Reasons for Drivers Failing To Yield at Multi-Lane Roundabout Exits: Transportation Pooled Fund Study Final Report

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Research, Development, and Technology
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FOREWORD

Roundabouts represent an important intersection control strategy for the Federal Highway Administration (FHWA) due to their ability to drastically reduce severe crashes. They are listed as one of FHWA's Proven Safety Countermeasures. Since FHWA published its first roundabout informational guide in 2000, the estimated number of roundabouts in the United States has grown from fewer than a hundred to several thousand.

As roundabouts become more common across a wide range of traffic conditions, roundabouts with more than one lane are seeing increased use. These multi-lane roundabouts have demonstrated good safety performance with respect to crashes involving injuries or fatalities, but some multi-lane roundabouts have experienced higher-than-desired property damage only (PDO) crashes, especially at exits. This final report details the work performed for a Transportation Pooled Fund project that investigates root causes and contributing factors for PDO crashes near multi-lane roundabout exits. The findings presented here provide guidance to practitioners and public agencies in support of proactive reductions in the potential for crashes at new multi-lane roundabouts and possible countermeasures to reduce PDO crashes at existing sites.

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Director, Office of Safety and Operations
Research and Development

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16. Abstract

The Federal Highway Administration (FHWA) has included roundabouts on a list of proven safety countermeasures since 2008. However, higher than expected numbers of property damage-only crashes occurring near multi-lane roundabout exits has emerged at some U.S. roundabouts. This report details a Transportation Pooled Fund study that investigates root causes and contributing factors for these crashes based on an evaluation of a sample of eight multi-lane sites. For each study site, the project team reviewed historical crash data; conducted field observations; collected drone video data; analyzed vehicular volumes and conflicts; and reviewed potential influences from roundabout geometry, signing, and markings and the roadway network. Findings related to each of these topics are presented throughout this report to provide guidance that supports proactive reductions in the potential for these crashes at new multi-lane roundabouts and potential countermeasures to reduce these crashes for existing sites.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1,000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or “metric ton”)	Mg (or “t”)
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or “t”)	megagrams (or “metric ton”)	1.103	short tons (2,000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	2.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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A	Incapacitating/Serious Injury (crash type)
AADT	average annual daily traffic
B	Nonincapacitating/Visible Injury (crash type)
C	Possible Injury/Complaint (crash type)
CTH	County Trunk Highway
EB	Eastbound
FHWA	Federal Highway Administration
ICD	inscribed circle diameter
K	Fatal (crash type)
MUTCD	*Manual on Uniform Traffic Control Devices*
NB	Northbound
NCHRP	National Cooperative Highway Research Program
O	No Injury (crash type)
PDO	property damage only
SB	Southbound
STH	State Trunk Highway
TPF	Transportation Pooled Fund
WB	Westbound

CHAPTER 1. BACKGROUND

The Federal Highway Administration (FHWA) has included roundabouts on a list of proven safety countermeasures since 2008.(1) However, higher-than-expected numbers of property damage only (PDO) crashes occurring near multi-lane roundabout exits have emerged at some U.S. roundabouts. This report details a Transportation Pooled Fund (TPF) study that investigates root causes and contributing factors for these crashes based on an evaluation of a sample of multi-lane sites. For each study site, the project team reviewed historical crash data; conducted field observations; collected drone video data; analyzed vehicular volumes and conflicts; and reviewed potential influences from roundabout geometry, signing and markings, and the roadway network. Findings related to each of these topics are presented throughout this report to provide guidance that supports proactive reductions in the potential for these crashes at new multi-lane roundabouts and potential countermeasures to reduce these crashes for existing sites.

