:

- The exit legs are the greatest risk for pedestrians because motorists are less likely to yield.
- Two-lane approaches are more difficult for pedestrians to cross than one-lane approaches; motorists are less likely to yield.
- Behavior of motorists and pedestrians at roundabout crosswalks appear to be consistent with that at other types of crosswalks, with better driver yielding behavior at roundabouts than at uncontrolled crosswalks but not as good as at signal- or stop-controlled crosswalks.

- When approaching a roundabout, more bicyclists travel at the edge of the lane with only a small number possessing the lane or using the sidewalk. When exiting the roundabout, the number of bicyclists using the sidewalks increases but the number of bicycles possessing the lane stays constant.

- In the event that a bicyclist might be traveling outside the travel lane when circulating the roundabout, instead of possessing the lane, no other interactions were observed. Bicyclists nearly always wait until there are no vehicles approaching the roundabout before crossing.

- Concern of wrong-way riding where the bicyclists enter the roundabout from the exit leg should be addressed to avoid collisions.

- Care must be considered for vehicle yielding behaviors to ensure that the motorists will yield to waiting and crossing pedestrians. Roundabouts need to be designed to provide adequate sight lines and to reduce vehicle speed at the exits. Multilane roundabouts may require additional design elements (e.g., pedestrian signals of some type or other treatments beyond a simple marked crosswalk) to improve accessibility for all users; these are currently being researched under NCHRP 3-78.

3.5. Traffic Collision Data

This section discusses the collision data from roundabouts at eight different roundabouts: four from Colorado, one from California, one from Washington, one from Maryland, and one from Michigan. The collisions studied were those provided in NCHRP 3-65 that involved pedestrians and bicyclists. Between 1996 and 2003 (not all years were available for all sites), thirteen pedestrian and bicyclist collisions occurred in the eight roundabouts. By looking at where the accidents occurred in the roundabouts, design recommendations may be made for future and current roundabout design.

Of the 13 collisions reported, 7 were between pedestrians and motorists and 6 were between bicyclists and motorists. The collisions occurred between the hours of 9:00 a.m. and 7:30 p.m., making lighting a generally insignificant issue. Seven occurred in the roundabout entry, 3 occurred in the roundabout exit, and 3 occurred in the roundabout itself. There were no fatal collisions, but 11 of the 13 collisions resulted in injuries.

This data sample is very small and a larger sampling is needed to make usable statistics. As more roundabouts are built, more data in the United States will be available in the future. The data shows more incidents on the entry leg than the exit leg, which is unexpected. Due to the small sample size, not much can be said other than visibility should be checked at those roundabouts to determine if the stopping sight distance is sufficient for incoming vehicles.

4. GEOMETRIC DESIGN CONSIDERATIONS

This chapter presents geometric design guidance for roundabouts based on the latest research available. First, a discussion of general design philosophy is presented, followed by discussions on specific topics. This chapter is not intended to be a complete document covering all aspects of roundabout design, nor does it cover important topics such as policy, planning, operational performance estimation, or safety performance estimation. Rather, this document presents a focused discussion on particular topics of interest to Caltrans that can be used by the agency in addition to FHWA's *Roundabouts: an Informational Guide* (*1*, hereafter FHWA Guide) and other documents to update Design Information Bulletin 80 (*3*) and the Highway Design Manual (*4*).

4.1. Review of Existing Guidelines

As more roundabouts are being built in the U.S., several states have initiated roundabout-related research and developed some type of roundabout application guidelines. In 2000, the FHWA published the first national-level roundabout guide in the United States (*1*). Several states have also developed state-level guidelines as a supplement to the FHWA Roundabout Guide; these are listed in Table 25.

Table 25. Published Guidelines and Research Documents

State	Name of Document	Year of Publication
Maryland	Roundabout Design Guidelines (*41*)	1995
Oregon	Modern Roundabouts for Oregon (*42*)	1998
Florida	Florida Roundabout Guide (*43*)	1998
Pennsylvania	Guide To Roundabouts (*44*)	2001
New York	Highway Design Manual, Chapter 26: Roundabout (*45*)	2001
California	Design Information Bulletin 80-01 (*3*)	2003
Kansas	Kansas Roundabout Guide: a Supplement to FHWA's Roundabout: an Informational Guide (*2*)	2003
Arizona	Roundabouts: an Arizona Case Study and Design Guidelines (*8*)	2003
Washington	WSDOT Highway Design Manual, Chapter 915 (*46*)	2004
Wisconsin	Facilities Development Manual, Design Chapter, Roundabouts Section (*9*)	2004
Utah	Evaluation of Four Recent Traffic and Safety Initiatives: Volume 1: Developing Guidelines for Roundabouts (*10*)	2005
Kentucky	Modern Roundabouts: a Guide for Application (*47*)	2005

As shown in the table, two states (Florida and Maryland) had developed guidelines and one state (Oregon) had conducted research before the publication of the FHWA Guide. These guidelines were mainly based on information from international studies and guides. The states that published guidance after the publication of the FHWA Guide have typically used the FHWA Guide as their primary reference. However, some documents have deviated from the FHWA Guide on several design and operating parameters, as documented in the following sections. The geometric design parameters include design vehicle, design speed, and inscribed circle diameter. Critical gap is addressed as an operating parameter, although it is used to calculate sight distance at roundabouts.

4.2. General Design Philosophy

The successful design of roundabouts, as with any intersection type, requires attention to how the components of the intersection fit together, as well as to how the intersection fits within the surrounding transportation system. It is insufficient, for example, to assume that the assembly of components using standard dimensions will result in a successful intersection. For example, a standard, four-legged intersection with through lanes and left-turn lanes that are 12 feet and 14 feet wide, respectively, meets most acceptable standards. If, however, the through lane on one approach is misaligned with the receiving lane on the opposite side of the intersection, the resulting composition of the intersection may result in an unacceptable crash experience. In addition, a similar intersection with 10-foot lanes but good alignment through the intersection may have a better crash experience than the misaligned intersection with standard lane widths, even though the intersection lane widths do not meet the standard for that component. Therefore, attention to the overall layout of the intersection is often more critical than the dimensions of individual components. In effect, roundabout design is performance-based; that is, success is measured from its output (operational and safety performance, accommodation of design vehicle, pedestrian and bicycle usability, etc.) rather than its input (individual design dimensions).

The guidance presented in this chapter is presented with this overall philosophy in mind. Each component is anchored to available research wherever possible; in other cases, the guidance represents the best judgment of the authors. Tables and figures have been provided to illustrate key points.

4.3. Lane Numbers and Arrangements

The overall number of lanes entering, circulating, and exiting a roundabout is the most important factor in determing the capacity of the intersection. In addition, the number of lanes has a direct influence on the safety of the intersection. Entries with more lanes provide capacity, but often at the expense of safety.

4.3.1. Methods and Considerations

A variety of operational analysis methods are available to determine appropriate lane numbers and arrangements. A detailed discussion of operational analysis methods, including specific software implementations, is beyond the scope of this document. The operational methods can be generalized into three basic categories:

- *Simple deterministic methods.* These include the simple linear equations presented in the FHWA Guide and the simple exponential regression equations developed within NCHRP 3-65 (*7*). These methods can be conducted either manually or with simple spreadsheets and are often sufficiently accurate for many applications. In addition, the research from NCHRP 3-65 suggests that simple methods can be supported by U.S. data at this time.

- *Complex deterministic methods.* These methods have more complicated mathematical models and iterative procedures that must be implemented by software. These models allow more tests of sensitivity to flow patterns and/or geometry. Examples include but are not limited to the methods presented in SIDRA and RODEL. These methods can be calibrated to U.S. data, although NCHRP 3-65 research could not conclude that the calibrated complex methods were more accurate than simple methods.

- *Microsimulation models.* These models account for individual vehicle behavior and thus are more complicated than the deterministic models identified above. Microsimulation models are also typically capable of modeling network effects, which allows for modeling of interactions between a roundabout and other nearby traffic control devices. Examples include but are not limited to VISSIM and Paramics.

From a design perspective, safety and operational performance are maximized by ensuring that lane numbers and arrangements are consistent throughout the design of the roundabout. For single-lane roundabouts, these are self-evident. However, for multilane roundabouts, lane numbers and arrangements become much more complex. By maintaining consistent lane numbers and arrangements throughout the roundabout, lane changes within the intersection are minimized and allow the roundabout to operate consistent with general driving practice at other intersections, where lane changes within the intersection are generally not desirable (although not specifically prohibited by the California Vehicle Code). For example, if two entry lanes are required for a particular turning movement for capacity reasons, these two lanes need to be carried through the circulatory roadway and exit to avoid unnecessary merging within the roundabout, which may result in less capacity and safety than could be achieved.

The next update to FHWA's *Manual on Uniform Traffic Control Devices* (*38*) is expected to contain examples of circulatory roadway striping arrangements that illustrate these points. Two examples of these that were approved by the National Committee on Uniform Traffic Control Devices in January 2006 are given in Figure 11 and Figure 12. Both roundabouts have two entry lanes on all approaches. However, the roundabout in Figure 12 has double-left turn movements for two approaches, presumably to accommodate heavy left-turn movements on those approaches. To accommodate these movements without inducing lane changing within the roundabout, a section of three-lane circulatory roadway is needed, as well as a single lane for the exit that has only one lane feeding it. By tracing the path of a vehicle in each lane, one can see that no lane changes are generally necessary within the roundabout, provided that a vehicle starts in the correct lane as assigned by the lane use arrows on the approach.

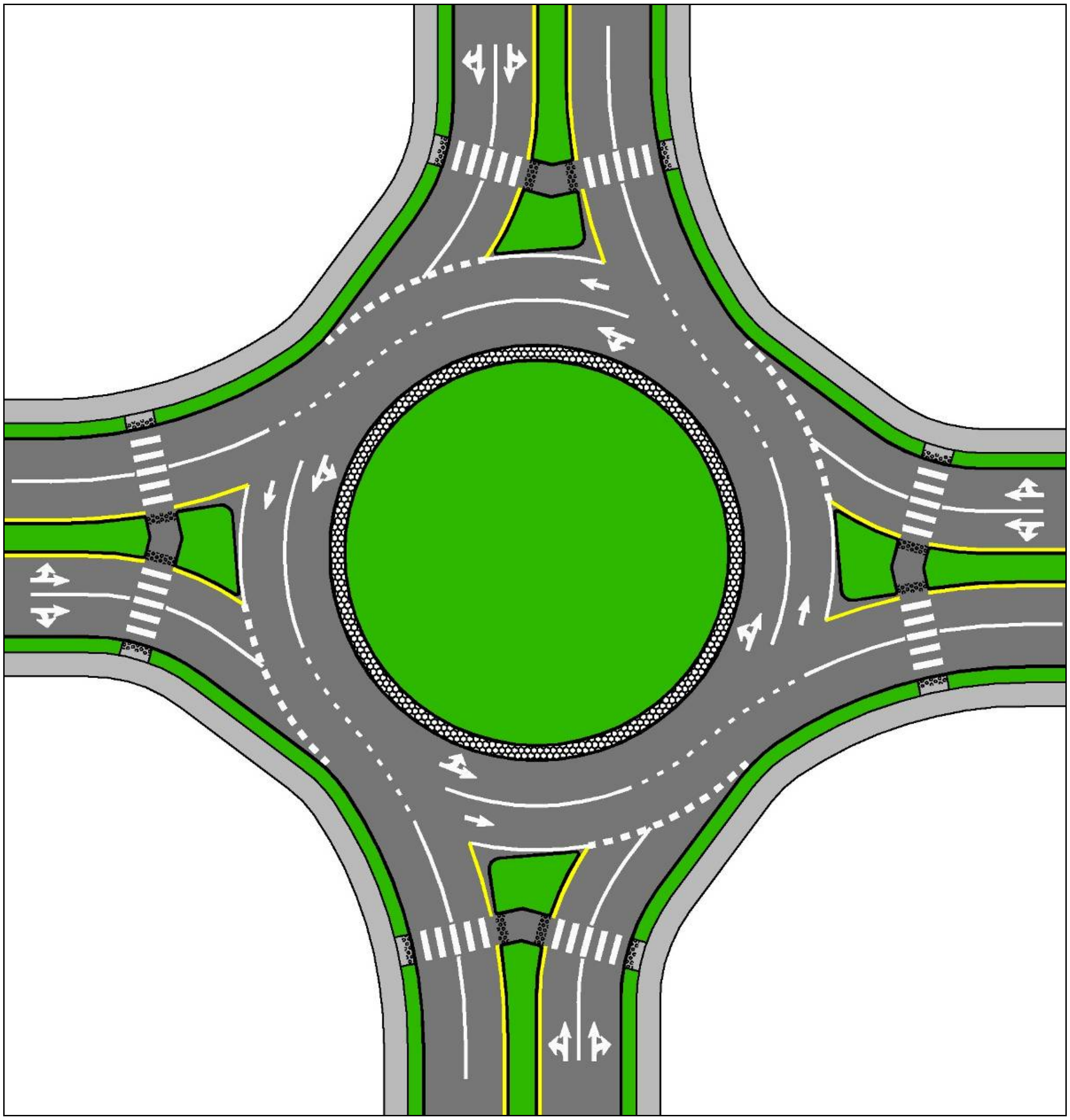


Figure 11. Lane Numbers and Arrangements for Typical Double-Lane Roundabout

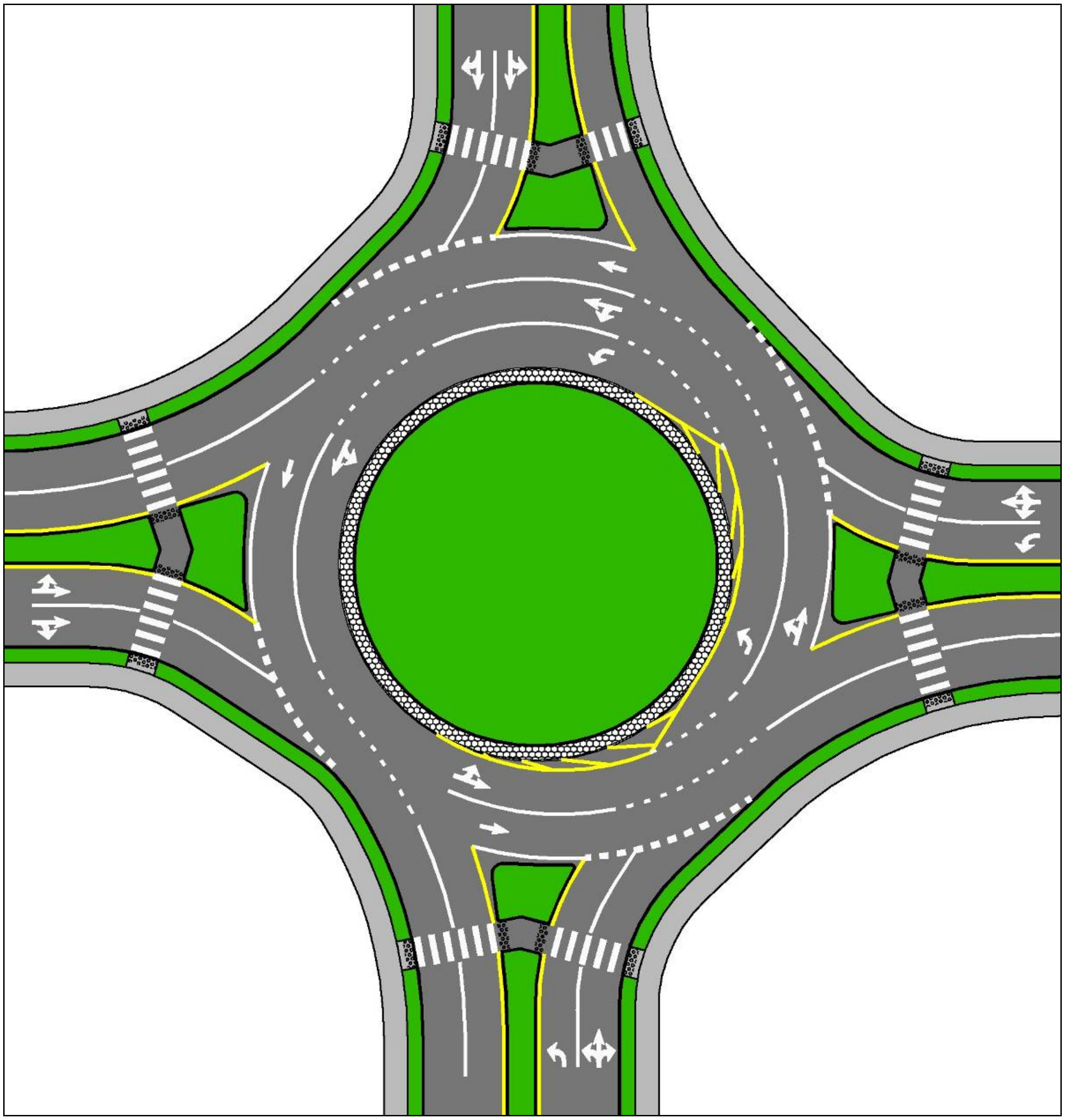


Figure 12. Lane Numbers and Arrangements for Roundabout with Consecutive Double-Left Turns

Under some circumstances, particularly for complex multilane roundabouts with more than four legs, it may be impossible to provide for every movement through the roundabout without lane changes. If these circumstances cannot be avoided, the designer should recognize that the lane changes within the roundabout run a higher risk of side-swipe crashes, poor entry lane utilization, and/or lower entry capacity. In these cases, a designer may need to omit circulatory lane striping in those portions of the circulatory roadway where their presence may induce undesirable safety and operational performance (this is referred to as partial circulatory roadway striping). These decisions must be made on a case-by-case basis; it is difficult to prescribe a set of conditions under which partial circulatory roadway striping will be necessary. However, poor striping may have more adverse safety consequences than no striping, so in some cases it may be preferable to not stripe at all rather than to put down stripes that induce conflicts.

4.3.2. Capacity Models Calibrated to California Data

Using the critical headway and follow-up headway values identified in Chapter 2, it is possible to calibrate the capacity equations recommended in the NCHRP 3-65 research.

- The following California-specific values for critical headway may be considered for calibration of capacity models to determine appropriate lane numbers and arrangements:
  - Single-lane roundabouts: 4.8 s
  - Multilane roundabouts: 4.7 s, left lane; 4.4 s, right lane
- The following California-specific values for follow-up headway should be considered for calibration of capacity models to determine appropriate lane numbers and arrangements:
  - Single-lane roundabouts: 2.5 s
  - Multilane roundabouts: 2.2 s, left lane; 2.2 s, right lane

The NCHRP 572 research provides the following general form for estimating capacity:

$$c = A \cdot \exp(-B \cdot v_c) \quad (1)$$

where: c = capacity (passenger car equivalents per hour),

v_c = conflicting flow rate (passenger car equivalents per hour),

A = $3600/t_f$,

B = $(t_c - t_f/2)/3600$,

t_c = critical headway (seconds), and

t_f = follow-up headway (seconds).

Using this general form and the California data described above,

A = 3600/2.5 = 1440 for single-lane

A = 3600/2.2 = 1640 for multilane.

B = (4.8 – 2.5/2)/3600 = 0.0010 for single-lane

B = (4.4 – 2.2/2)/3600 = 0.0009 for multilane right lane

B = (4.7 – 2.2/2)/3600 = 0.0010 for multilane left lane

Therefore, the calibrated capacity equations are given as follows in Equations 2, 3, and 4, with c equal to capacity (passenger car equivalents per hour) and v_c equal to the conflicting flow rate (passenger car equivalents per hour):

- Single-lane: $c = 1440 \cdot \exp(-0.0010 \cdot v_c)$ (2)
- Multilane right lane: $c = 1640 \cdot \exp(-0.0009 \cdot v_c)$ (3)
- Multilane left lane: $c = 1640 \cdot \exp(-0.0010 \cdot v_c)$ (4)

4.4. Design Speed

The design speed of a roundabout is widely recognized as one of its most important attributes in terms of safety performance. Generally speaking, although the frequency of crashes is most directly tied to volume, the severity of those collisions is more directly correlated to speed. Therefore, careful attention to the design speed of a roundabout is fundamental to attaining good safety performance.

This section is divided into two parts. The first part discusses a methodology for estimating various speeds through a roundabout, and the second part discusses desirable thresholds for those speeds.

4.4.1. General Speed Estimation

The speed prediction formula presented in the FHWA Guide is based on the basic highway design principles found in the AASHTO *Policy on Geometric Design of Streets and Highways (48)*. The basic relationship between speed, radius, superelevation, and side friction factor is as follows:

$$V = \sqrt{15R(e + f)} \quad (5)$$

where V = speed (mph),

R = radius (ft),

e = superelevation (ft/ft), and

f = side friction factor.

The FHWA Roundabout Guide presents its speed methodology using a series of graphs to demonstrate the relationship among these parameters, recognizing that side friction factor varies with speed. NCHRP 3-65 researchers developed a simplified relationship between speed and radius for the two most common superelevation values, e = +0.02 and e = –0.02 *(7)*. These fitted equations are as follows:

$V = 3.4415R^{0.3861}$, for e = +0.02 (6a)

$V = 3.4614R^{0.3673}$, for e = –0.02 (6b)

where V = predicted speed (mph), and

R = radius of curve (ft).

The NCHRP 3-65 researchers found that the above relationships provide a reasonable prediction for the left-turn and through movement circulating speeds. However, the researchers found that current methodologies significantly overpredict entry and exit speed in cases where the path radius is large.

4.4.2. Exit Speed

To improve the prediction fit for exit speeds, the NCHRP 3-65 researchers proposed the following formulation:

$$V_3 = \min\left\{\begin{array}{c} V_{3pbase} \\ \frac{1}{1.47}\sqrt{(1.47V_2)^2 + 2a_{23}d_{23}} \end{array}\right\} \quad (7)$$

where V_3 = exit speed (mph),

V_{3pbase} = V_3 speed predicted based on path radius (mph),

V_2 = circulating speed for through movements predicted based on path radius (mph),

a_{23} = acceleration along the length between the midpoint of V_2 path and the point of interest along V_3 path = 6.9 ft/s^2, and

d_{23} = distance between midpoint of V_2 path and point of interest along V_3 path (ft).

This formulation suggests that tangential exits do not inherently result in excessive exit speeds as compared to exits with some curvature, provided that circulating speeds are low and the distance to the point of interest on the exit (typically the crosswalk) is short. While the authors believe it is desirable to provide some degree of curvature on the exit to reduce the visual appearance of a “straight shot,” such curvature does not appear to always be the controlling factor for exiting speeds.

In practice, the use of exits with broad curvature or tangential alignments becomes more critical for roundabouts with multilane exits. It may be possible, for example, to use a smaller inscribed circle diameter with tangential exits than what might be possible with exits with more curvature. The smaller diameter may result in lower circulating speeds and lower exiting speeds. As with all elements of roundabout design, the authors believe that the most important principle is that the components fit together to achieve a desired result.

4.4.3. Entry Speed

To improve the prediction fit for entry speeds, the NCHRP 3-65 researchers proposed the following formulation:

$$V_1 = \min\left\{ \begin{array}{c} V_{1pbase} \\ \frac{1}{1.47}\sqrt{(1.47V_2)^2 - 2a_{12}d_{12}} \end{array} \right\} \qquad (8)$$

where V_1 = entry speed (mph),

V_{1pbase} = V_1 speed predicted based on path radius (mph),

V_2 = circulating speed for through vehicles predicted based on path radius (mph),

a_{12} = deceleration between the point of interest along V_1 path and the midpoint of V_2 path = –4.2 ft/s^2, and

d_{12} = distance along the vehicle path between the point of interest along V_1 path and the midpoint of V_2 path (ft).

The NCHRP 3-65 researchers noted that the proposed entry-speed prediction method appears to be a substantial improvement on the current method. However, given the hesitancy presently exhibited by drivers under capacity conditions, the observed entry speeds may increase over time after drivers acclimate further. Therefore, they noted their belief that a designer should be cautious when using deceleration as a limiting factor to establish entry speeds for design. Furthermore, they noted their belief that a good design should rely more heavily on controlling the R_1 path radius as the primary method for controlling entry speed, particularly for the fastest combination of entry and circulating path (typically the through movement).

4.4.4. Speed Thresholds

Achieving appropriate vehicular speeds through a roundabout is commonly considered the most critical design objective. Most documents suggest that design speeds should be between 15 and 30 mph, depending on the size and type of a roundabout. Table 26 shows the FHWA Guide design recommendations and notes the states where deviations exist. Because the Kansas and Arizona guides were prepared concurrently by the same authors, the recommendations from those documents have been combined here for clarity.

Table 26. Recommended Maximum Entry Design Speeds

Roundabout Category*	Recommended Maximum Entry Design Speed (mph)	
	FHWA	**Kansas/Arizona**
Mini-Roundabout	15	20
Urban Compact	15	20
Urban Single Lane	20	25
Urban Double Lane	25	25
Rural Single Lane	25	25
Rural Multilane	30	30

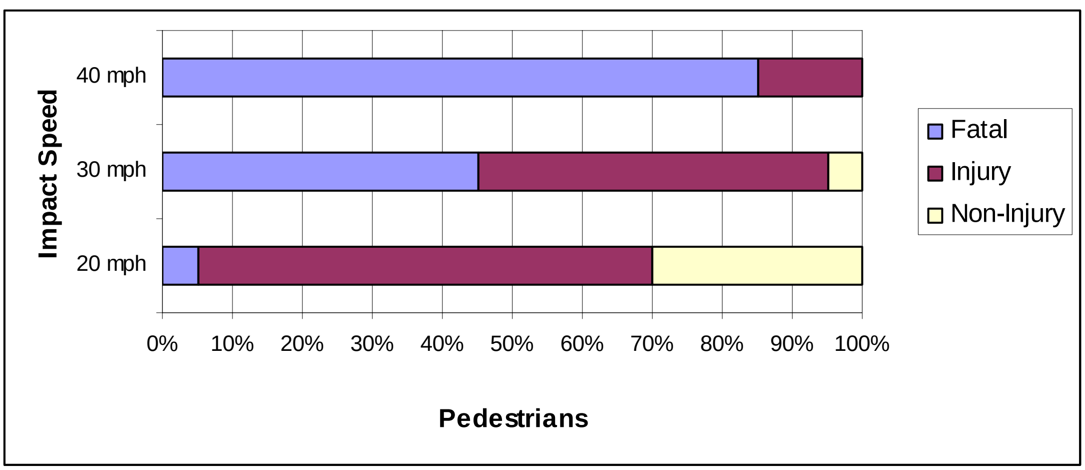
*Note: Roundabouts are categorized based on the size of the ICD, the number of circulating lanes, and urban/rural environment. Refer to the FHWA Roundabout Guide for further details.

Kansas and Arizona have slightly modified the entry design speeds. Both states recommend a 5-mph higher entry speed for mini-roundabouts, urban compact roundabouts, and urban single lane roundabouts (*2*, *8*).

Two factors particularly contribute to the selection of a maximum design speed for a roundabout:

- Pedestrian and bicycle safety (particularly in urban areas); and
- Severity of vehicle-vehicle collisions.

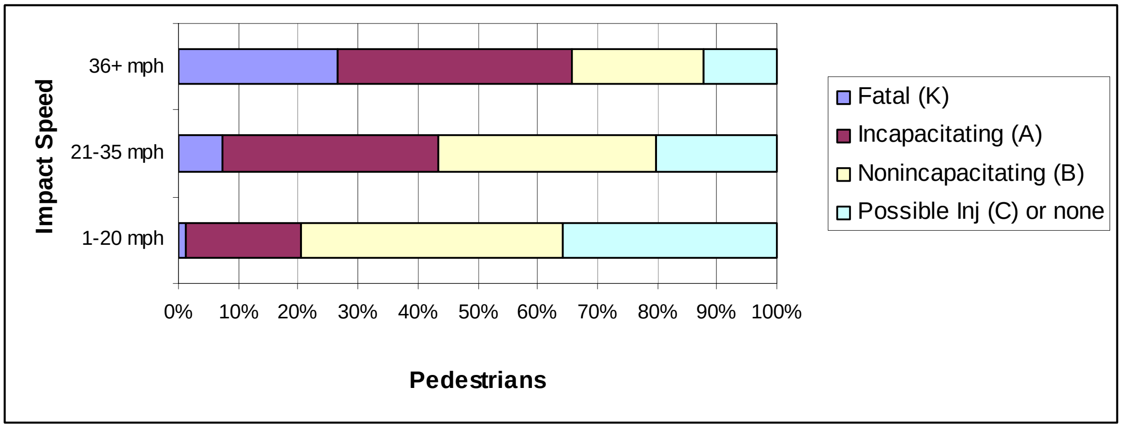
Although not specific to roundabouts, research conducted in the U.S. and UK has demonstrated a clear relationship between vehicle speed and pedestrian injury severity. UK experience, as cited by Leaf and Preusser *(49)*, suggests the relationships shown in Figure 13.



Source: (*49*)

Figure 13. Pedestrian Injury Severity Versus Impact Speed: United Kingdom Experience

The same study reviewed crash experience in Florida involving pedestrians in single-vehicle collisions. The results shown in Figure 14 suggest a similar pattern as the UK experience, although the severity of collisions at higher speeds does not appear to be quite as high as the UK experience. A direct comparison is not possible due to the limits of ranges for which data were reported in the cited study. Nonetheless, there is clear evidence that pedestrian safety deteriorates rapidly as vehicle speed increases.



Source: (*49*)

Figure 14. Pedestrian Injury Severity Versus Impact Speed: Florida Experience (1993-1996)

For this research effort, the authors examined the speed, geometric, and crash data collected for NCHRP 3-65 to determine whether any trends could be established between design speed and crash experience. The analysis examined crash and geometric data from 112 individual approaches. Two groupings of crashes were examined that are expected to have some relationship to entry speed: entering-circulating crashes (as determined by the NCHRP 3-65 researchers from a review of individual accident reports), and "all" crashes (entering-circulating crashes, plus entering rear-end, approach rear-end, and loss of control crashes).

Table 27 presents the distribution of crash rates (measured as crashes per million entering vehicles) by entry speed, which accounts for deceleration into the roundabout (V_1, adjusted) using the methodology described previously. Crashes have been grouped into a series of speed bins, and each bin shows five percentiles—5th, 25th, 50th, 75th, and 95th—to give a sense for the distribution of crashes within each speed bin. Figure 15 presents the same information graphically, grouping the data into two larger bins: 0-25 mph and 25-40 mph. Although the sample size is relatively small, the graphs generally suggest that the median crash rate increases with speed. However, the variation from site to site within a speed bin is considerable, with some sites with higher speeds having better safety performance than some sites with lower speeds. Indeed, the graphs suggest that although design speed appears to be a factor affecting the mean safety performance, factors other than design speed may contribute significantly to the safety performance of an individual roundabout.

Table 27. Distribution of Entry-Circulating Crash Rates by Adjusted Entry Speed

Speed Bin	**0-20 mph**	**20-25 mph**	**25-30 mph**	**30-40 mph**
Number of Observations	19	48	32	13
Mean Crash Rate (entry-circulating crashes per million entering vehicles)	0.31	0.55	0.88	0.55
Standard Deviation of Crash Rate	0.59	0.92	1.06	0.80
5th-percentile	0.00	0.00	0.00	0.00
25th-percentile	0.00	0.00	0.09	0.14
50th-percentile	0.00	0.15	0.49	0.41
75th-percentile	0.31	0.71	1.22	0.51
95th-percentile	1.56	2.23	3.19	1.74

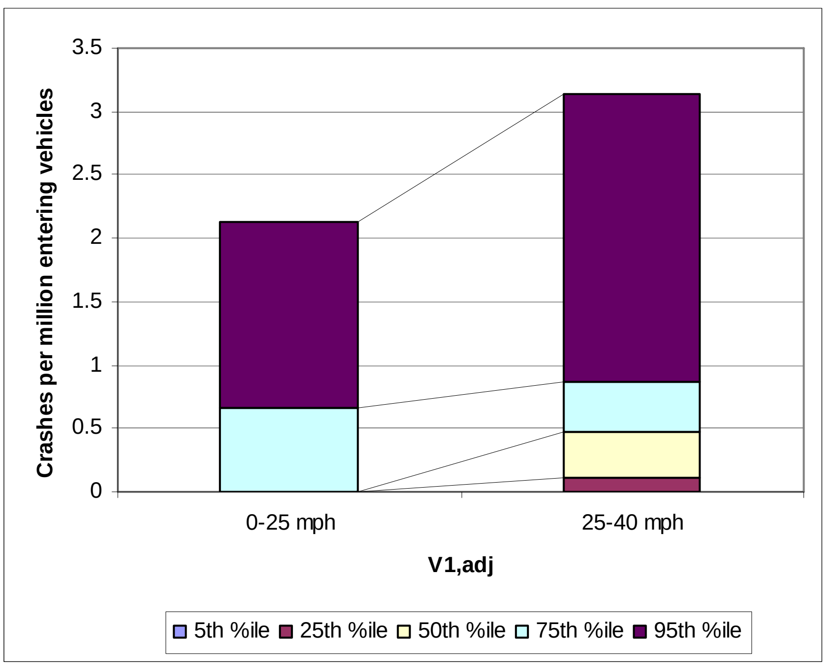


Figure 15. Vehicle Crash Rate Versus Adjusted Entry Speeds Accounting for Deceleration

More revealing information can be revealed when comparing the crash rate with the speed differential, as measured by the difference between predicted entry speed, V_1, and predicted left-turn circulating speed around the central island, V_4. As before, both unadjusted and adjusted entry speeds were used. Table 28 and Figure 16 show a speed differential of more than 20 mph between an unadjusted entry speed and the circulating speed appears to correspond to an increase in entry-circulating crashes. In particular, the figure shows that fewer than 50 percent of the sites with unadjusted speed differentials less than 20 mph show any entry-circulating crashes, whereas more than 75 percent of the sites with speed differentials greater than 20 mph show some crashes. This suggests that the recommendations in the current FHWA Guide of maximum speed differentials of 12 mph appears more conservative than necessary when using unadjusted entry speeds, and there does not appear to be justification for a more stringent speed differential requirement of 6 mph.

Table 28. Distribution of Entry-Circulating Crash Rates by Differential between Unadjusted Entry Speed and Circulating Speed

Speed Bin	0-20 mph	20-35 mph
Number of Observations	97	15
Mean Crash Rate (entry-circulating crashes per million entering vehicles)	0.15	0.53
Standard Deviation of Crash Rate	0.35	0.64
5th-percentile	0.00	0.00
25th-percentile	0.00	0.07
50th-percentile	0.00	0.40
75th-percentile	0.15	0.58
95th-percentile	0.99	1.97

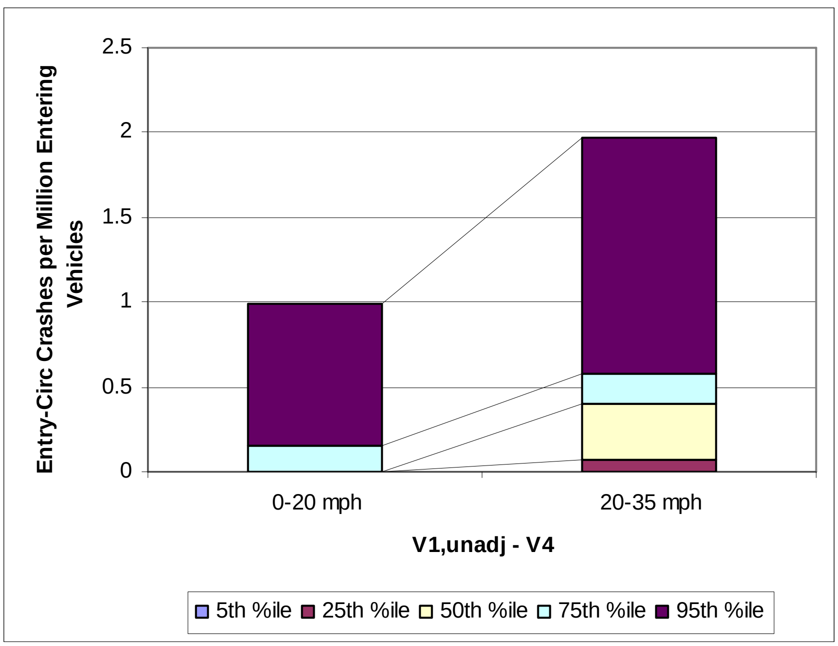


Figure 16. Entry-Circulating Vehicle Crash Rate Versus Differential in Speed between Unadjusted Entry Speeds and Conflicting Circulating Speeds

The trend becomes even clearer when the speed differential between adjusted entry speeds (entry speeds adjusted for deceleration) and circulating speeds is examined. The data in Table 29 and the graph in Figure 17 shows that a speed differential of more than 10 mph between an adjusted entry speed and the circulating speed appears to correspond to an increase in entry-circulating crashes. At least 75 percent of the sites with adjusted speed differentials of 10 mph or less had no reported entry-circulating crashes, whereas at least 50 percent of the sites with adjusted speed differentials of more than 10 mph had at least one entry-circulating crash. Therefore, the FHWA

Guide's recommendation for a maximum speed differential of 12 mph appears to be reasonable if the entry speeds are adjusted for deceleration effects. There appears to be no justification for a more stringent use of a 6 mph speed differential.