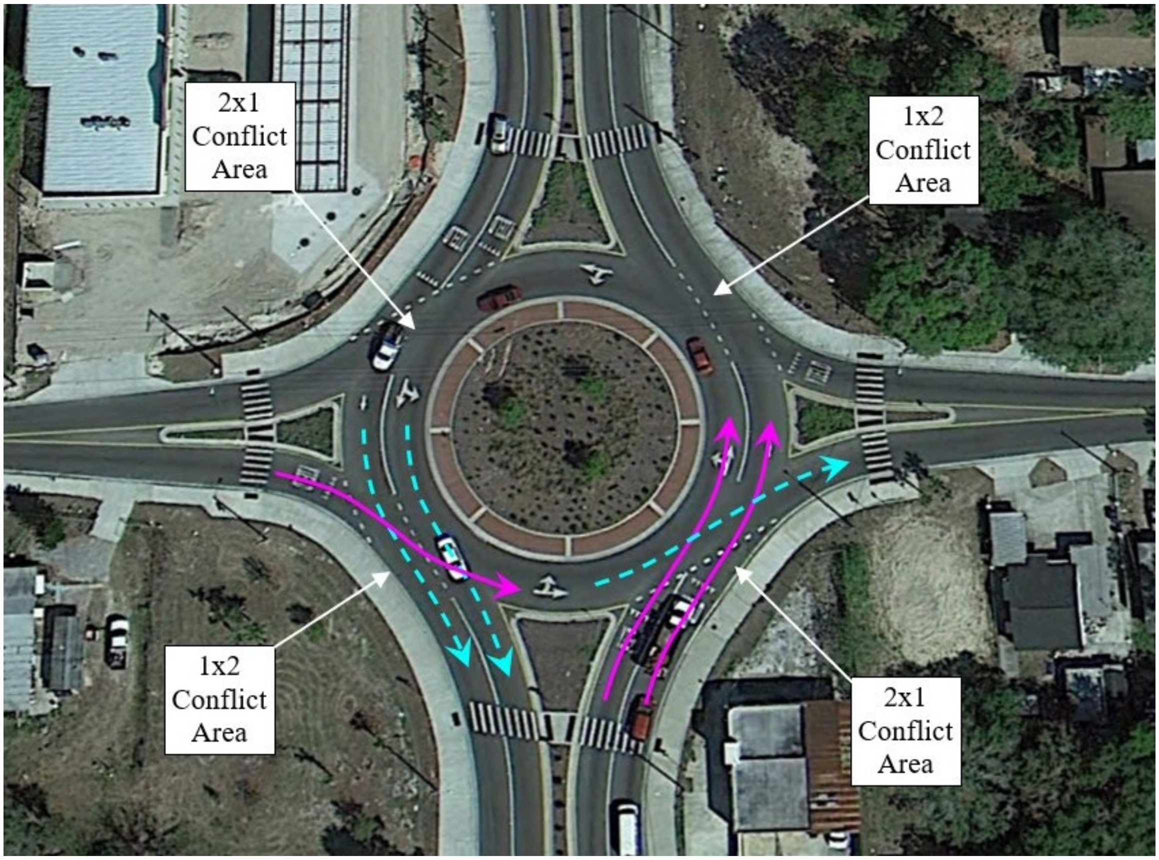
Studies of U.S. roundabouts dating back to the 1990s indicate that converting signalized or stop-controlled intersections into roundabouts of varying sizes and types leads to strong reductions in crashes. In 2007, based on aggregated data from 55 sites, the National Cooperative Highway Research Program (NCHRP) identified a 76-percent reduction in crashes involving severe injuries and fatalities and a 35-percent reduction in total crashes after signalized or stop-controlled intersections were converted to roundabouts. The 55 sites included a range of settings (urban and rural), number of legs (3 and 4), number of lanes (single or multi-lane), and prior traffic control (two-way stop, all-way stop, and traffic signal). In general, single-lane roundabouts demonstrated better reductions in both total and severe crashes after conversion than multi-lane roundabouts. At multi-lane roundabouts, instances of injury crashes were typically low, but higher numbers of PDO crashes were often observed. A greater number of conflict points at multi-lane roundabouts is one factor that will vary depending on number of lanes and complexity of lane configurations.(2)

The following terminology is used in this report to describe different multi-lane roundabout lane configurations and conflict area complexities:

- A 2x1 configuration refers to a conflict area with two entering lanes and one conflicting circulating lane. This configuration reflects the mainline entry of a partial two-lane roundabout, as illustrated in figure 1.
- A 1x2 configuration refers to a single-lane entry with two conflicting circulating lanes. This configuration reflects the minor road entry of a partial two-lane roundabout, as illustrated in figure 1.
- A 2x2 configuration reflects two entering lanes with two conflicting circulating lanes, as illustrated in figure 2.