Table 29. Distribution of Entry-Circulating Crash Rates by Differential between Adjusted Entry Speed and Circulating Speed

Speed Bin	**0-10 mph**	**10-20 mph**
Number of Observations	65	47
Mean Crash Rate (entry-circulating crashes per million entering vehicles)	0.11	0.34
Standard Deviation of Crash Rate	0.30	0.51
5^{th}-percentile	0.00	0.00
25^{th}-percentile	0.00	0.00
50^{th}-percentile	0.00	0.14
75^{th}-percentile	0.00	0.43
95^{th}-percentile	0.65	1.57

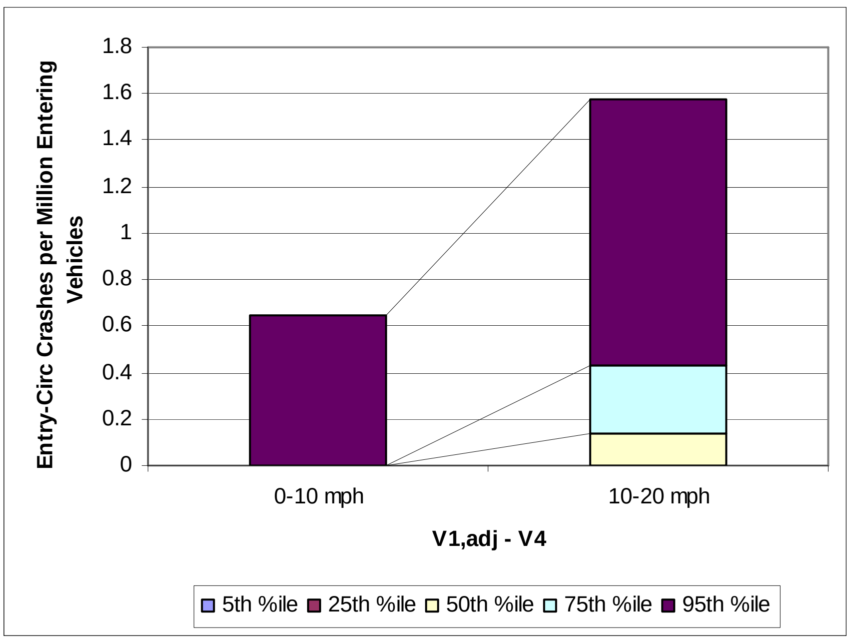


Figure 17. Entry-Circulating Vehicle Crash Rate Versus Differential in Speed between Entry Speeds Adjusted for Deceleration and Conflicting Circulating Speeds

The conclusions from this work are as follows:

- While speed prediction for the various movements through a roundabout is reasonably accurate, the data show a trend between increased speeds and increased crash experience. However, this trend is not necessarily statistically conclusive. Many sites in the NCHRP 3-65 database experienced very few crashes, if any, and the variation between the sites with nonzero crash rates can be significant.

- The NCHRP 3-65 data generally support the use of a threshold of 25 mph for an entry speed adjusted for the effects of deceleration. However, the resulting crash experience can vary significantly among sites.

- Speed differentials of more than 20 mph between unadjusted entry speeds (based solely on entry path radius) and left-turn circulating speeds, or 10 mph between adjusted entry speeds (accounting for deceleration) and left-turn circulating speeds, appear to correspond to an increase in entry-circulating crashes. Therefore, the FHWA Guide's recommendation for a maximum speed differential of 12 mph appears to be supported if the entry speeds are adjusted for deceleration effects.

4.5. Design Vehicle

Design vehicle accommodation often plays a major role in roundabout design. The roundabout geometry should generally accommodate the swept path of the vehicle tires and body. Because designing for large semi-trailers generally has adverse effects on the ability to manage speeds (e.g., wider lanes and larger radii for trucks results in faster speeds for passenger cars), truck aprons are often used around the perimeter of the central island. Truck aprons are typically elevated above the surface of the circulatory roadway to discourage passenger car use, while providing a mountable surface for semi-trailers to traverse.

Figure 18 displays a sample swept path for a typical semi-trailer making a left turn and a right turn.

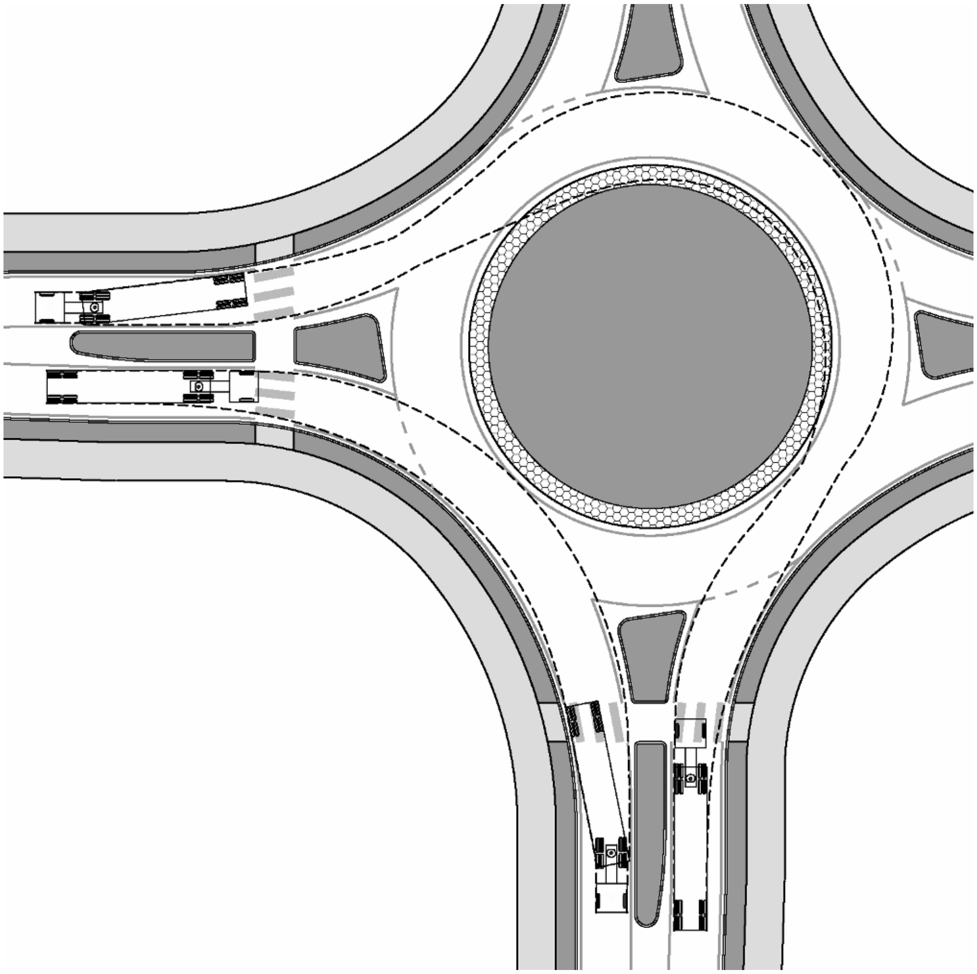


Figure 18. Design Vehicle Swept Path

4.5.1. Selection of Design Vehicle

According to the FHWA Guide, the choice of a design vehicle will vary depending upon the approaching roadway types and the surrounding land use characteristics. Local and state agencies who maintain the roadway should be consulted to identify an appropriate design vehicle at each site. Commonly, WB-50 vehicles are the largest vehicles along collectors and arterials. Larger trucks, such as WB-67, may need to be addressed at intersections on interstate freeways or state highway systems. Smaller design vehicles may often be chosen for local street intersections.

In California, trucks with single 48-foot semi-trailers represent the most common large vehicle; these are represented by the STAA Design Vehicle (for routes on the National Network and Terminal Access Routes) or the California Legal Design Vehicle (for all other facilities in California), as described in the California *Highway Design Manual* Section 404.2 *(4)*. Smaller design vehicles such as emergency vehicles may often be chosen for local street intersections, although large moving trucks may use such intersections on occasion.

States have adopted different policies to determine design vehicles to use. For example, according to the Washington State Department of Transportation (*46*), it is desirable to design the circulating roadway so that a BUS design vehicle in urban areas and a WB-40 in rural areas can use the roundabout without encroaching on the truck apron. Roundabouts on Washington's state routes need to be designed to handle a WB-67 design vehicle using truck aprons as appropriate.

The Kansas Department of Transportation (*2*) also identifies typical design vehicles for various roadway types. For freeway ramp terminals and other intersections on the state highway routes, the design vehicle is normally a WB-67. At urban collector or arterial intersections, the design vehicle is often a WB-50 semi-trailer. For urban intersections, a bus or single-unit truck is commonly used.

Recent research by Harwood et al. *(50)* has suggested that the WB-50 design vehicle is no longer common in the U.S. truck fleet and that the WB-62 design vehicle is more common.

It is generally common practice to have passenger vehicles completely contained within the circulatory roadway of the roundabout and to only allow truck trailers to track onto a truck apron.

4.5.2. Multilane Design Vehicle Considerations

At multilane roundabouts, the choice of design vehicle is more complex than for single-lane cases. In most cases, it is not feasible and not necessary to accommodate two semi-trailer vehicles side-by-side through the roundabout. Semi-trailers are usually allowed to track over lane markings within the roundabout entries, circulatory roadway, and exits. However, there is a certain combination of side-by-side vehicles that should be accommodated at each given roundabout design.

Table 30 summarizes guidance available through national and state agencies on the subject of accommodating side-by-side vehicle circulation in roundabouts. Information from Australia is also included in the table. Most agencies include in their guidance the caveat that site-specific conditions should be taken into account to appropriately identify the design vehicle (or pair of design vehicles).

Table 30. Guidance on Multilane Circulatory Roadway Width

Agency	Source	Inscribed Circle Diameter	Circulatory Roadway Width for WB-67 Design Vehicle	Recommended Pair of Side-by-Side Vehicles for Design
FHWA	*Roundabouts: An Informational Guide* (*1*)	180 feet	30 feet (minimum)	• Depending on site conditions: • Two passenger cars OR • Passenger car + single-unit truck OR • Semi-trailer + passenger car OR • Semi-trailer + single-unit truck
Kansas DOT	*Kansas Roundabout Guide (2)*	180 feet	30 feet (minimum)	• Depending on site conditions: • Passenger car + bus OR • Passenger car + single-unit truck OR • Semi-trailer + passenger car
Washington State DOT	*WSDOT Design Manual (46)*	N/A	• Maintain 2-ft clearance to any curb face • Minimum circulatory with equal to or slightly wider (120%) than maximum entry width.	N/A
New York State DOT	*Roundabouts: Interim Requirements and Guidance (45)*	N/A	Maintain 3-ft horizontal clearance	N/A
Missouri DOT	*Project Development Manual*	N/A	N/A	Two trucks (type and size not specified)
Wisconsin DOT	*Facilities Development Manual (9)*	N/A	N/A	N/A
Pennsylvania DOT	*Guide to Roundabouts (44)*	N/A	N/A	N/A
Florida DOT	*Florida Roundabout Guide (43)*	N/A	Will not normally exceed 1.2 times the maximum entry width	N/A
Oregon DOT	*Modern Roundabouts for Oregon (41)*	N/A	Will not normally exceed 1.2 times the maximum entry width	N/A
Austroads	*Design Guide For Roundabouts (14)*	180 feet	32 feet	• 1 articulated vehicle + 1 car

4.5.3. Potential Intersection Applications

Table 31 provides a list of potential design vehicle guidelines based on the functional class of intersecting roadways.

Table 31. Potential Design Vehicles by Roadway Type

Approach Roadway Type	Typical Single-Vehicle Accommodation	Typical Side-by-Side Accommodation
Single-Lane Non-State Highway	WB-50	--
Single-Lane State Highway off National Network	STAA or California Maximum	--
Single-Lane State Highway on National Network	STAA	--
Multilane Non-State Highway	WB-50 or STAA/California	Bus and Passenger Car
Multilane State Highway off National Network	STAA or California Maximum	Bus/Motorhome and Passenger Car
Multilane State Highway on National Network	STAA	Bus/Motorhome and Passenger Car

The potential guidelines in Table 31 are typical applications and will not apply in all cases. It may be appropriate, for example, to design a roundabout located off the state highway system to accommodate an STAA vehicle if the area is in an industrial district. In addition, the combination of side-by-side vehicles at multilane roundabouts may vary depending on site-specific considerations. For instance, if the percentage of truck traffic is considerable and a given roundabout approach is expected to operate at or near its capacity limit, it may be desirable to accommodate the design vehicle and a passenger car simultaneously through the roundabout. However, it should be understood that such a design will likely require such wide lanes and/or large turning radii that speed control and overall safety may be compromised.

Accommodating an STAA vehicle and passenger car side-by-side is frequently infeasible at double-lane roundabouts, because the STAA vehicle would require lane widths of approximately 20 feet. At a three-lane roundabout, it could be possible to accommodate an STAA vehicle and one passenger car simultaneously due to the generally wider circulatory roadway.

Figure 19, Figure 20, and Figure 21 display example swept paths of design vehicles at single-lane non-state highway, single-lane state highway, and multilane roundabouts, respectively.

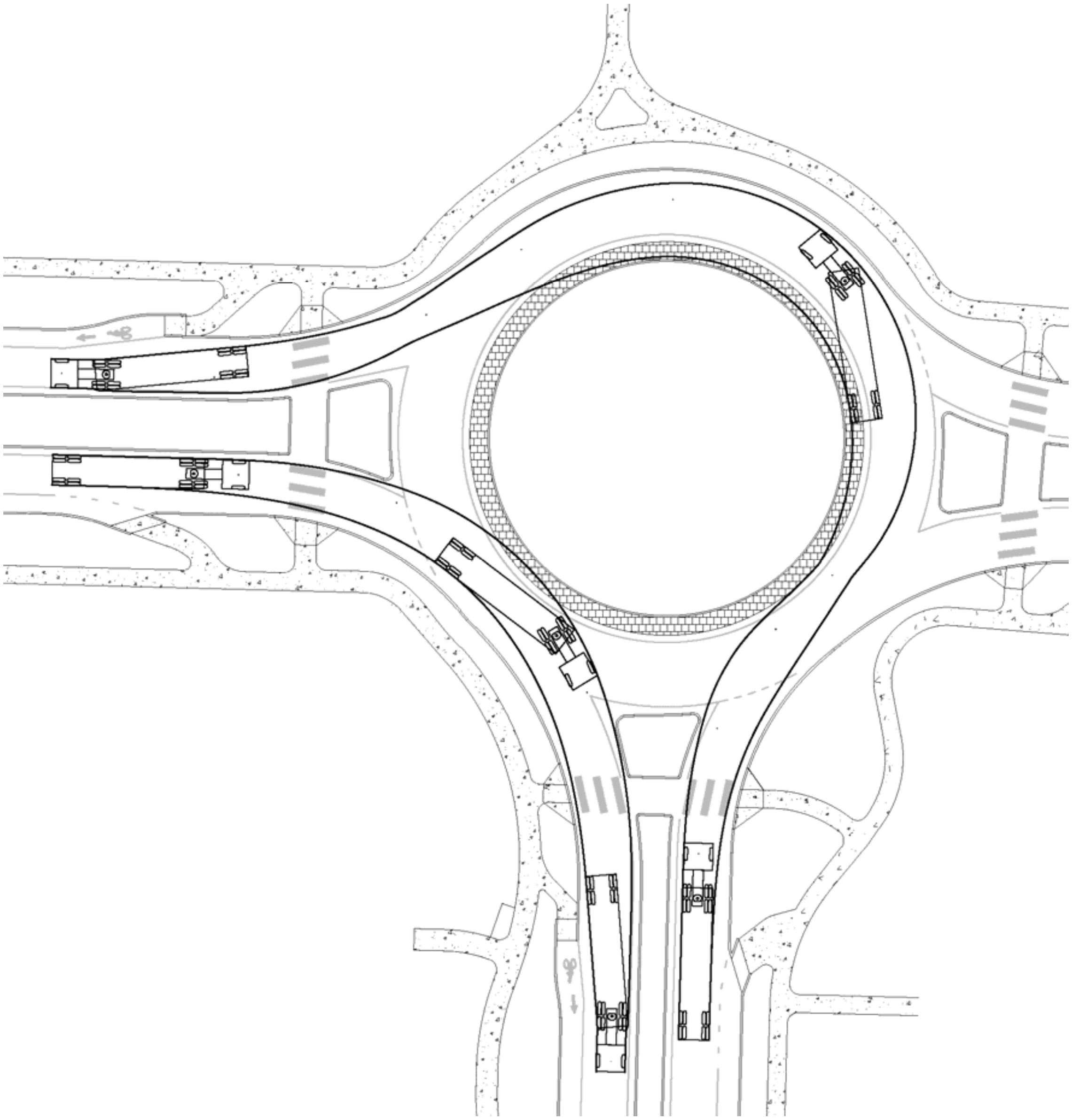


Figure 19. WB-50 Swept Paths, Single-Lane Non-State Highway Roundabout

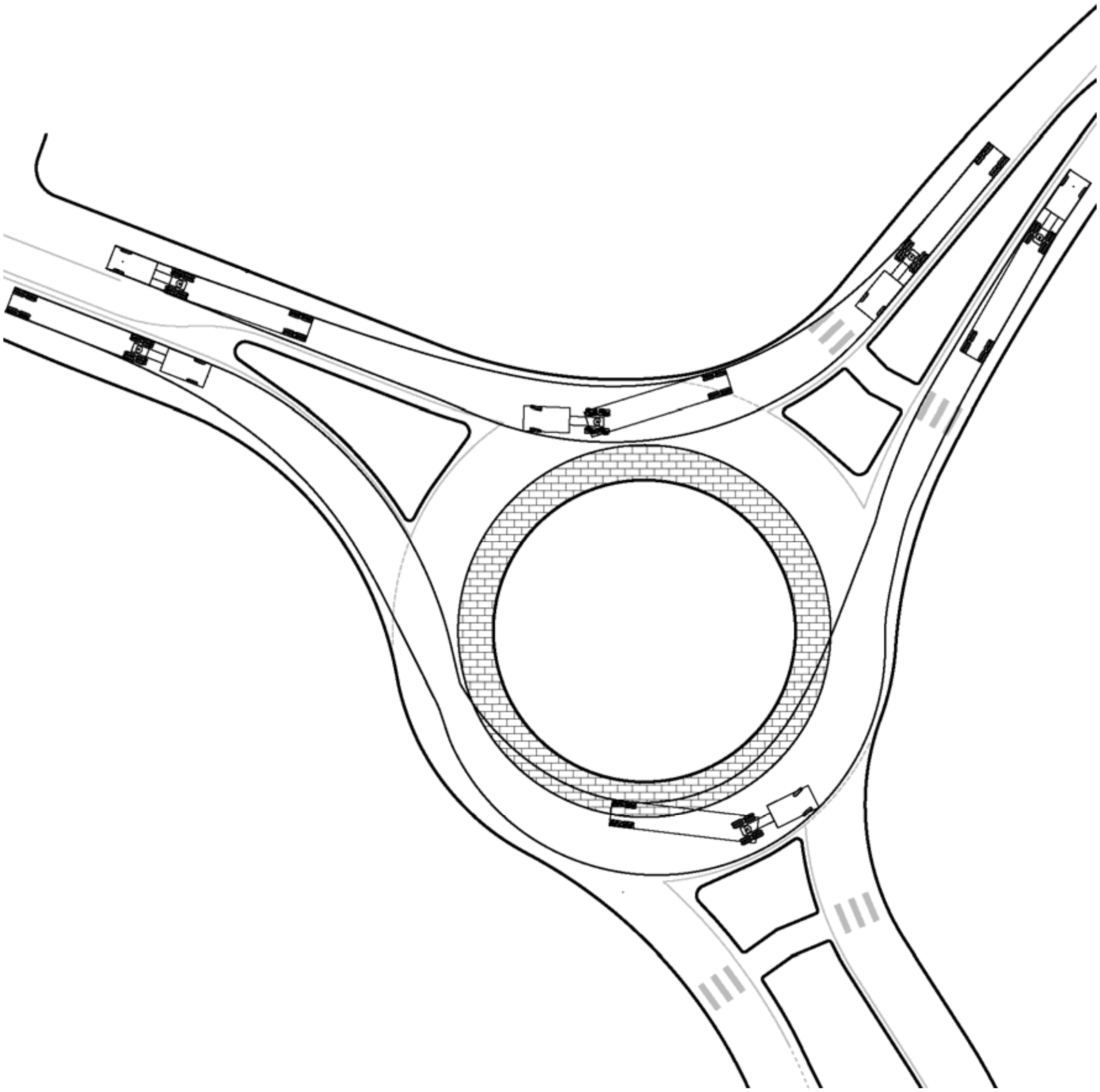


Figure 20. STAA Vehicle Swept Paths, Single-Lane State Highway Roundabout

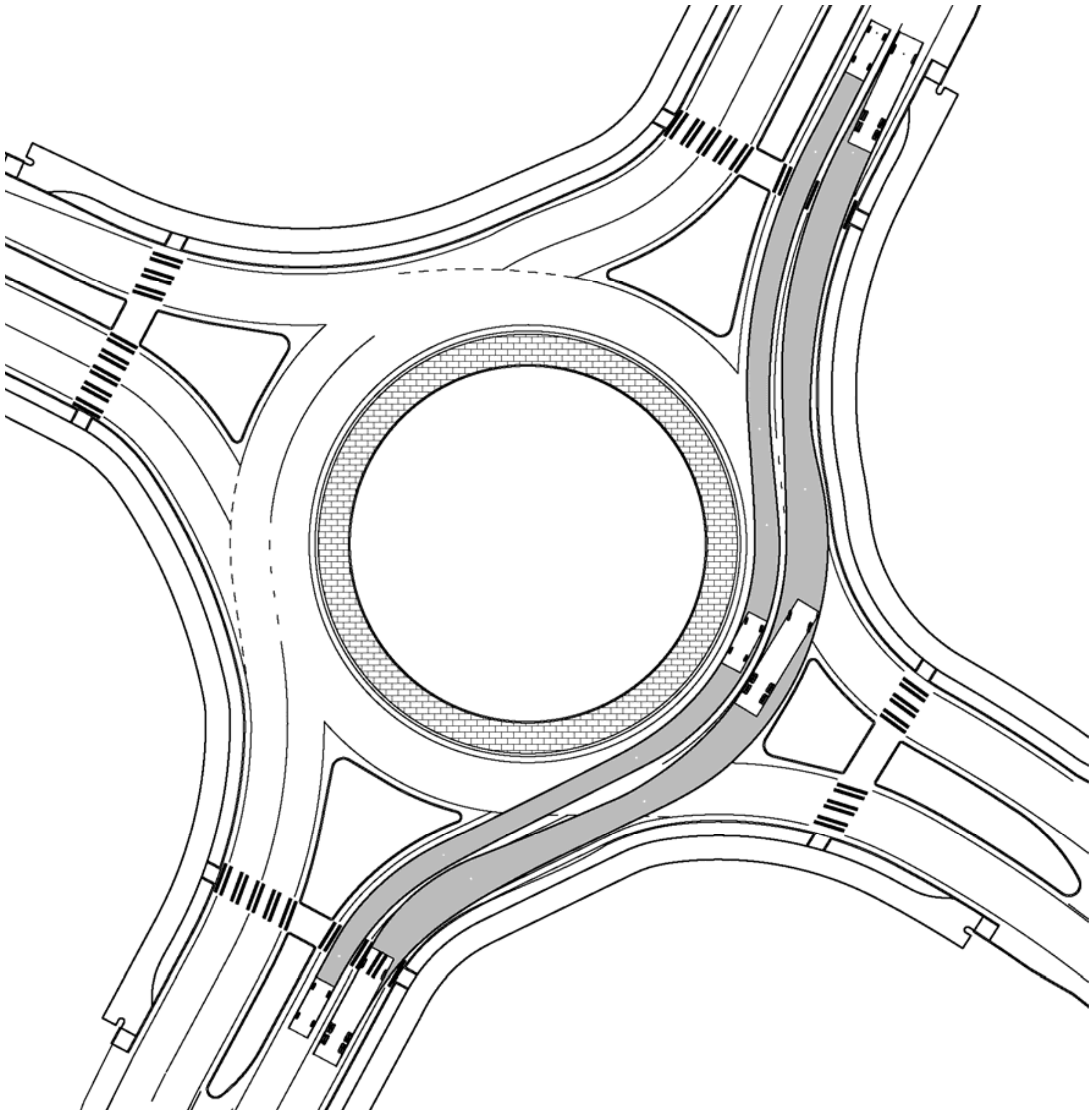


Figure 21. Bus and Passenger Car Swept Paths, Multilane Roundabout

4.6. Spacing of Entries and Exits

The spacing of entries and exits is particularly important at roundabouts with more than four legs, roundabouts with skewed legs, and multilane roundabouts. This section discusses two key components: entry-exit separation and consecutive entries.

4.6.1. Entry-Exit Separation

At multilane roundabouts, problems can occur when there is too much separation between the entry and exit of adjacent legs. The problem occurs when vehicular paths from the entry merge with the vehicular paths in the circulatory roadway and then diverge at the next exit. Under this type of design, an entering vehicle in the outside lane may be tempted to enter next to a circulating vehicle in the inside lane. Depending on the turning movement pattern of each vehicle (e.g., both vehicles are intending to make through movements), this may cause an exit-circulating conflict. Figure 22 displays an example of a roundabout design with this problem. Note that this example has the same lane configuration as the roundabout presented previously in Figure 11; however, the intersection skew creates a section of circulatory roadway between an entry and subsequent exit for which the striping creates an exit-circulating path conflict.

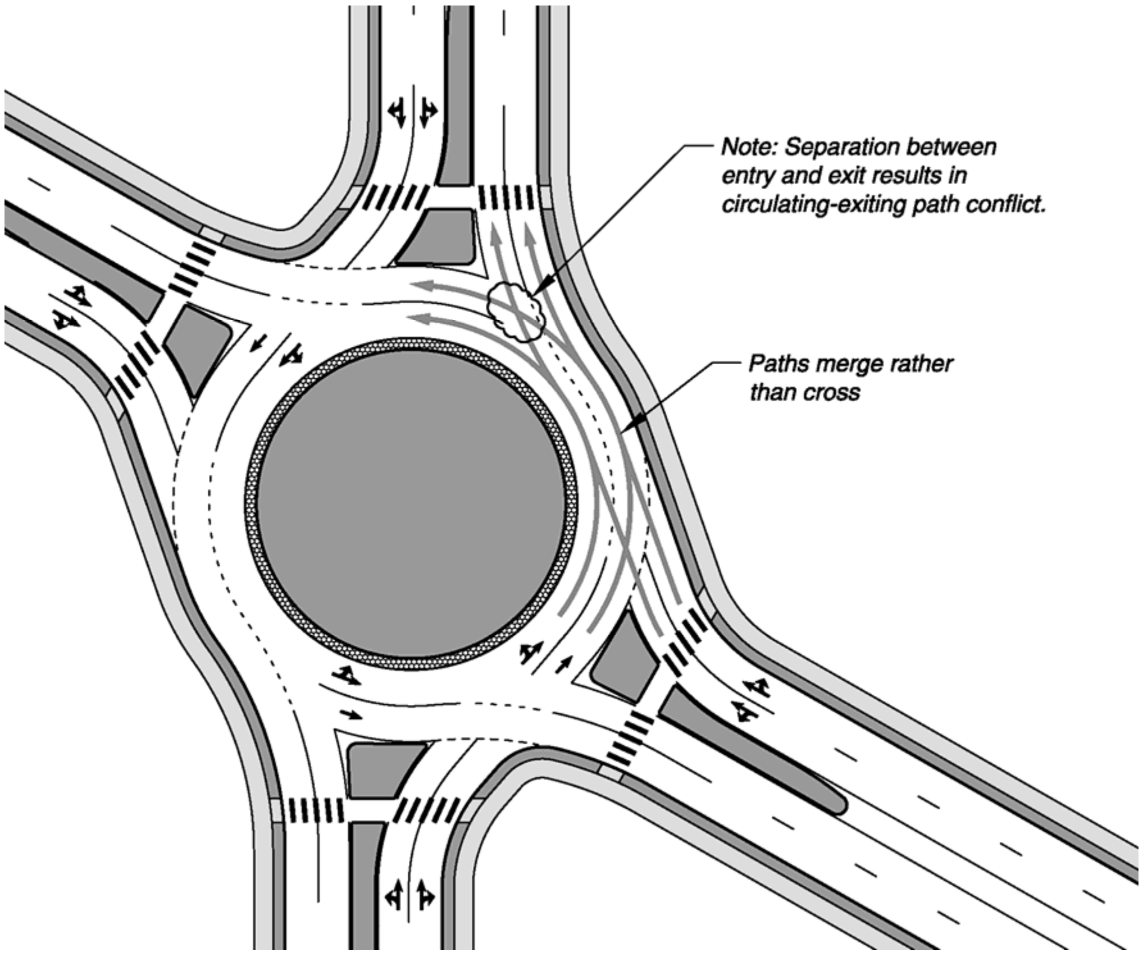


Figure 22. Example Design with Circulating-Exiting Path Conflict

In this example, the design consists of double-lane entries and double-lane exits at all approaches. The separation between legs causes the entry and circulatory paths to merge, creating conflicts at the downstream exit.

At least two general solutions to the problem exist. One solution, shown in Figure 23, maintains the basic approach alignments but modifies the lane assignments. In this case, the right lane of the westbound approach is converted to a right-turn only lane. An alternative solution (not shown) could be converting the left lane of the northbound approach to a left-turn only lane. In either of these cases, the new lane configurations would need to be evaluated under the projected traffic volumes to determine whether they would provide adequate capacity.

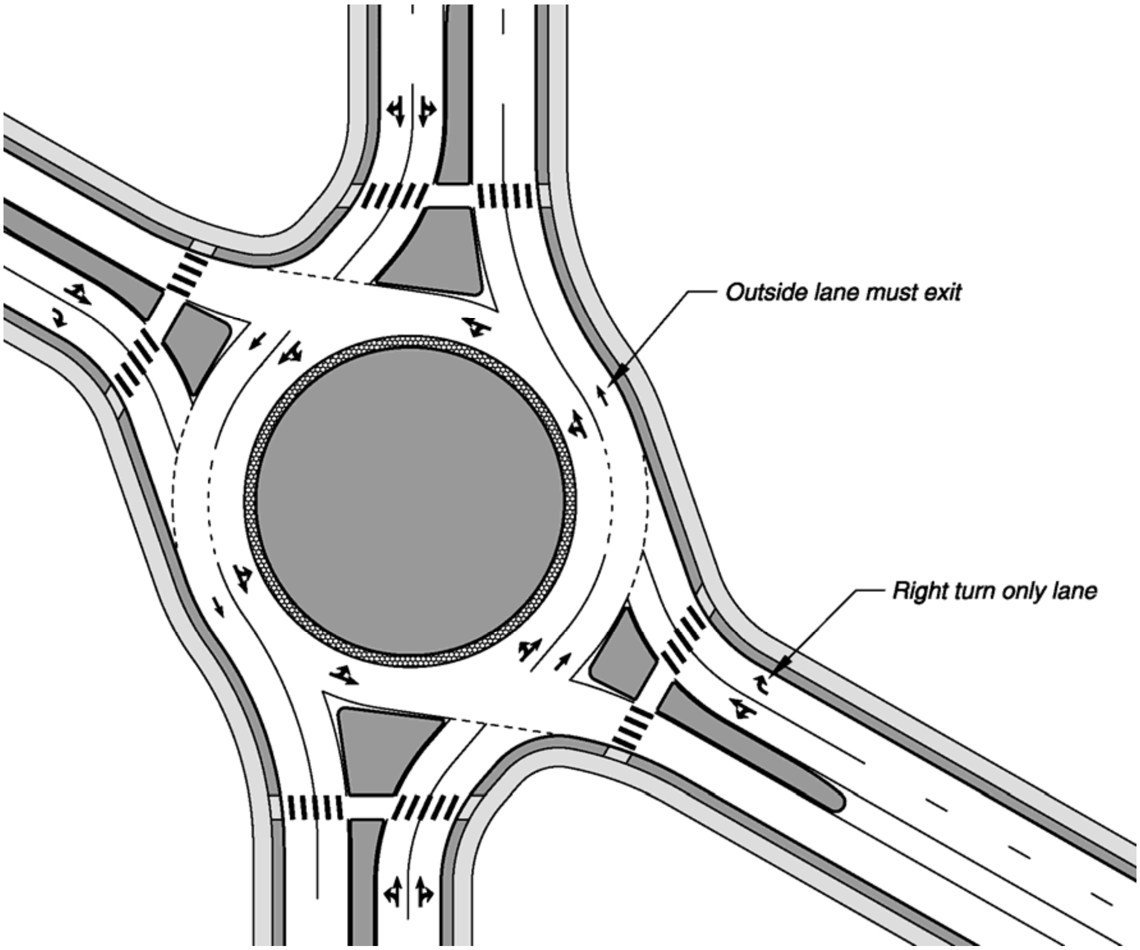


Figure 23. Solution Option #1: Modify Lane Configuration

A second general solution option, shown in Figure 24, would be realigning one or more approaches to reduce the separation between legs. As shown in the figure, realigning the eastbound approach creates a more perpendicular intersection angle and results in entry-circulating paths that cross, rather than merge.

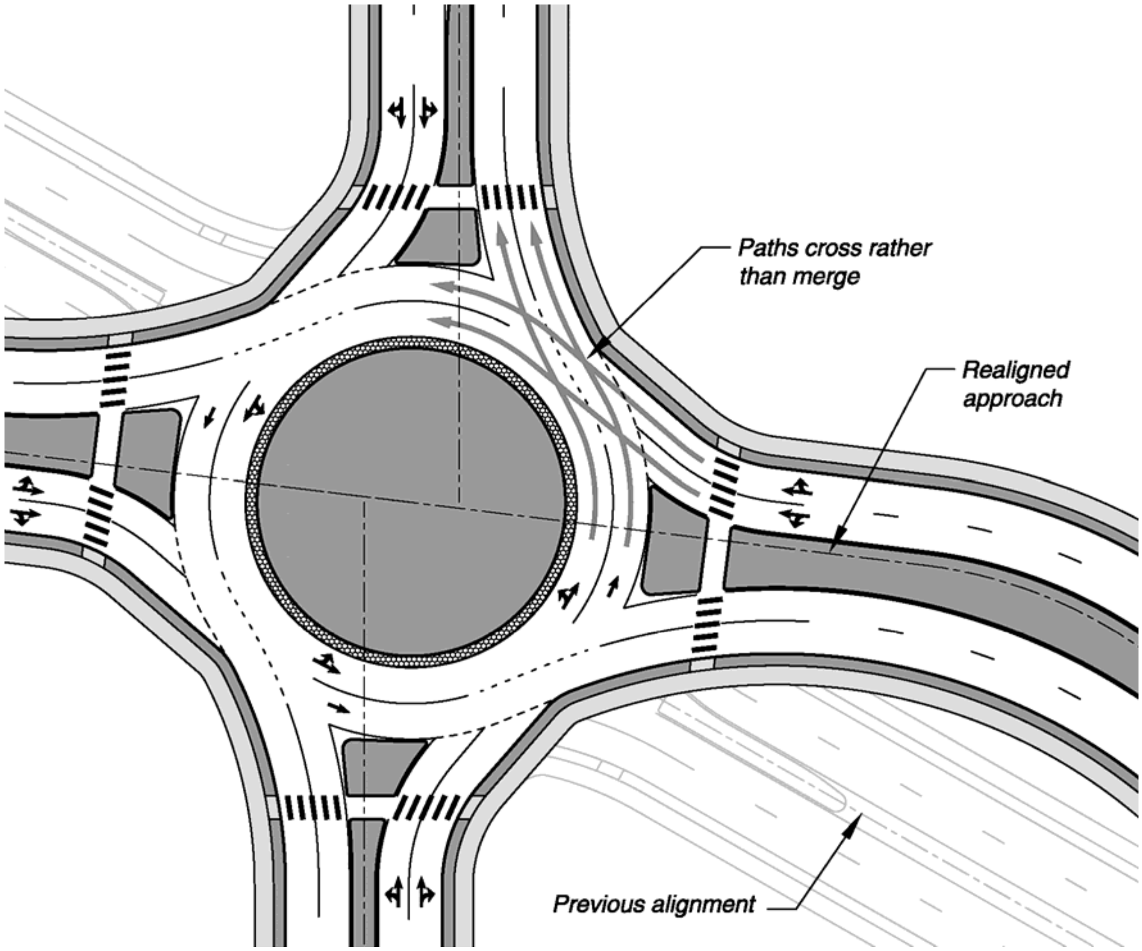


Figure 24. Solution Option #2: Realign Approaches

4.6.2. Design of Consecutive Entries

For most roundabouts, an exit is located between a subject entry and the immediate upstream entry. However, at roundabouts involving one-way roadways, it is possible for two entries to be located immediately adjacent to one another. This is particularly common at interchange ramp terminals. The close spacing of these entries can present a unique challenge to the design.

The primary issue that can occur is that the angle between the consecutive entries becomes overly acute, which can cause problems because drivers may not be able to physically turn their heads back far enough and left to view oncoming traffic from the immediate upstream entry.

In general, the intersection angle between consecutive roundabout entries, and indeed the angle of visibility to the left for all entries, should conform to the same design guidelines as for conventional intersections. AASHTO recommends avoiding intersection angles of less than 60 degrees *(48)*. The Caltrans *Highway Design Manual* recommends intersection angles of no less than 75 degrees for at-grade intersections *(4)*, and FHWA's *Highway Design Handbook for*

Older Drivers and Pedestrians also recommends using 75 degree as the minimum intersection angle *(51)*.

At roundabouts, the intersection angle may be measured as the angle between a vehicle's alignment at the yield line and the sight line required according to intersection sight-distance guidelines.

Figure 25 displays an example of a roundabout design at an interchange in which the angle between entries is more severe than desirable.