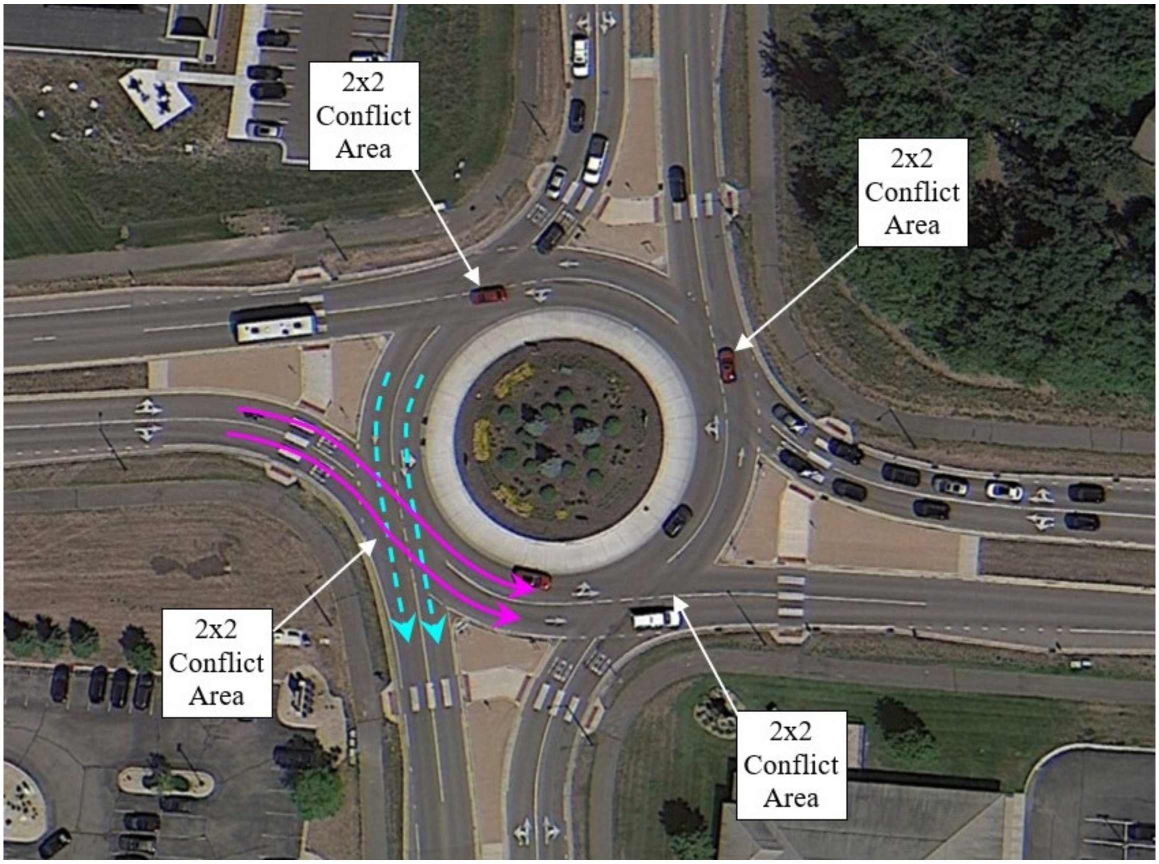
As illustrated in figure 1, 2x1 configurations with a mix of single-lane and two-lane entries result in fewer conflict points in the critical conflict areas near the entries and exits as compared to 2x2 configurations, illustrated in figure 2. Introduction of exclusive or dual left-turn movements has the potential to further increase the intersection complexity, requiring design details to support appropriate navigation. Various elements of the geometric design, signing, and pavement markings also have the potential to influence driver behavior and crash trends.

Previous research completed as part of *NCHRP Report 888: Development of Roundabout Crash Prediction Models and Methods* developed crash prediction models for multi-lane roundabouts at the intersection level and at a design level for individual legs.(3) However, the nature of the modeling in the report established possible correlations between geometric parameters and crash experience; it did not go into the level of detail needed to assess potential causes.



Original map: © 2013 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 14, 2013. 28° 00′ 12.37″ N, 82° 24′ 50.57″ W. Elevation 59 ft. Eye altitude 670 ft.