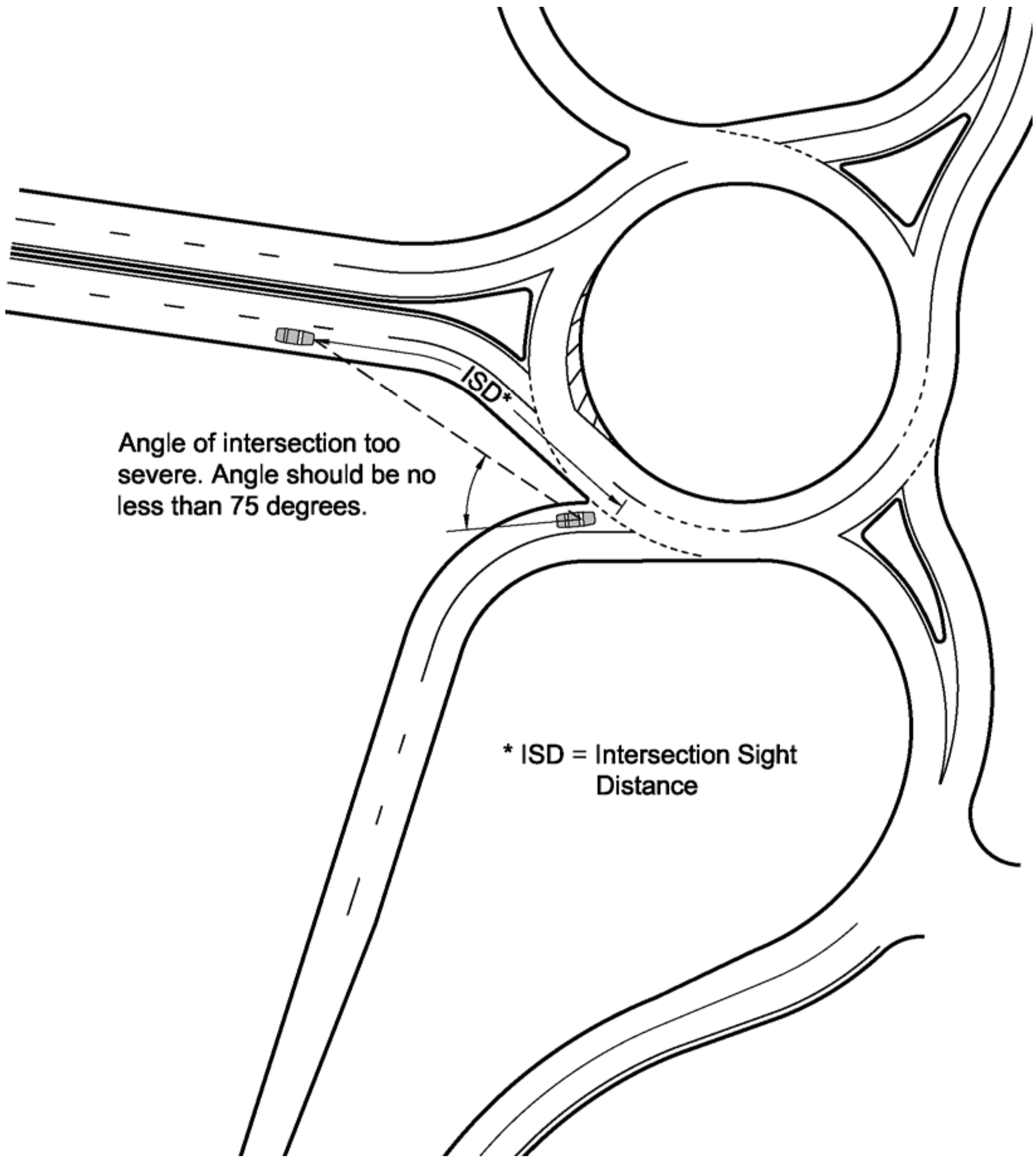


Figure 25. Example Design with Angle of Visibility to Left That Is Too Severe

In the design in Figure 25, the angle between the driver and the position of oncoming traffic is less than the recommended 75 degrees. A possible solution, in this case, would be realigning the off-ramp approach, as shown in Figure 26, to improve the intersection angle.

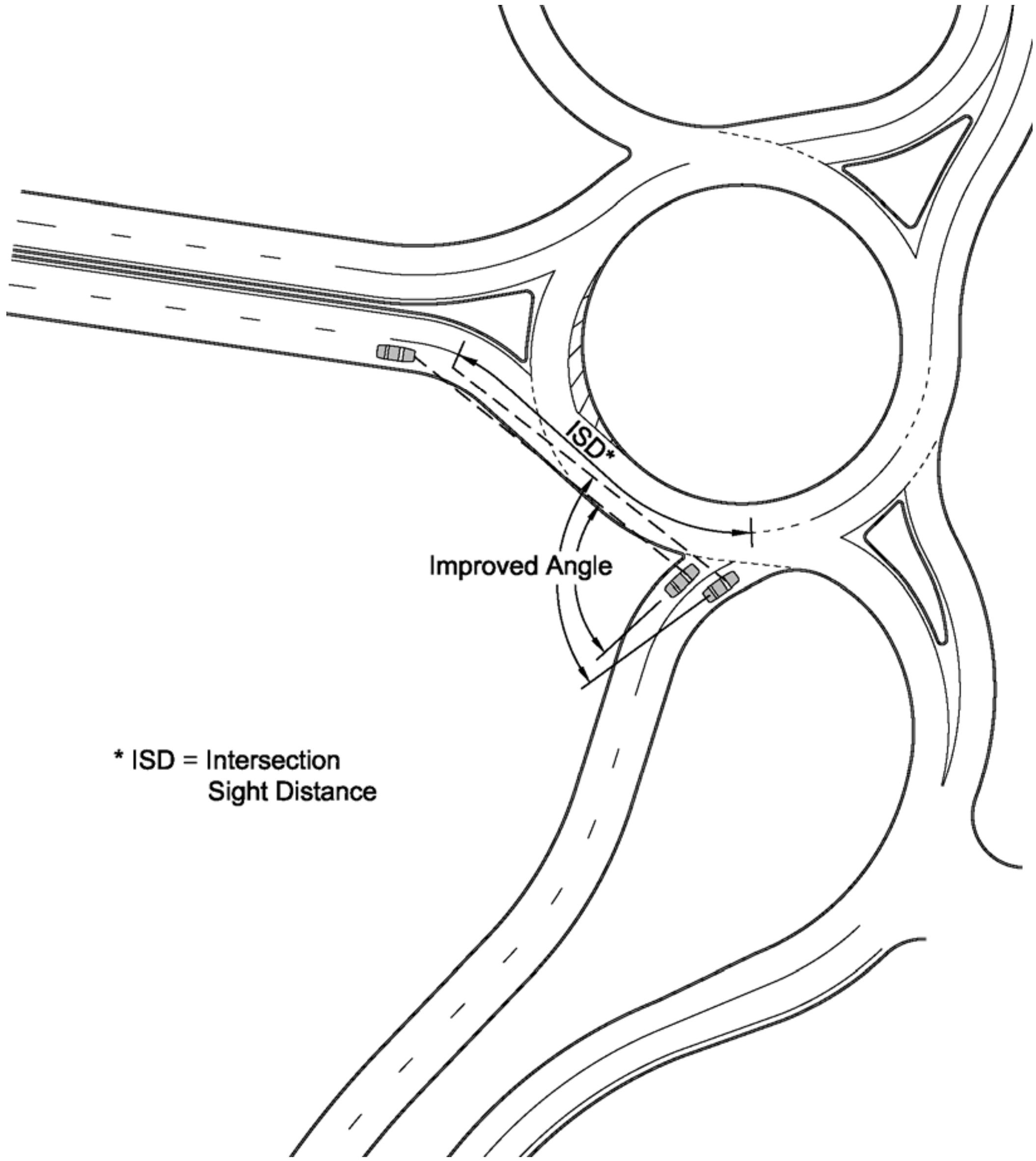


Figure 26. Roundabout with Realigned Ramp Terminal Approach to Provide Better Angle of Visibility to Left

4.7. Inscribed Circle Diameter

The inscribed circle diameter (ICD) is one of the major dimensions in roundabout design. It represents the overall size of a roundabout and is usually determined by a number of design parameters such as design speed, design vehicle, number of lanes, and natural path alignment. An iterative process is usually required to determine the optimal ICD size.

The ICD is the most common dimension used to describe the overall size of a roundabout. Table 32 summarizes the FHWA Guide recommendations and notes where states have deviated. As can be seen in the table, some states identify broader ICD ranges than those provided in the FHWA Roundabout Guide. Although slightly deviated from the FHWA guide, both the Kansas and Arizona guides have similar recommendations due to similar authorship. In practice, it is not uncommon that the actual value may fall outside these typical ranges.

Table 32. Typical Inscribed Circle Diameter Ranges

Roundabout Category*	**Inscribed Circle Diameter Range (ft)**		
	FHWA	**Kansas/Arizona**	**Wisconsin**
Mini-Roundabout	45-80	50-90	N/A
Urban Compact	80-100	90-120	N/A
Urban Single Lane	100-130	120-150	100-160
Urban Double Lane	150-180	150-220	150-200
Urban Multilane (3 or 4-lane entry)	N/A	N/A	180-330
Rural Single Lane	115-130	130-200	115-180
Rural Double Lane	180-200	175-250	180-230
Rural Multilane (3 lane entry)	N/A	N/A	180-330

*Note: Roundabouts are categorized based on the size of the ICD, the number of circulating lanes, and urban/rural environment. Refer to the FHWA Guide for further details.

Although ICD is an important dimension when laying out a roundabout, it is a byproduct of multiple factors rather than a critical input chosen on its own. These factors include the following:

- *Lane numbers and arrangements.* The number of lanes that a roundabout needs to serve has the largest influence on the ICD. Two-lane roundabouts generally have larger ICDs than single-lane roundabouts to accommodate a greater number of lanes. Likewise, roundabouts with more than two lanes are generally larger than two-lane roundabouts. Note that overly large ICDs with multilane roundabouts can create entry-exit separation problems.

- *Design vehicle.* The design vehicle that a roundabout must accommodate can have a direct influence on the ICD. This is particularly true of single-lane roundabouts, where the design vehicle has the most direct influence on ICD. It can also have some influence on multilane roundabouts, depending on how trucks are expected to circulate within the roundabout. See the previous section on design vehicle for a more detailed discussion.

- *Number of legs.* Roundabouts with more than four legs are typically larger than roundabouts with four legs, given the same number of lanes. This is necessary, in part, to facilitate turning movements between consecutive legs.

- *Approach alignment.* The alignment of individual approaches affects the appropriate ICD for the roundabout. Angles less than 90 degrees between consecutive legs sometimes require a larger ICD to facilitate turning movements between those legs. In addition, a larger ICD may be used as a method to provide adequate speed control for right-turn movements between legs that are greater than 90 degrees apart.

Due to the interactive and sometimes conflicting nature of these elements, the ICD is often the result of an iterative process that attempts to balance competing objectives. As a result, there is no one correct ICD for a given roundabout, provided that the overall objectives for the roundabout are met. Table 33 provides common ICDs for a variety of situations, for illustration purposes; successful exceptions may be found in the field.

Table 33. Common Ranges of Inscribed Circle Diameters

Scenario	**Common Range of Inscribed Circle Diameters***
Single-lane roundabout, 3 to 4 legs, 90-degree angles, WB-50 design vehicle	115**–130 ft
Single-lane roundabout, 3 to 4 legs, 90-degree angles, STAA/WB-67 design vehicle	130–150 ft
Single-lane roundabout, 5 to 6 legs, WB-50 design vehicle	130–180 ft
Single-lane roundabout, 5 to 6 legs, STAA/WB-67 design vehicle	150–200 ft
Double-lane roundabout, 3 to 4 legs	150–220 ft
Double-lane roundabout, 5 to 6 legs	180–240 ft
Triple-lane roundabout, 4 legs	180–330 ft

* Ranges are representative but not inclusive of all possible values
** Smaller diameters are possible but may require trucks to circulate at very low speeds
Source: Adapted from FHWA (*1*), Kansas (*2*), and Wisconsin (*9*) roundabout guidance, as well as the authors' experience and judgment.

While the preceding discussion assumes a single ICD representing the entire roundabout, this is only true if the roundabout is circular in shape. Non-circular roundabouts (e.g., elliptical roundabouts) are sometimes the best choice for an intersection to balance the competing objectives.

In some cases, the ICD may reflect an anticipated ultimate configuration rather than a near-term, interim configuration. For example, it may be appropriate to design a single-lane roundabout with 4 legs and an STAA design vehicle with an ICD of 180 ft if it has been designed for potential future conversion to a double-lane roundabout, even though the "typical" ICD for a single-lane roundabout is much smaller.

4.8. Roundabouts in High-Speed Environments

Roundabouts have demonstrated success in high-speed environments. Recent NCHRP 3-65 research has found that roundabouts located in rural environments (commonly associated with speeds of 55 to 65 miles per hour) has improved crash experience compared to previous control (typically two-way stop control): 72 percent reduction in all crashes (standard error of 4 percent) and 87 percent reduction (standard error of 3 percent) (*7*, Table 28).

The authors believe that the following features of the roundabout are likely to have contributed to the reported safety record:

- The shape of a roundabout physically prevents the type of high-speed angle and head-on collisions that cause fatalities and severe injuries at conventional intersections.

- The predictably slow speed of all traffic through a roundabout provides consistency in speed through the intersection. Speeds at signalized intersections vary widely from full running speed to completely stopped conditions, and two-way stop-controlled intersections have significant speed differentials between through traffic and turning traffic. These speed differentials are often the source of rear-end crashes and angle-collisions due to misjudged gaps.

- The low-speed design of the roundabout reduces the likely severity of any type of collision, should it occur.

A high speed environment requires adequate time (distance) for drivers to interpret the impending intersection configuration and to appropriately react (slow down) to the changing operational needs. A longer distance between the roadway typical section and the roundabout entry (combined with cross-sectional features that reinforce the change from the upstream typical section), creates more opportunities for drivers to reduce speed, compared with the traditional roundabout approach configuration. The design of a roundabout in a high-speed rural environment typically employs all of the techniques of roundabouts in a lower speed environment, with greater emphasis on the following items:

- The visibility of the roundabout from a distance. These include the use of a prominent central island, prominent splitter islands, and appropriate illumination and signing.

- Alignment and cross sectional cues to present the intersection geometry to the driver. These include the use of flatter and longer painted tapers in advance of the splitter islands, longer splitter islands, and curbing on approaches. Figure 27 shows a typical roundabout with minimal approach treatments; Figure 28 shows the same roundabout with an extended approach treatment. One possible way to determine appropriate splitter island lengths is to use principles of freeway exit ramp design, which considers the transition from free flow speeds to the speed of the controlling ramp curve. In addition, some agencies have employed reverse curvature on the approach to transition driver speeds, as shown in Figure 29; the use of this technique is under debate.

- Use of signs and pavement markings to supplement the geometric features. These often include larger-sized signs than are typically used in urban areas. In addition, some agencies around the U.S. have supplemental signs and pavement markings with continuously flashing beacons, rumble strips, and/or speed-activated warning signs.

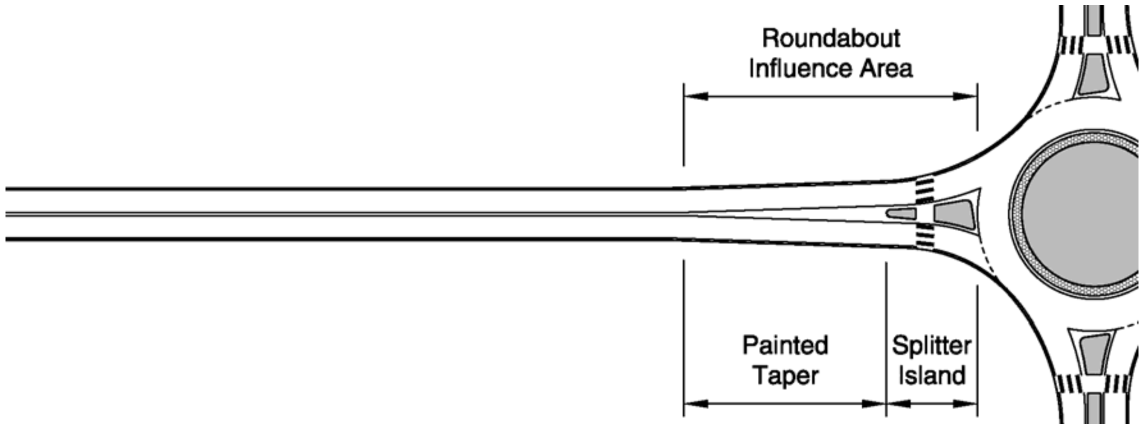


Figure 27. Approach Treatment with Minimal Splitter Island Length

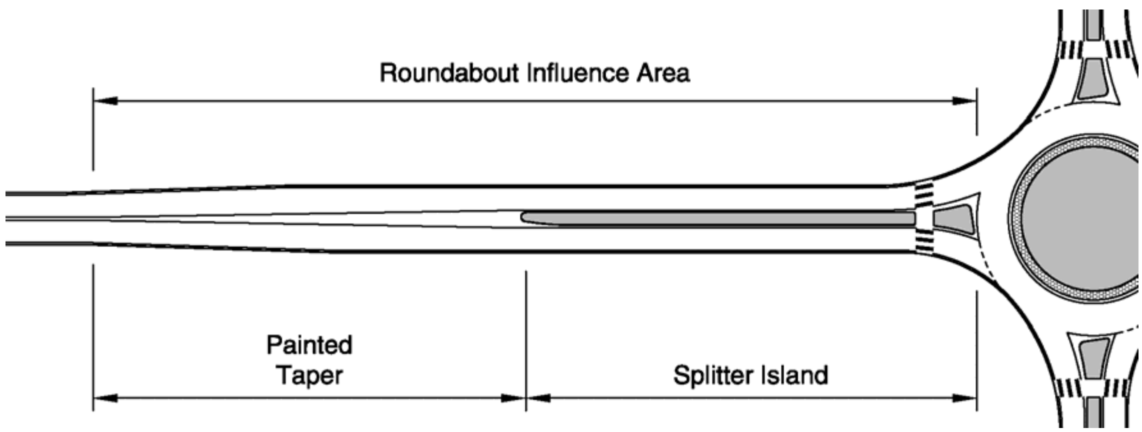


Figure 28. Approach Treatment with Extended Splitter Island Length

Source: W&H Pacific, Inc.

Figure 29. Annotated Photograph of Roundabout in Kittitas County, Washington, Showing Painted Taper and Splitter Island Incorporating Geometric Reverse Curves to Transition Driver Speeds.