Figure 1. Photo. Example 2x1 roundabout configuration (Tampa, FL).



Original map: © 2021 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: August 12, 2021. 44° 40′ 53.36″ N and 93° 16′ 40.49″ W. Elevation 1085 ft.
Eye altitude 1,700 ft.

Figure 2. Photo. Example 2x2 roundabout configuration (Lakeville, MN).

As roundabouts have become more prevalent in the United States, roundabout design guidance has been developed and updated as part of an evolution in roundabout implementation. This evolution includes the development of the original publication in 2000 of the FHWA report *Roundabouts: An Informational Guide*.(4) This guide was replaced in 2010 by *NCHRP Report 672: Roundabouts: An Informational Guide: Second Edition*.(5) At the time of this writing, a new national roundabout guide is under development as part of NCHRP Project 03-130. Some individual States and agencies have also released their own design guidance to supplement the national document. State agencies participating in this TPF study, including Florida, Georgia, New York, Washington, and Wisconsin, each have either stand-alone roundabout guides or roundabout content incorporated into State design manuals.

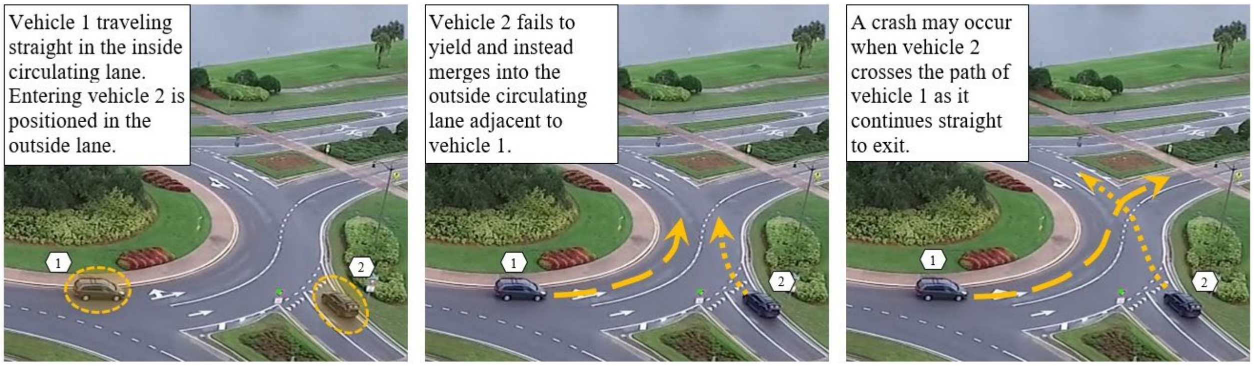
Through the various iterations of State and National guidebooks, multi-lane roundabout design guidance has evolved in significant ways since 2000. Geometrically, additional emphasis is now placed on entry and exit vehicle path alignments, a range of strategies have been introduced for designing for trucks, and enhanced guidance has been introduced for multimodal design elements. Some agencies have also shifted their preferences toward the use of approach alignments that offset the centerline of the leg to the left of the roundabout center. This strategy results in more deflection and speed control through the entries and less curvature through the exits.

In the 2000 FHWA informational guide, no lane markings were recommended within the circulatory roadway.(4) However, use of lane markings was later introduced into the 2009 *Manual on Uniform Traffic Control Devices* (MUTCD) and has become a standard component of roundabout design.(6) Various patterns of lane markings within the circulatory roadway have been implemented, along with different styles of arrows on the approach signs and markings. These changes in practice, among others, reflect a goal of continuing to maximize safety performance at multi-lane roundabouts. However, crashes near roundabout exits remain a common type, particularly at 2x2 roundabout configurations.

There are several violation and conflict types that may be contributing to crashes near roundabout exits. Example violations and conflicts that may be attributable to design components include:

- Failure of entering vehicles to yield to vehicles in both circulating lanes (figure 3).
- Left-turn movement from the incorrect outside lane (figure 4).
- Right-turn movement from the incorrect inside lane (figure 5).