4.9. Intersection Sight Distance

The critical headway data discussed previously can be used to provide California-specific calibration of the intersection sight-distance methodology given in the FHWA Guide. Based on the findings from the operational research on California roundabout presented in Chapter 2 of this report, the authors recommend that for California conditions, the value of 6.5 seconds given in Equation 6-3 of the FHWA Guide should be replaced with a value of 5.9 seconds (equal to the mean plus one standard deviation of critical headway for single-lane roundabouts, or 4.8 + 1.1 seconds).

It should be noted that the overall procedure for estimating intersection sight distance at roundabouts should be considered interim until a more comprehensive analysis of intersection sight distance issues unique to roundabouts can be analyzed. One of the anticipated products from the NCHRP 3-65A work to update the FHWA Guide is to prepare a complete research problem statement to support funding of a comprehensive look at intersection sight distance at roundabouts.

4.10. Design Recommendations for Pedestrians

The evidence examined under this research effort (both literature review and field observation of California and other roundabouts) suggests that current design practices for pedestrians at roundabouts generally appear to be appropriate, although further research is needed to develop appropriate treatments to accommodate pedestrians with vision disabilities. The uncontrolled crosswalk treatments appear to operate well for the majority of users (pedestrians and conflicting vehicles). The use of a setback of one to two vehicles from the roundabout appears to be effective. Stopping sight distance needs to be provided so that motorists have the proper time to react after observing a pedestrian using the roundabout crosswalk; the same sight distance requirement helps pedestrian determine the appropriate time to enter the crosswalk. The pedestrian crossing treatments and methodology for selecting treatments as suggested in TCRP Report 112/NCHRP Report 562 should be considered.

For pedestrians with visual impairments, recent and ongoing research suggests that a simple, uncontrolled crosswalk may be insufficient to provide access at some roundabouts, particularly at multilane roundabouts. The Access Board has made the draft recommendation that all pedestrian crossings that span two or more entry or exit lanes be provided with some form of signalization. Research on this treatment and other less restrictive treatments is being conducted as part of NCHRP 3-78 and other studies. The authors recommend caution in establishing a California-wide policy until that research is complete.

4.11. Design Recommendations for Bicycles

Current design practices for accommodating bicyclists at roundabouts incorporate the use of treatments to provide cyclists of varying abilities with the option to circulate as motorists or as pedestrians. This includes the provision of a wider sidewalk or shared path around the perimeter of the roundabout and ramps to connect the sidewalk or path to the bicycle facilities on each leg as appropriate. The research conducted for this report suggests that such practice is appropriate in California.

On roundabouts with high volumes of bicyclists using the crosswalk as part of a shared path (i.e., they are not dismounted and walking their bicycles) that yield signs may be provided for bicyclists entering the crosswalk. The observational analysis in this study found that bicyclists used the crosswalk more at multilane roundabouts than at single-lane roundabouts where a bicyclist-pedestrian shared path exist around the roundabout. The yield sign will serve to remind the bicyclist that they do not have the right-of-way when riding across a crosswalk. Many motorists stopped for bicyclists that were riding in the crosswalk, but of the collisions looked at, 44% of the incidents involved a bicyclist/motorist conflict.

5. SUMMARY AND RECOMMENDATIONS

This report presents the results of a literature review, data collection and analysis, and an expert review of roundabout design practices to develop a set of recommendations for Caltrans to consider as it updates its roundabout design policies and standards. The authors suggest the following:

- Attention to the overall layout of a roundabout is often more critical than the dimensions of individual components. In effect, roundabout design is performance-based; that is, success is measured from its output (operational and safety performance, accommodation of design vehicle, pedestrian and bicycle usability, etc.) rather than its input (individual design dimensions).

- The following California-specific values for critical headway and follow-up headway may be considered to calibrate capacity models to determine appropriate lane numbers and arrangements:

    - Single-lane roundabouts: critical headway = 4.8 s, follow-up headway = 2.5 s.

    - Multilane roundabouts, left lane: critical headway = 4.7 s, follow-up headway = 2.2 s.

    - Multilane roundabouts, right lane: critical headway = 4.4 s, follow-up headway = 2.2 s.

- Using the above calibrated values, the following capacity models can be used in a manner consistent with the recommendations from NCHRP 572, with c equal to capacity (passenger car equivalents per hour) and v_c equal to the conflicting flow rate (passenger car equivalents per hour):

    - Single-lane: $c = 1440 \cdot \exp(-0.0010 \cdot v_c)$

    - Multilane right lane: $c = 1640 \cdot \exp(-0.0009 \cdot v_c)$

    - Multilane left lane: $c = 1640 \cdot \exp(-0.0010 \cdot v_c)$

- The current methodology presented in the FHWA Guide for estimating vehicular speeds throughout the roundabout should be modified to account for acceleration and deceleration effects.

- While speed prediction for the various movements through a roundabout is reasonably accurate, the data show a trend between increased speeds and increased crash experience. However, this trend is not necessarily statistically conclusive. Many sites in the NCHRP 3-65 database experienced few to zero crashes, and the site-to-site variation for the sites with nonzero crash rates is often significant.

- The NCHRP 3-65 data generally support the use of a 25-mph threshold for an entry speed adjusted for the effects of deceleration. However, the resulting crash experience can vary significantly among sites.

- Speed differentials of more than 10 mph between adjusted entry speeds (accounting for deceleration) and left-turn circulating speeds appear to correspond to an increase in entry-circulating crashes. Therefore, the FHWA Guide's recommendation for a maximum speed differential of 12 mph appears to be supported if one adjusts entry speeds for deceleration effects.

- The report has suggested the appropriate design vehicles and side-by-side accommodation through single-lane and multilane roundabouts for various types of roadways.

- Care must be taken with the design of roundabouts to minimize exit-circulating conflicts through appropriate spacing of entries and following exits. Examples have been provided.

- Care must be taken with the design of roundabouts to ensure appropriate visibility angles to the left. This need occurs most commonly in roundabouts with consecutive entries, such as at freeway interchange terminals. Examples have been provided.

- Typical ranges of inscribed circle diameter have been provided; however, inscribed circle diameter is a product of other factors and not a critical input parameter by itself.

- For intersection sight distance calculations, a critical headway of 5.9 seconds is recommended instead of the 6.5 seconds presented in the FHWA Roundabout Guide. This methodology should be considered interim until a study on roundabout intersection sight distance is completed.

- The effect of roundabouts on pedestrian and bicyclist demand remains an open question. Data collected from sites anticipated to be converted to roundabouts will support a future research effort to address this question.

- Current U.S. design methods to accommodate pedestrians appear to be appropriate, although further research is needed to develop appropriate treatments to accommodate pedestrians with vision disabilities. The uncontrolled crosswalk treatments appear to operate well for the majority of users (pedestrians and conflicting vehicles). The use of a setback of one to two vehicles from the roundabout appears to be effective. Stopping sight distance needs to be provided so that motorists have the proper time to react after observing a pedestrian using the roundabout crosswalk; the same sight distance requirement helps pedestrian determine the appropriate time to enter the crosswalk. The pedestrian crossing treatments and methodology for selecting treatments as suggested in TCRP Report 112/NCHRP Report 562 should be considered.

- For pedestrians with visual impairments, recent and ongoing research suggests that a simple, uncontrolled crosswalk may be insufficient to provide access at some roundabouts, particularly at multilane roundabouts. The Access Board has made the draft recommendation that all pedestrian crossings that span two or more entry or exit lanes be provided with some form of signalization. Research on this treatment and other less restrictive treatments is being conducted as part of NCHRP 3-78 and other studies. The authors recommend caution in establishing a California-wide policy until that research is complete.

- Current U.S. design methods to accommodate bicyclists of a range of abilities—allowing cyclists to circulate as vehicles or as pedestrians—appear to be appropriate. This includes the provision of a wider sidewalk or shared path around the perimeter of the roundabout and ramps to connect the sidewalk or path to the bicycle facilities on each leg as appropriate. The current U.S. recommendations to not stripe bike lanes within a roundabout help to address the exit-circulating conflict found in European experience. At multilane roundabouts, the evidence from this study suggests that it may be appropriate to use yield signs on a shared path around the roundabout, as many cyclists are riding rather than walking their bicycles.

The authors recommend close coordination with the ongoing NCHRP 3-65A project to produce a second edition of the FHWA Guide. It is anticipated that many of the recommendations in this report will be considered by that project.

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Appendix A: Annotated Bibliography

This Annotated Bibliography provides detailed information pertaining to the selected literature cited in the report. This literature is grouped into five categories: (1) State Guidelines and Research Documents; (2) Application and Policy; (3) Geometric Design; (4) Safety; and (5) Pedestrian and Bicycles.

A.1. State Guidelines and Research Documents

A.1.1. California Department of Transportation (Caltrans). "Design Information Bulletin 80-01". California Department of Transportation, Division of Design, Office of Geometric Design Standards, October 2003.

Caltrans provides guidance in the form of a Design Information Bulletin (DIB) that serves as a supplement to the FHWA guide. After the publication of the FHWA guide, Caltrans updated its previously published DIB on Roundabouts dated September 8, 1998. The current version, DIB 80-01, is dated October 3, 2003. Besides providing a general description of its policy, some background, and its applicability of the DIB, it includes an Attachment A. Attachment A spells out Caltrans design requirements which overlay and supplement those addressed in the FHWA guide.

Attachment A provides two more term definitions: approach and intersection. In terms of treatment of pedestrian crossings, it clarifies that the location of the pedestrian crosswalk is measured from the inscribed circle at both entry and exit. The crosswalk at multi-lane roundabouts should be located two-car lengths from the inscribed circle. In all cases, the pedestrian crossing shall be no closer than 6 m from the inscribed circle.

The document recommends a 6.5-second critical gap as the initial value for calculating intersection sight distance; however, the design speed and speed consistency through the circulatory roadway must be checked to ensure that the target speed is accomplished through the roundabout. Otherwise, modification on the initial critical gap value may be necessary, with a minimum of 5.0 seconds.

For crosswalks, it recommends use of a "ladder" type crosswalk on state highways to make the crossing location more visible to both drivers and pedestrians.

A.1.2. Saito, M., and M. Lowery. "Evaluation of Four Recent Traffic and Safety Initiatives: Volume 1: Developing Guidelines for Roundabouts (Report No. UT-04.10)". Utah Department of Transportation Research and Development Division, October 2005.

Field observations were conducted in this study at four roundabout locations in Utah during the a.m., p.m., and off-peak periods in the summer of 2003. The report summarizes the key issues concerning roundabouts and provides preliminary draft design guidelines and policies for roundabouts. This report does not provide as much detailed information about geometric design and operational analyses as those prepared in other states.

A.1.3. Kentucky Community Transportation Innovation Academy. "Modern Roundabouts: a Guide for Application". Kentucky Community Transportation Innovation Academy, 2005.

This guide document is very short. It includes some general concepts, example applications, and design considerations of roundabouts as a form of intersection control that can be considered by communities and transportation professionals. This document is not intended to include detailed information for the planning, design, and operation of roundabouts. More detailed practice relies heavily on the FHWA guide.

A.1.4. Wisconsin Department of Transportation. "Facilities Development Manual Design Chapter, Roundabouts Section", July 2005.

WisDOT adopted the design principles described in the FHWA guide and published the roundabout design guide as a portion of the WisDOT Facilities Development Manual (FDM) published in July 2005. This guideline incorporates the design principles from British roundabout guidance and recommended computer software "RODEL" for capacity and safety analyses to supplement the FHWA guide.

The document includes a section of recommended design procedures. It identifies three phases for a roundabout project: feasibility; alternatives analysis and preliminary design; and final design. A feasibility study includes crash evaluation, intersection capacity evaluation, queue storage evaluation, and unconventional intersection geometry evaluation. The process to determine the location of the roundabout should consider these issues: adjacent intersections; highway segments and coordinated signal systems; entry lanes and volume balance; approach alignment; pedestrian and bicyclist accommodations; transit, large vehicle and emergency vehicle considerations; social, environment, and economic considerations; and access management.

WisDOT's guidelines provide some useful information that may be beneficial to this project and Caltrans practice on roundabouts. For example, Wisconsin DOT established a roundabout design review process to ensure that roundabouts are properly selected and designed to meet a balance of needs (WisDOT, FDM Procedure 11-26-1). The WisDOT's guide discussed the issues related to roundabout installation in an arterial network, closely spaced roundabouts, and roundabout interchange ramp terminals in much more detail.

A.1.5. Kittelson & Associates, Inc., and TranSystems Corp. "Kansas Roundabout Guide: a Supplement to FHWA's Roundabout an Informational Guide", October 2000.

Kittelson & Associates, Inc. developed a statewide roundabout guide for the Kansas Department of Transportation as a supplement to the FHWA guide. The Kansas guide is intended to provide consistent information regarding the planning, design, construction, and operation of roundabouts in Kansas.

The outline of the Kansas Roundabout Guide is similar to the FHWA guide. It provides more detailed site selection guidance in the planning section (Chapter 3), which identifies locations, and conditions where roundabouts are often advantageous over other traffic controls and sites where caution should be exercised with roundabouts. The operational analysis procedures in the Kansas guide totally adopts the FHWA guide, with simplified statements about traffic volumes, single-lane roundabout capacity, double-lane roundabout capacity, pedestrian effects on entry capacity, queues, and delay.

Similar to the FHWA guide, three key performance measures are used to assess the operating performance for a particular roundabout design: degree of saturation, delay, and queue length. For design purpose, KDOT adopts 0.85 as the maximum volume-to-capacity ratio for satisfactory operation and the 95th-percntile queue length to estimate the maximum resulting queue for a given approach. Furthermore, control delay is used to represent the delay component of roundabout performance in Kansas, as it is the same measure used for other types of intersections. An example operational analysis summary table is provided to summarize these three measures for each proposed roundabout.

In the Geometric Design chapter, the Kansas guide recommends a procedure for designing a roundabout, based on Exhibit 6-2: Roundabout Design Process in the FHWA guide. Fundamental principles are discussed in this guide about design speed, speed consistency, approach alignment, angles between approaches, and design vehicle. Some higher maximum entry design speeds are recommended in the Kansas guide. For example, maximum entry design speed of an urban single-lane roundabout recommended by the Kansas guide is 25 miles per hour, compared to 20 miles per hour in the FHWA guide.

A.1.6. Lee Engineering, L.L.C., and Kittelson & Associates, Inc. "Roundabouts: an Arizona Case Study and Design Guidelines". Lee Engineering, L.L.C., July 2003.

The report addresses a case study of the first roundabout in Arizona, located at the I-17/Happy Valley Road interchange. The objective of the study was to identify possible improvements that could be incorporated at this location and into future Arizona Department of Transportation roundabout initiatives. Guidelines were developed for designing roundabouts in the State of Arizona. The guidelines are similar to the FHWA Guide; however, some minor deviations were found in design parameters such as entry design speed and inscribed circle diameter.

A.1.7. Pennsylvania Department of Transportation. "Guide to Roundabouts". Publication No. 414. May 2001.

The Pennsylvania Department of Transportation's "Guide to Roundabouts" is developed as a supplement to the FHWA guide. This document will aid transportation professionals and engineers in determining whether a roundabout is a feasible alternative for a specific location.

This guide provides an array of questions and insights that can be applied in the preliminary design of intersections. Site and traffic characteristics determine the benefits of using a roundabout at a particular location. This guide is intended to help determine which intersections are best suited for roundabouts.

The Pennsylvania guide begins with a detailed description of modern roundabouts. Differences between modern roundabouts and traffic circles are described, and the benefits of implementing a roundabout are discussed. The core of the guide is a questionnaire that directs transportation professionals and engineers toward a decision regarding the feasibility of implementing a roundabout. The questions are applicable to either the planning or study phases of the design process. Following the questionnaire, there are several important issues discussed regarding pedestrians, bicyclists, and public education. Several case studies are also included to facilitate the design process.

A.1.8. New York State Department of Transportation. "Highway Design Manual Chapter 26: Roundabout". 2001.

The guidelines for the New York State Department of Transportation are contained in chapter 26 of the *Highway Design Manual* and rely heavily on the FHWA guide. Many of the figures and tables are taken directly from the FHWA guide, although some have been modified slightly to reflect the standards of New York State Department of Transportation. The operation analyses and geometric parameters are mostly based on the British standards.

A.1.9. Taekratok, T. "Modern Roundabouts for Oregon (Report No. #98-SRS-522)". Oregon Department of Transportation Research Unit, June 1998.

This report provides a comprehensive review of current research and practice on modern roundabouts, both in the U.S. and internationally. The report compares the advantages and disadvantages of roundabouts, summarizes safety implications, and discusses pedestrian and bicyclist considerations. Three software models for roundabouts—ARCADY, RODEL, and SIDRA—are compared, and some issues are raised for future considerations. For example, SIDRA showed an agreement between delay output and field data at low-volume roundabouts, but the model underestimated the results at higher volumes. The report also includes French recommendations on handling public transit at roundabouts.

A.2. Application and Policy Consideration

A.2.1. Retting, R. A., et al. "Traffic Flow and Public Opinion: Newly Installed Roundabouts in New Hampshire, New York, and Washington". CD-ROM, TRB 2006 Annual Meeting, 2006.

The author suggests that roundabouts can provide substantial safety and traffic flow benefits compared with conventional intersections, but are opposed in the planning stage by local residents and elected officials who question their effectiveness. The purpose of this study was to measure public opinion before and after construction of roundabouts in several communities, and to evaluate the impact of roundabout construction on traffic flow. Three communities where stop-sign or traffic-signal-controlled intersections were replaced with roundabouts in 2004 were the subjects of this research. Overall, 36 percent of drivers supported the roundabouts before construction, compared to 50 percent shortly after construction. Roundabouts had very positive effects on traffic flow. Average intersection delays during peak hours at the three sites were reduced by 83 to 93 percent. Traffic congestion, as measured by the vehicle-to-capacity ratio, was reduced by 58 to 84 percent. These results provide further evidence that roundabouts can improve traffic flow and that public support for roundabouts increases after they are in place.

A.2.2. Kyte, M., et al. "Characteristics of Modern Roundabouts in the United States: A Summary of the NCHRP 3-65 Operations Database". CD-ROM, TRB 2006 Annual Meeting, 2006.

This paper describes the basic characteristics of the more than 300 modern roundabouts that have been constructed in the United States since 1990. The paper also describes the traffic operations data that were collected at a subset of these sites, 474 hours of data recorded at 31 sites throughout the U.S. The database that has been assembled is the most extensive to date for U.S. conditions. Changes to the *Highway Capacity Manual*, and other standard traffic engineering references, will be made based on the conclusions drawn from this database. Eventually, the database will be made available to other researchers investigating the many other research problems that remain unanswered regarding roundabout operations. The database will also serve as a benchmark for changes in capacity flow rates at U.S. roundabouts as design, usage, and driver behavior mature over time.

A.2.3. Rodegerdts, L.A. "State-of-the-Art in U.S. Roundabout Practice". Institute of Transportation Engineers 2005 Annual Meeting, Melbourne, August 2005.