A variety of factors or combinations of factors may contribute to these violations. A recent study by the Minnesota Department of Transportation discussed in the report titled *Evaluation of Safety and Mobility of Two-Lane Roundabouts* is one example of previous efforts to evaluate driver behavior and violation rates.(7) The study looked at violations at four multi-lane roundabouts over an extended period, including before/after analysis for effectiveness of improvements. The study identified the benefits of lane markings and overhead signing, particularly on reducing instances of improper left turns or right turns. However, the study was not able to produce any additional insights into the nature of the problem or potential solutions related to entering vehicles failing to yield to both circulating lanes. All sites featured geometric designs with offset-left configurations and tangential or near-tangential exits.

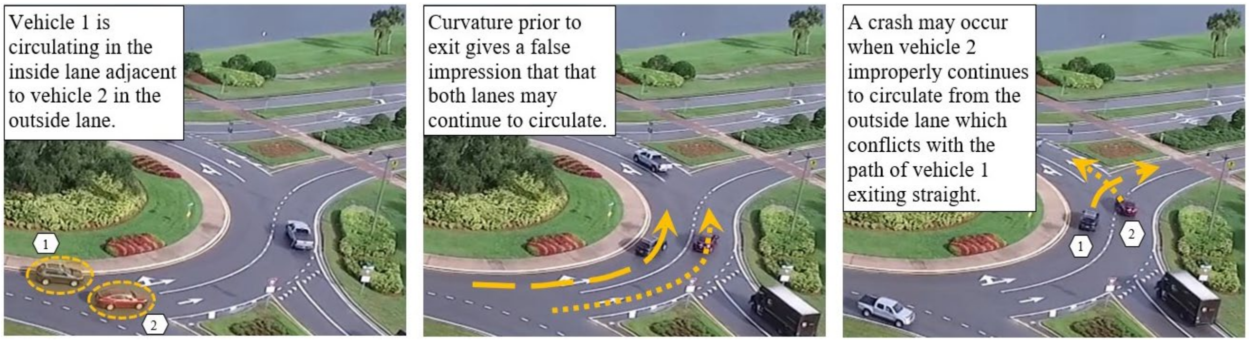

Vehicle 1 traveling straight in the inside circulating lane. Entering vehicle 2 is positioned in the outside lane.

Vehicle 2 fails to yield and instead merges into the outside circulating lane adjacent to vehicle 1.

A crash may occur when vehicle 2 crosses the path of vehicle 1 as it continues straight to exit.

Source: FHWA.

Figure 3. Photo. Entering vehicle failing to yield to both lanes.

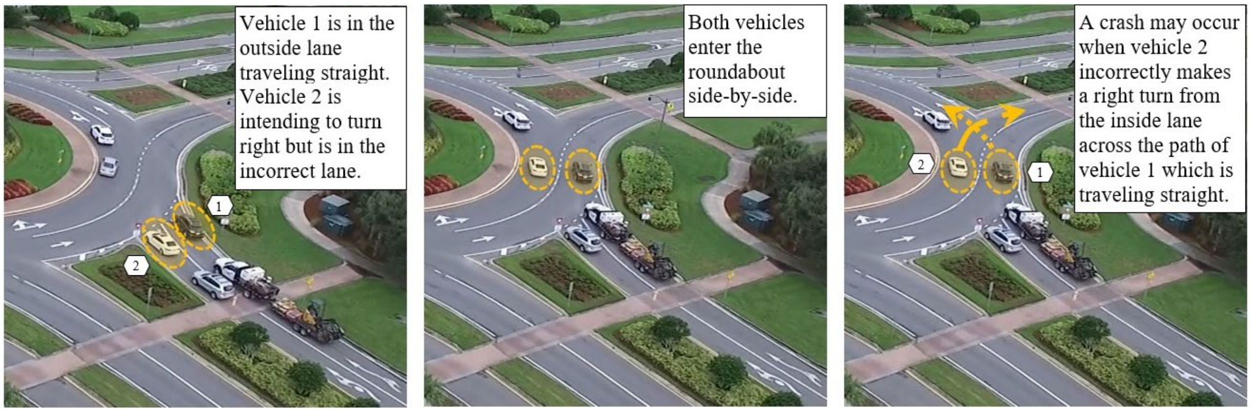

Vehicle 1 is circulating in the inside lane adjacent to vehicle 2 in the outside lane.

Curvature prior to exit gives a false impression that that both lanes may continue to circulate.

A crash may occur when vehicle 2 improperly continues to circulate from the outside lane which conflicts with the path of vehicle 1 exiting straight.

Source: FHWA.

Figure 4. Photo. Left turn from incorrect lane.


Vehicle 1 is in the outside lane traveling straight. Vehicle 2 is intending to turn right but is in the incorrect lane.

Both vehicles enter the roundabout side-by-side.

A crash may occur when vehicle 2 incorrectly makes a right turn from the inside lane across the path of vehicle 1 which is traveling straight.

Source: FHWA.

Figure 5. Photo. Right turn from incorrect lane.

CHAPTER 2. SITE SELECTION AND DATA COLLECTION

Candidate study sites were identified and screened following a tiered framework and coordination with the project panel. This chapter summarizes criteria considered during each tier of the screening process and a summary of the characteristics of the final selected sites, including geometric features, signing, and pavement markings. Further discussion is provided regarding data sources and field data collected as part of the project investigations.

SITE SELECTION PROCESS AND SITE CHARACTERISTICS

The team selected sites to provide a range of geometric, signing, marking, and traffic conditions to capture potential key factors contributing to crash patterns occurring near multi-lane exits. The study project scope included a total of eight study sites, divided into five "problem sites" and three "control sites." Problem sites were defined for this project as multi-lane roundabouts that experience high frequencies of failure-to-yield crashes or exit-circulating crashes. Control sites were defined as multi-lane roundabouts with similar geometric and traffic design features as the problem sites but lower crash frequencies. This definition of problem sites and control sites is used throughout the remainder of the report.

Candidate multi-lane roundabout sites were identified and reviewed through a two-tier screening process based on geometric and traffic control device configuration. The following criteria were established by the project team for candidate sites:

- Intersection configuration:
    - Preference for 2x2 entry/exit roundabout configuration, which provides four conflict areas, each with two entering and two conflicting circulating lanes.
    - Preference for four legs.
    - Priority for sites where geometric design is without clear deficiencies and inscribed circle diameters (ICDs) are within the typical range for a two-lane roundabout (140–200 ft).
- Age of roundabout: Minimum of 2 yr in operation to provide sufficient crash history.
- Average annual daily traffic (AADT): Daily traffic volumes within the typical range for a multi-lane roundabout configuration (minimum of 20,000 daily vehicles).
- Crash history:
    - Data available on annual crashes and crash patterns.
    - Access to individual crash reports or similar crash details sufficient to review the crash location and type.

- Location:
    - Preference for sites in States contributing to the TPF project, although site screening was not limited to those States.
    - Consideration of the ability to cluster sites to provide efficiency in data collection and allow for comparison between similar driver populations.
    - Consideration of proximity to airports, railroads, or similar areas that would limit the use of drones for data collection.

The team compiled an initial long list of potential multi-lane roundabout sites based on multiple sources. All sites included on the long list featured one or more 2x2 conflict areas (two entering lanes with two conflicting circulating lanes). The database of sites generated as part of *NCHRP Report 888, Development of Roundabout Crash Prediction Models and Methods* provided geometric, crash, and volume data for 10 multi-lane sites with 2x2 configurations across 5 States: Florida, Minnesota, New York, Washington, and Wisconsin.(3) Additional sites were added based on a review of a national roundabout database.(8) Possible multi-lane roundabout sites and data were also contributed by TPF member agencies.

Using the data sources mentioned previously, the team compiled an initial long list of 47 multi-lane roundabouts across the United States for consideration in this study. For each site in the long list, the team compiled information related to intersection configuration, age, AADT, and crash history. The team also gathered the following information related to roundabout geometric considerations, signing, markings, and context:

- Roundabout design case to accommodate heavy vehicles, as described in several State DOT roundabout guides, including Wisconsin DOT:(9)
    - Case 1: Roundabouts "designed to allow trucks to encroach into adjacent lanes as they approach, enter, circulate, and exit the intersection."
    - Case 2: Roundabouts "designed to accommodate trucks in-lane as they approach and enter the roundabout but may require trucks to encroach into adjacent lanes as they circulate and exit the intersection. Case 2 roundabouts have a painted 'gore' area between lanes on the approaches."
    - Case 3: Roundabouts "designed to accommodate trucks in-lane as they approach and traverse the entire intersection. Case 3 roundabouts have a painted 'gore' area between lanes on the approaches. Case 3 roundabouts typically are designed to allow trucks to stay in lane for through and left turning movements, while right turning trucks may occupy multiple lanes as they exit."
- Key dimensions, including ICD, entry and exit widths, and circulating width.
- Pavement marking scheme and style (i.e., fishhook versus standard arrows, circulatory roadway lane marking patterns, use of gore striping through entries, etc.).