This paper presents the author's view on the current state of practice in the United States, including a vision of the coming years. The issues addressed in this paper include safety analysis, operational analysis, geometric design, multilane roundabout issues, and illumination. The author believes that roundabout practice in the U.S. will continue to evolve over the coming years. The practice has improved considerably with the publication of the FHWA and state roundabout guides and continued guidance from experts. The technical issue of properly accommodating non-motorized users, particularly pedestrians with visual impairments, is likely to continue to dominate the U.S. debate.

A.2.4. E.R. Russell, G. Luttrell, M. Rys. "Roundabout Study in KANSAS". 4th Transportation Specialty Conference of the Canadian Society for Civil Engineering, Jun 2002.

The Kansas Department of Transportation became interested in roundabouts in 1998 and started designing and building roundabouts on state highways in Kansas. They sponsored three research projects to gather before and after data at several Kansas roundabout locations. These studies are ongoing at Kansas State University. Concurrently, the City of Manhattan's traffic engineer chose a roundabout over other options when confronted with a high crash rate at the intersection of two residential collector streets with two-way stop control. The City cosponsored a project with Mack Blackwell Transportation Center to compare the traffic operations of the roundabout with other options. The Insurance Institute for Highway Safety funded an additional project to gather before and after data and analyze operation of roundabouts in Harford County, Maryland; Hutchinson, Kansas; and Reno, Nevada. The paper reviews the data collection and analysis techniques and present results of several comparisons of roundabouts to other types of traffic control that show that the roundabout is superior to almost every other type of traffic control based on the measures of effectiveness used. The results of the analysis led the authors to conclude that roundabouts are the safest and most effective type of intersection traffic control available today. The paper also presents a brief review of some public opposition.

A.2.5. National Cooperative Highway Research Program (NCHRP). "Modern Roundabout Practice in the United States", A Synthesis of Highway Practice, NCHRP, Washington, D.C., 1998.

This synthesis is a comprehensive summary of current practices related to modern roundabouts in the United States. It presents the results of a survey conducted of departments of transportation throughout the United States and Canada. These results illustrate the perception and use of roundabouts today. It further examines the current state guidelines and various international guidelines. The report addresses safety, capacity, pedestrian, and bicyclist concerns and suggests a methodology for determining where roundabouts are appropriate.

A.3. Geometric Design

A.3.1. Thomas, G., et al. "Rural Roundabout and Their Application in New Zealand", Web document.

This paper presents research results on design and operational guidelines required for safe application of rural roundabouts. It documents current national and international practices, and defines a set of criteria and recommendations suitable for New Zealand.

The speed (*v*) of a vehicle on a circular path is related to the path radius (*R*) as follows:

$$(e + f) = \frac{v^2}{gR}$$

where *e* is the superelevation, *f* is the coefficient of sideways friction, and *g* is the acceleration due to gravity. The value for the design side friction coefficient varies with vehicle speed, and Austroads (1999) suggests that the maximum design value be 0.35 at 50 km/h, decreasing to 0.11 at 120 km/h for rural road design.

The safe intersection sight distance (SISD) comprises the distance approaching vehicles travel at the 85th percentile operating speed with an alerted stopping distance in 3 seconds (the observation time). It can be estimated as follows:

$$SISD = T_0 V + R_T V + \frac{V^2}{2d}$$

where T_0 is the observation time (3 s), R_T is the perception-reaction time, V is the initial speed of approaching vehicles, and d is the deceleration rate of approaching vehicles.

A.3.2. Akcelik, R. "Estimating Negotiation Radius, Distance and Speed for Vehicles Using Roundabouts". Sydney, Australia: 24th Conference of Australian Institutes of Transport Research, December 2002.

This paper discusses models for estimating negotiation radius, distance, and speed values of through and turning vehicles at roundabouts. This model is based on the method introduced in aaSIDRA version 2.0. aaSIDRA version 2.1 introduced a new method for estimating the side friction factor as a function of speed.

Figures showing simplified constructions of vehicle paths for through, left-turning, and right-turning vehicles are given. The method for determining negotiation radius, distance, and speed of vehicles at roundabouts allows for path smoothing by drivers. Vehicle paths are constructed using the entry and exit curb line arcs, inscribed and central island circles, and a layout circle. The safe negotiation speed formula uses a side friction factor that is a function of vehicle mass. Graphs showing the side friction factor as a function of vehicle mass, and negotiation speed as a function of turn radius are presented.

The negotiation radius, distance, and speed values as a function of the roundabouts size are given for through, left-turn and right-turn movements. Graphs are given to show the sensitivity of average geometric delay for through, left-turn and right-turn movements to 1) roundabout size and 2) approach and exit cruise speeds.

A.3.3. Baranowski, B. et al. "Alternate Design Methods for Pedestrian Safety at Roundabout Entries and Exits: Crash Studies and Design Practices in Australia, France, Great Britain and the USA". Transportation Engineer, RoundaboutsUSA, Provo, UT, USA

The paper and presentation discuss study results of pedestrian/vehicle crashes and design practices at roundabouts in Australia, France, Great Britain, and the U.S. There are conflicting roundabout design practices among transportation engineers in the U.S., with alternate opinions and claims about the safe design of entries and exits for both single-lane and multi-lane roundabouts. This paper compares two recent designs constructed in the U.S. that use alternate design methods to reduce travel speeds. The meeting presentation illustrated various alternate design applications at roundabouts currently operating in the U.S.

This paper came about as the result of the authors observing roundabout designers in the U.S. who, in an attempt to slow exiting traffic to protect pedestrians, have constructed roundabouts with excessively tight exit radii. This practice has resulted in roundabouts with unnecessarily low capacity and high vehicle crash rates in some cases. This paper makes a case for the design of high capacity roundabouts that are safe for pedestrians.

A.3.4. Campbell, D., et al. "Improved Multi-lane Roundabout Designs for Cyclists". Web Document, GHD Ltd, 2004.

In 2004, GHD Ltd was engaged to improve multilane roundabout designs for cyclists, as part of Land Transport New Zealand's 2004–2005 research programs. This paper is a summary of the project. Duncan Campbell (GHD Ltd) also completed a Masters thesis that included further work on this subject.

Multilane roundabouts are generally viewed by experienced cyclists as a reasonably hazardous element of the road network to be avoided if conveniently possible. A literature review, an analysis of crash statistics in Auckland, and a survey of cyclists confirmed the original focus of this research, which was to design a low-speed multi-lane roundabout for on-road cyclists. This should substantially treat the critical "entering vehicle versus circulating cyclist" crash type, and is anticipated to address roundabout exits, which are the other main safety concern of bike riders. Good street lighting is also imperative, as nighttime crashes comprise a significant proportion of Auckland cyclist crashes at these types of junctions.

The design of a roundabout that reduces maximum car speeds to 30 km/h rather than the conventional 50 km/h requires a confined geometry. The outcome of this research project is the Cyclist Roundabout, or "C" Roundabout, which requires a narrow roundabout entry that requires larger vehicles to straddle both entry lanes. An alternative measure is the use of vertical deflection devices on roundabout approaches. While these devices have implications for bus passenger comfort, and emergency and heavy vehicles, they are an economic form of speed reduction for roundabout entries compared to substantial roundabout redesign.

The "C" Roundabout is a design that may not be suitable for every intersection situation. Rather it is hoped that the design concept demonstrated here, will be taken into consideration alongside other options for any new intersection designs or improvements. In the context of improving the road network for cyclists, the "C" Roundabout is just another tool at the traffic engineer's disposal.

A.4. Safety

A.4.1. Al-Ghirbal, A., et al. "Prediction Severe Accident Rates at Roundabouts Using Poisson Distribution". TRB 2006 Annual Meeting CD-ROM, 2006.

The author argues that highway engineers have been interested in the safety aspects of roadway design since the inception of transportation engineering. Conventionally, the most practicable measure to evaluate the level of safety for an existing highway facility is historical accident records or, for a proposed facility, prediction of accident rates. Because at-grade intersections are the areas of the highway network most likely to experience higher accident rates because of the presence of conflict points, these intersections deserve considerable attention from highway engineers studying safety issues.

Roundabouts are becoming acceptable as a feasible alternative to other types of at-grade intersections. This is due to their distinct advantages with respect to safety and smooth traffic movement, especially for moderate levels of traffic flow.

This paper focuses on the development of an accident prediction model to enable engineers and designers to appreciate the effects of different design features of roundabouts. Accidents that occurred at several roundabouts in Bahrain over the period from 1991–2002 were analyzed. The different geometric and traffic characteristics were used as the input parameters in the model to estimate their significance for traffic safety at roundabouts. The GLIM statistical package is utilized to develop a statistical model that relates these characteristics with the level of safety.

A.4.2. Russell, E.R., et al. "Can Modern Roundabouts Safely Accommodate All Users?" Web Document, *http://www.mtjengineering.com/pdfs/Gene_Russel_Paper.pdf*

These authors studied the safety, operational, and environmental benefits of roundabouts for motorists for several years. Research in recent years has documented significant safety benefits, particularly in decreased injury crashes and fatalities, when modern roundabouts have replaced stop sign and traffic signal control. One reliable U.S. study concluded that where roundabouts replace stop signs and traffic signals, overall crashes are reduced 39 percent, injury crashes are reduced 76 percent and fatal crashes are predicted to decrease 90 percent. Roundabouts have the potential to save thousands of motorists' lives. Research results also have concluded that roundabouts significantly reduce delay, stopping, queuing, and motor vehicle emissions.

The effects on pedestrians and bicycles have not been studied much in the United States; however, international studies indicate that roundabouts are safer for pedestrians than intersections with conventional traffic control and no more dangerous for bicyclists. There is concern that roundabouts are not accessible to blind and visually impaired pedestrians and the access-board has put language in draft guidelines that would require pedestrian signals at all roundabouts. The challenge is to find a solution(s) to make roundabouts accessible without slowing or stopping their growth, which could negate the life saving benefits to motorists. This paper presents the issues involved in finding a balance that will accommodate and benefit all roundabout users.

A.4.3. Marco, R., et al. "Model to Evaluate Potential Accident Rate at Roundabouts". Journal of Transportation Engineering, Volume 130, Issue 5, pp. 602-609 September/October 2004.

This paper states that the increasing use of roundabouts calls for an evaluation of the potential accident rate for this kind of intersection. This gives a further element for the choice between alternative typologies of intersection for the re-qualification and the adjustment of road junctions. This paper presents a model to evaluate the potential accident rate in large and medium roundabouts. The model is based on dynamic considerations and on the user's behavior when crossing the intersection. The model's response to the traffic conditions in the intersection and to capacity formulations is also analyzed.

This paper defines some models to predict the crashes number. For example, the number of potential conflicts per time unit for collision due to failure to yield is defined as:

$$N_{1a} = Q_e \rho P(t_{\inf} \leq t \leq t_{\sup})$$

Where Q_e is the entering volume;

ρ is the traffic intensity;

$Q_e \rho$ is the number of entering vehicles that have to stop behind other vehicles before approaching the ring; and

$P(t_{\inf} \leq t \leq t_{\sup})$ is the portion of such vehicles ($Q_e \rho$) that faces a gap between two vehicles circulating in the ring included in the band.

A.4.4. Stone, J.R., et al. "The Effects of Roundabouts on Pedestrian Safety". Southeastern Transportation Center, August 2002.

This project examines the safety aspects of modern roundabouts with respect to pedestrians. In the U.S., safety has been recognized as a major concern for the effectiveness of roundabout performance since their emergence. Pedestrians may be more prone to unsafe crossings at roundabouts due to new geometries, signalization (or lack of it), right-of-way assignments for pedestrians and vehicles, and visual and auditory cues. This project documents case study, statistical, and simulation analyses regarding pedestrian safety at roundabouts. The results suggest that roundabouts are safe with respect to pedestrians.

*A.4.5. Persaud, B.N., et al. "Crash Reductions Following Installation of Roundabouts in the United States". **American Journal of Public Health, Vol. 91, Issue 4 628-631.***

This study evaluated changes in motor vehicle crashes after 24 intersections were converted from stop sign and traffic signal control to modern roundabouts. These intersections were located in 8 states and were in a mix of urban, suburban, and rural environments. A before-after study was conducted using the empirical Bayes approach, which accounts for regression to the mean. Overall, the empirical Bayes procedure estimated statistically significant reductions of 39 percent for all crash severities combined and 76 percent for all injury crashes. Reductions in the numbers of fatal and incapacitating injury crashes were estimated at approximately 90 percent. Overall, results are consistent with numerous international studies and suggest that roundabout installation should be strongly promoted as an effective safety treatment for intersections.

A.5. Pedestrian and Bicycle

A.5.1. Ashmead, D.H., et al. "Street Crossing by Sighted and Blind Pedestrians at a Modern Roundabout". Journal of Transportation Engineering, Volume 131, Issue 11, pp. 812-821, November 2005.

This paper argues that pedestrian behavior and safety at roundabouts is not well understood, particularly for pedestrians with sensory or mobility impairments. A previous study, in which participants indicated when they would cross, suggested that blind pedestrians miss more crossing opportunities and make riskier judgments than sighted pedestrians. This study replicated these findings and analyzed actual street crossings. Six blind and six sighted pedestrians negotiated a double-lane urban roundabout under high and low traffic volumes. Blind participants waited three times longer to cross than sighted participants. About 6 percent of the blind participants' crossing attempts were judged dangerous enough to require intervention, compared to none for sighted pedestrians. Drivers yielded frequently on the entry lanes but not the exit lanes. Sighted participants accepted drivers' yields, where blind participants rarely did so. Auditory access to information about traffic and policy implications is discussed regarding accessibility of transportation systems.

A.5.2. Fortuijn, L. G. H. "Pedestrian and Bicycle-Friendly Roundabouts: Dilemma of Comfort and Safety". 2003 ITE Annual Meeting. Seattle, Washington, 2003

This paper addresses the circulatory speed of motorized traffic on roundabouts. For the safety of pedestrians and cyclists, the difference in speed between cars and bicycles at a conflict point is very important: a reduction in collision speed from 30 mph (48 km/h) to 20 mph (32 km/h) means that the risk of fatal injury is reduced from 45 percent to as little as 5 percent. The speed through roundabouts is determined by the vehicle path curvature. On single-lane roundabouts, an increase in the vehicle path curvature results in a reduction of vehicular accidents. On multi-lane roundabouts, however, increasing the vehicle path curvature can result in a higher potential for sideswipe collisions. On double-lane roundabouts, designers are faced with a dilemma: accepting a higher number of sideswipe collisions involving motorized traffic (when they increase vehicle path curvature by reducing the radius of the vehicle path) or accepting serious accidents involving pedestrians and cyclists (when they decrease vehicle path curvature). The turbo-roundabout offers a solution to this dilemma. This kind of roundabout is based on important principles applying to single-lane roundabouts: 1) no weaving traffic on the roundabout and 2) dealing with conflict points by means of slow speeds.

The paper also addresses the right-of-way regulations for cyclists and pedestrians; cyclists are usually given priority in the Netherlands. But in the case of roundabouts, this leads to a situation in which either safety or convenience is diminished. In attempts to resolve this dilemma, Dutch guidelines (as stated in CROW publication 126) recommend that within built-up areas, cyclists on the cycle track going around the roundabout be given right-of-way (for convenience) but that outside of built-up areas (and when another design is applied), they should not be given right-of-way (for reasons of safety). It is concluded that further research is needed to demonstrate the degree to which roundabouts that give cyclists the right-of-way decrease their safety, even when given the best roundabout design possible.

Finally, this publication devotes attention to the design of cycle crossings for two double lanes. For pedestrians, a width of 3 m for the splitter island is sufficient to anticipate motorized traffic satisfactorily. The conclusion is that the higher speed of the cyclists places additional demands on the geometric design for creating sufficient anticipation time (offered by a jog).

A.5.3. Baranowski, B. "Pedestrian Crosswalk Signals at Roundabouts: Where are they Applicable?" ITE District 6 Annual Meeting CD-ROM, June 2004.

The proposed American Disability Act (ADA) Guidelines have recommended that traffic signals be located at all roundabout crosswalks to improve pedestrian safety and to allow for the crossing of the visually impaired. The author presents applications of pedestrian signals at roundabouts recently constructed in the U.S. and discusses examples located in Australia and Great Britain. Many engineers and planners feel that the decision to install pedestrian crosswalk signals at a roundabout or at mid-block locations should be made only where warranted, and should not be mandated by a blanket policy.

A.5.4. Singer, L.I., et al. "An Engineer's Dilemma: Accommodating the Needs of People with Disabilities at Modern Urban Roundabouts". Straits Knowledge 2002: www.straitsknowledge.com

Fundamental concerns are developing between those who must address traffic congestion and safety in older communities and stakeholders with special needs and protections under the Americans with Disabilities Act. These came into focus with an urban roundabout in Maryland.

Until these issues are resolved, the authors argue that traffic engineers must function within a framework lacking in standards and techniques to make roundabouts readily usable to pedestrians with disabilities, particularly blind pedestrians, while still adhering to engineering requirements. Representatives from various groups within this community come to the highway agency with distinctly different goals, frustrating the engineers' ability to satisfy their needs. Similarly, these stakeholders are becoming frustrated and fearful of the increasing use of a traffic management and calming tool, which appears to be anything but that for them. Some, in fact, argue urban roundabouts may be inherently unsafe for blind pedestrians. They also perceive unwillingness on the part of traffic engineers to meet their needs.

Indeed, the authors argue there is little in the way of common vocabulary or solutions that exist between traffic experts on the one hand, and blind pedestrians, their advocates, and accessibility and mobility experts on the other. While there is certainly emotion and conviction on both sides, there are few standards and guidelines for field application beyond ADAAG, which does not address situations such as roundabouts. This problem is particularly critical in older communities, which often can no longer handle the traffic congestion typically found in downtown areas, as they undergo revitalization.

This paper presents some of the critical issues, various perspectives, and lessons Maryland learned through designing and constructing this modern urban roundabout. Some traditional and new approaches, including human factors elements that may be feasible in addressing these issues, are examined. Finally, a challenge is issued to find workable, field-level, multi-disciplinary solutions to provide industry-wide guidance for the future.

A.5.5. Access Board Research. "Pedestrian Access to Modern Roundabouts: Design and Operational Issues for Pedestrians Who Are Blind". Web document. http://www.access-board.gov/research/roundabouts/bulletin.htm#BACKGROUND

This paper states that roundabouts are replacing traditional intersections in many parts of the U.S. This trend has led to concerns about the accessibility of these free-flowing intersections to pedestrians who are blind and visually impaired. Most pedestrians who cross streets at roundabouts use their vision to identify a "crossable" gap between vehicles. While crossing, sighted pedestrians visually monitor the movements of approaching traffic and take evasive action when necessary. Blind pedestrians rely primarily on auditory information to make judgments about when it is appropriate to begin crossing a street. Little research has been conducted about the usefulness of such non-visual information for crossing streets at roundabouts. Recent research sponsored by the Access Board, the National Eye Institute, and the American Council of the Blind suggests that some roundabouts can present significant accessibility challenges and risks to the blind user. This bulletin:

- Summarizes orientation and mobility techniques used by pedestrians who are blind in traveling independently across streets;

- Highlights key differences between roundabouts and traditional intersections with respect to these techniques;

- Suggests approaches that may improve the accessibility of roundabouts to blind pedestrians; and

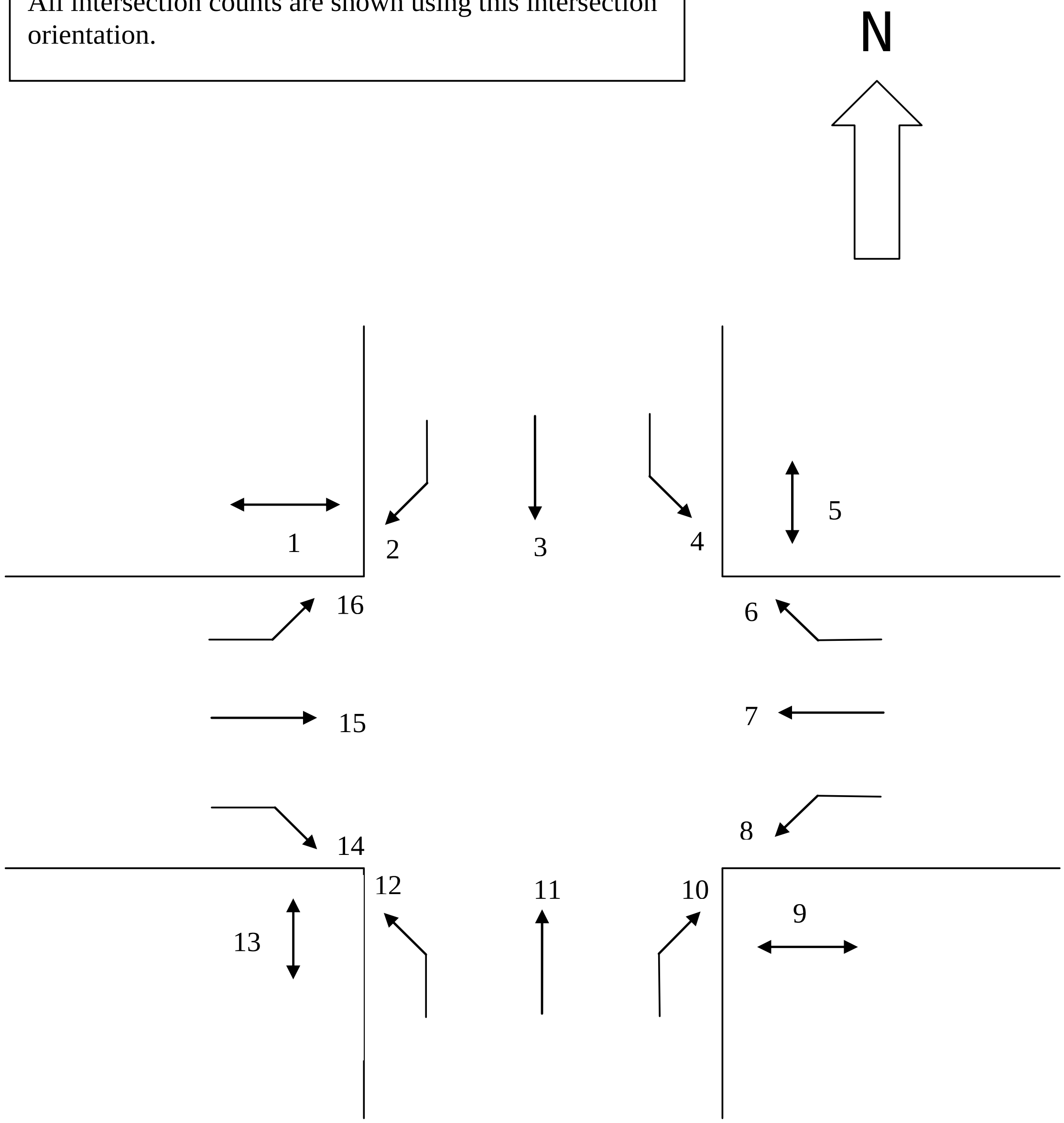
- Encourages transportation engineers and planners to implement and test design features to improve roundabout accessibility.

A.5.6. Swedish National Road and Transport Research Institute. "What Roundabout Design Provides the Highest Possible Safety?" Nordic Road & Transport Research, 2000, No.2, pp.17-21.

According to this study recently carried out by the VTI, roundabouts with a maximum permissible speed of 50 km/h are typically safer for motorists than grade-separated intersections. Single-lane roundabouts can be just as safe for cyclists as other types of intersection, and for pedestrians they are perhaps safer than any other type. Out of all of the modes of transportation that travel through a roundabout, the bicycle is the most vulnerable. This study found that more bicyclists avoided the roundabouts than went through them. There are fewer bicycle accidents when the radius of the central island is greater than 10 meters and if there are special bicycle crossings. The VTI suggests that there be a distance of 2 to 5 meters between the roundabout and the bicycle crossing. A motorist entering a roundabout on the approach will be able to pay attention to cyclists on the crossings. Then, upon entering the roundabout, the motorist would have the space beyond the crossing to give way to the bicycles in the roundabout.

Appendix B – Count Data

All intersection counts are shown using this intersection orientation.



Movements 2,3,4,6,7,8,10,11,12,14,15,16 are bicycle movements

Movements 1,5,9,13 are pedestrian movements

RAW COUNTS

Washington Avenue and Montgomery Street, Orvoville CA Thursday 5/18/06 with North being Washington Street

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	0	0	0	0	6	0	0	0	0	0	2	0	0	0	0	0	**8**
2:45	0	0	1	0	3	0	0	0	0	0	0	0	0	0	0	0	**4**
3:00	0	0	1	0	24	0	0	0	0	0	0	0	0	0	0	0	**25**
3:15	0	0	1	0	9	0	0	0	1	0	1	0	0	0	0	0	**12**
3:30	0	0	0	0	2	0	0	0	2	0	0	0	0	0	0	0	**4**
3:45	0	0	0	1	2	0	0	0	1	0	0	0	0	0	0	0	**4**
4:00	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
4:15	0	0	1	0	2	0	0	0	0	0	0	0	0	0	0	0	**3**
4:30	0	0	3	0	3	0	0	0	0	0	2	2	0	0	0	0	**10**
4:45	0	0	0	0	2	0	3	0	0	0	0	0	0	0	0	0	**5**
5:00	0	0	0	0	1	0	0	0	0	0	1	0	0	0	0	0	**2**
5:15	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
5:30	1	0	1	0	2	0	0	0	0	0	0	0	0	0	3	0	**7**
5:45	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**1**
Total	**1**	**0**	**8**	**1**	**59**	**0**	**3**	**0**	**4**	**0**	**6**	**2**	**0**	**0**	**3**	**0**	**87**

*Attractions at intersection: Boss Burger restaurant

Total Pedestrians:	64
Total Bicycles:	23

Sylvan Avenue and Roselle Avenue in the city of Modesto Monday 5/22/06. Roselle runs north and south in the intersection.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2:45	0	0	0	0	0	0	0	0	1	0	0	0	0	0	1	0	**2**
3:00	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
3:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:00	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	**1**
4:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
4:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:00	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	**1**
5:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
Total	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**2**	**0**	**1**	**0**	**0**	**0**	**3**	**0**	**7**

*There was construction near the intersection and no businesses nearby. There are homes located west of the intersection.

Total Pedestrians:	2
Total Bicycles:	5

Fresno Street/North Fresno Street/ Divisadero Street in Fresno Tuesday 5/23/06. North Fresno Street runs north and Fresno Street runs south.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	6	0	1	0	0	0	0	0	9	0	0	0	2	0	0	0	**18**
2:45	7	0	0	0	0	0	0	0	11	0	1	0	7	0	0	0	**26**
3:00	4	0	1	2	0	0	0	0	9	0	0	0	2	0	1	0	**19**
3:15	3	0	0	0	1	0	0	0	11	0	1	0	1	0	0	0	**17**
3:30	1	0	0	0	0	0	1	0	10	0	0	0	5	0	0	0	**17**
3:45	8	0	0	0	0	0	0	2	6	0	0	0	3	0	0	0	**19**
4:00	1	0	0	0	0	0	0	0	8	0	0	0	1	0	0	0	**10**
4:15	7	0	0	0	0	0	0	0	4	0	0	0	2	0	0	0	**13**
4:30	2	0	0	0	0	0	1	0	2	1	0	0	5	0	0	0	**11**
4:45	0	0	0	0	0	0	0	0	4	0	0	0	1	0	0	0	**5**
5:00	2	0	1	0	0	0	0	0	5	0	0	0	4	0	0	0	**12**
5:15	1	0	0	1	0	0	0	0	2	0	2	0	3	0	0	0	**9**
5:30	3	0	0	0	0	0	0	0	0	0	1	0	3	0	0	0	**7**
5:45	5	0	0	0	0	0	0	0	0	0	1	0	1	0	0	0	**7**
Total	**50**	**0**	**3**	**3**	**1**	**0**	**2**	**2**	**81**	**1**	**6**	**0**	**40**	**0**	**1**	**0**	**190**

*Medical Facilities are located all around the intersection.

Total Pedestrians:	172
Total Bicycles:	18

Main Street and Freedom Boulevard in Watsonville Wednesday 5/24/06. Freedom is the east leg, main constitutes south and west legs, and Southern Circle is the north leg.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	3	0	1	0	2	0	0	0	1	1	0	0	0	0	0	0	**8**
2:45	5	0	0	0	2	0	0	0	0	1	0	0	0	0	0	0	**8**
3:00	2	0	0	0	4	1	0	0	0	1	0	0	0	0	0	0	**8**
3:15	7	0	0	1	10	0	0	0	0	0	0	0	0	0	0	0	**18**
3:30	3	0	0	0	3	0	1	1	1	1	1	0	0	0	0	0	**11**
3:45	6	0	0	0	9	0	0	0	0	0	0	0	0	0	0	0	**15**
4:00	5	0	0	0	4	0	0	0	0	1	0	0	0	0	0	0	**10**
4:15	1	0	0	1	0	0	0	1	0	0	0	0	0	0	0	0	**3**
4:30	3	0	0	0	4	0	0	0	0	0	0	0	0	1	1	0	**9**
4:45	0	0	0	1	1	0	0	1	0	0	1	0	0	0	0	0	**4**
5:00	6	0	1	0	3	0	1	0	0	2	0	0	0	0	0	0	**13**
5:15	3	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	**4**
5:30	3	0	1	0	4	0	0	2	0	0	0	0	0	0	0	0	**10**
5:45	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	**1**
Total	**47**	**0**	**3**	**3**	**47**	**1**	**2**	**6**	**2**	**7**	**2**	**0**	**0**	**1**	**1**	**0**	**122**

* The local attractions are a church along with a diner and a fast food place at the intersection. Also in the area are hotels and an elementary school.

Total Pedestrians:	96
Total Bicycles:	26

Beach Street and Pacific Avenue in Santa Cruz Thursday 5/25/06. Pacific Avenue runs north and south.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	5	0	0	0	19	4	2	0	19	0	2	1	10	1	7	1	**71**
2:45	2	0	6	1	12	0	3	0	30	0	4	0	8	0	3	1	**70**
3:00	2	1	0	0	42	0	2	0	47	0	3	2	13	1	3	0	**116**
3:15	5	0	3	0	40	0	7	1	43	1	3	0	14	0	11	0	**128**
3:30	9	1	2	3	11	7	3	0	16	0	1	0	16	0	9	1	**79**
3:45	5	1	1	2	35	2	5	1	27	0	1	1	8	0	11	2	**102**
4:00	5	1	1	0	27	3	2	0	21	0	1	0	26	0	13	1	**101**
4:15	10	2	1	1	37	1	8	0	28	2	1	0	16	1	4	2	**114**
4:30	2	2	4	1	24	1	13	0	27	1	2	0	10	0	11	1	**99**
4:45	12	0	5	0	21	3	0	1	34	3	1	1	13	0	5	1	**100**
5:00	9	0	5	0	26	2	2	2	29	1	1	2	12	0	5	2	**98**
5:15	8	0	1	5	26	1	7	2	25	4	4	0	9	1	10	4	**107**
5:30	3	0	0	0	30	1	9	0	21	0	1	1	3	1	9	2	**81**
5:45	2	0	3	2	21	4	7	1	22	0	1	0	12	1	8	1	**85**
Total	**79**	**8**	**32**	**15**	**371**	**29**	**70**	**8**	**389**	**12**	**26**	**8**	**170**	**6**	**109**	**19**	**1351**

*The intersection is a very popular pedestrian intersection. The wharf runs south and there are hotels in all other directions around the intersection.

Total Pedestrians:	1009
Total Bicycles:	342

47th Street East and State Route 138 in Palmdale Wednesday 5/31/06. State Route 138 runs north and south.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	**1**
2:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
Total	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**1**

* There is a lot of developments such as Big 5 in the area but there isn't a high probablility that people will have to cross this intersecion to get to the development.

Total Pedestrians:	0
Total Bicycles:	1

Junction of Highway 46 west and Route 101 in Paso Robles 6/01/06. Route 101 runs north and south.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:00	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
5:30	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	**1**
5:45	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
Total	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**2**

* In the area are gas stations, fast food and motels but none of them require people to cross at the interection.

Total Pedestrians:	2
Total Bicycles:	0

Gilman Street intersection at I-80 Berkeley Monday 6/05/06. I-80 runs north and south in the intersection.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	**1 (P)**	**2 (R)**	**3 (T)**	**4 (L)**	**5 (P)**	**6 (R)**	**7 (T)**	**8 (L)**	**9 (P)**	**10 (R)**	**11 (T)**	**12 (L)**	**13 (P)**	**14 (R)**	**15 (T)**	**16 (L)**	**Total**
2:30	3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**3**
2:45	1	0	0	0	0	0	0	1	0	0	0	1	0	0	1	0	**4**
3:00	0	0	0	0	0	0	3	0	0	0	0	0	5	0	0	0	**8**
3:15	2	0	0	0	0	0	2	0	0	0	0	0	1	0	0	0	**5**
3:30	1	0	0	0	1	0	0	0	0	0	0	0	2	0	0	0	**4**
3:45	1	0	0	0	0	0	0	0	0	0	0	0	1	0	1	0	**3**
4:00	1	0	0	0	0	0	0	0	1	0	0	0	9	0	3	0	**14**
4:15	3	0	0	0	0	0	0	0	1	0	0	1	25	0	1	0	**31**
4:30	1	0	0	0	0	0	0	0	0	0	0	0	2	1	0	0	**4**
4:45	7	0	0	0	0	0	3	0	0	0	0	1	5	0	1	0	**17**
5:00	4	0	0	0	0	0	0	0	1	0	0	1	3	0	1	0	**10**
5:15	3	1	0	0	0	0	3	0	1	0	0	2	5	0	2	0	**17**
5:30	1	0	0	0	1	0	1	0	0	0	0	0	1	2	1	0	**7**
5:45	1	0	0	0	2	0	1	0	1	0	0	1	1	0	1	0	**8**
Total	**29**	**1**	**0**	**0**	**4**	**0**	**13**	**1**	**5**	**0**	**0**	**7**	**60**	**3**	**12**	**0**	**135**

* There were two intersections treated here as one intersection. The reason that they were treated as one intersection is because peds or bicycles traveling through one of the intersections had to travel through both interections. The reason is that bicycles and pedestrians aren't allowed to enter onto the freeway.
A major attraction in the area was the race track, which attracted a lot of the pedestrian and bicycle movement in the intersection.

Total Pedestrians:	98
Total Bicycles:	37

Alder Drive and Prosser Dam Road near Highway 89 near Truckee Tuesday 6/06/07. Highway 89 runs north and south.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	1 (P)	2 (R)	3 (T)	4 (L)	5 (P)	6 (R)	7 (T)	8 (L)	9 (P)	10 (R)	11 (T)	12 (L)	13 (P)	14 (R)	15 (T)	16 (L)	Total
2:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
2:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:00	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**
3:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
3:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:00	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	**1**
4:15	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:30	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	**0**
4:45	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	**1**
5:00	0	0	0	0	0	0	0	0	0	0	3	0	0	0	0	0	**3**
5:15	0	0	0	0	0	0	0	1	0	0	9	0	0	0	0	0	**10**
5:30	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	**1**
5:45	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	**1**
Total	**0**	**0**	**1**	**0**	**0**	**0**	**0**	**1**	**0**	**2**	**12**	**0**	**1**	**0**	**1**	**0**	**18**

*The only attraction near this intersection is a middle school that is located west on Alder Drive.
A group of touring bicylists passed through at approximately 5:15 pm.

Total Pedestrians:	1
Total Bicycles:	17

Bear Street and State Route 28 in Kings Beach at Lake Tahoe Wednesday 6/07/06. Bear Street runs north from the intersection.

2:30-6:00 PM	Southbound				Westbound				Northbound				Eastbound				
Start 15 Minute Intervals	1 (P)	2 (R)	3 (T)	4 (L)	5 (P)	6 (R)	7 (T)	8 (L)	9 (P)	10 (R)	11 (T)	12 (L)	13 (P)	14 (R)	15 (T)	16 (L)	Total
2:30	10	0	2	0	0	0	0	0	8	0	0	0	7	0	0	0	**27**
2:45	13	1	4	0	1	2	1	0	6	0	0	0	12	0	0	0	**40**
3:00	9	0	0	0	0	0	2	0	0	0	0	0	2	0	0	0	**13**
3:15	4	0	0	0	0	0	0	0	6	0	0	2	7	0	2	0	**21**
3:30	7	0	0	0	2	0	0	0	3	0	1	0	4	0	0	0	**17**
3:45	2	3	0	0	0	0	1	0	10	0	1	0	11	0	0	1	**29**
4:00	4	0	0	0	0	0	1	0	0	0	0	0	13	0	1	0	**19**
4:15	2	1	1	0	0	0	1	0	1	0	0	0	8	2	2	0	**18**
4:30	11	0	3	0	2	0	0	0	6	0	0	0	18	0	0	0	**40**
4:45	3	1	1	1	0	0	1	0	4	0	0	0	13	0	0	1	**25**
5:00	5	0	0	0	1	0	1	0	3	0	0	0	12	0	1	1	**24**
5:15	3	2	0	0	2	1	1	0	5	0	3	0	10	0	0	0	**27**
5:30	2	1	0	1	0	0	3	0	0	0	0	0	3	0	1	3	**14**
5:45	8	1	1	0	0	0	1	0	0	1	0	0	7	0	1	0	**20**
Total	**83**	**10**	**12**	**2**	**8**	**3**	**13**	**0**	**52**	**1**	**5**	**2**	**127**	**2**	**8**	**6**	**334**

*The main attraction of the area would be the Kings Beach State Recreation Center.
There is also a coffe shop that is located across State Route 28 from the beach.

Total Pedestrians:	270
Total Bicycles:	64