- Signing scheme and placement (i.e., side-mounted versus overhead-mounted).
- Site context (i.e., urban, suburban, rural).

The team ranked the sites in the long list into three tiers based on the following characteristics:

- Tier 1: Sites observed to have the following:
    - Full 2x2 configuration with four legs.
    - AADT greater than 20,000 vehicles per day.
    - High or low numbers of historical crashes that clearly fit into a "problem site" or "control site" category.
- Tier 2: Sites observed to meet most of the Tier 1 criteria but that have a possible deficiency in one category, such as the following:
    - Four legs but not a full 2x2 configuration (e.g., use of an exclusive left-turn lane that results in one leg having a single-lane exit).
    - AADT less than 20,000 vehicles per day.
    - Geometric characteristics substantially different from the guidance presented in *NCHRP Report 672*.(5)
    - Historical crash totals in the middle of the range.
- Tier 3: Sites observed to have the following characteristics:
    - Three approach legs or only one 2x2 conflict area.
    - AADT of less than 20,000 vehicles per day.
    - Geometric characteristics substantially different from the guidance presented in *NCHRP Report 672*.
    - Signing or marking deficiencies possibly influencing crash history.

Table 1 summarizes the long list of candidate sites by State and tier.

Table 1. Long list of candidate sites.

State	Number of Sites Screened	Number of Sites in Tier 1	Number of Sites in Tier 2	Number of Sites in Tier 3
Florida	9	1	3	5
Illinois	1	1	—	—
Indiana	9	8	1	—
Michigan	1	1	—	—
Minnesota	2	2	—	—
New York	4	—	3	1
Ohio	6	3	2	1
Texas	4	3	—	1
Washington	1	1	—	—
Wisconsin	10	4	6	—
Total	47	24	15	8

—No data.

Based on desktop screening efforts for each of the long-list sites and discussions with Technical Advisory Panel members from TPF-member agencies, the team narrowed down the long list to a short-list of 25 sites from which the final 8 study roundabout sites would be selected. Alternate sites were also identified in case chosen sites had to be disqualified later for some reason. The distribution of the 25 short-listed sites was as follows:

- One site in Florida.
- One site in Illinois.
- Seven sites in Indiana.
- One site in Michigan.
- Two sites in Minnesota.
- Four sites in New York.
- One site in Ohio.
- One site in Washington.
- Seven sites in Wisconsin.

From the short list, the team selected five problem sites and three control sites. Two primary clusters of sites were selected to facilitate comparisons within driver populations and considerations for streamlining data collection, as follows:

1. Three sites in Indiana and Ohio: 2 in Carmel, IN, and 1 in Hilliard, OH.
2. Three sites in Wisconsin.

The remaining two study sites were selected in Florida and New York to provide geographic diversity among the TPF participants. Table 2 summarizes the characteristics of the three selected control sites.

Table 2. Control site characteristics.

Intersection	Location	Lane Config.	ICD (ft)	Lane-Use Signing	Pavement Marking	AADT	Crash History
106th St. and Illinois St.	Carmel, IN	2x2; single lane exit, one leg	165	Side-mounted	Fishhook arrows	N/A[1]	44 crashes (2016–2019)
Jackson St. and Murdock Ave.	Oshkosh, WI	2x2	135	Overhead mounted	Standard arrows	28,450	39 crashes (2017–2019)
Monroe Rd. and Dickinson Rd.	De Pere, WI	2x2	184	Side-mounted	Standard	22,050	23 crashes (2017–2019)

[1] AADT was not available at all sites at time of data collection/screening.

Config. = configuration.

Table 3 summarizes the characteristics of the five selected problem sites and one alternate site.

Table 3. Problem site characteristics.

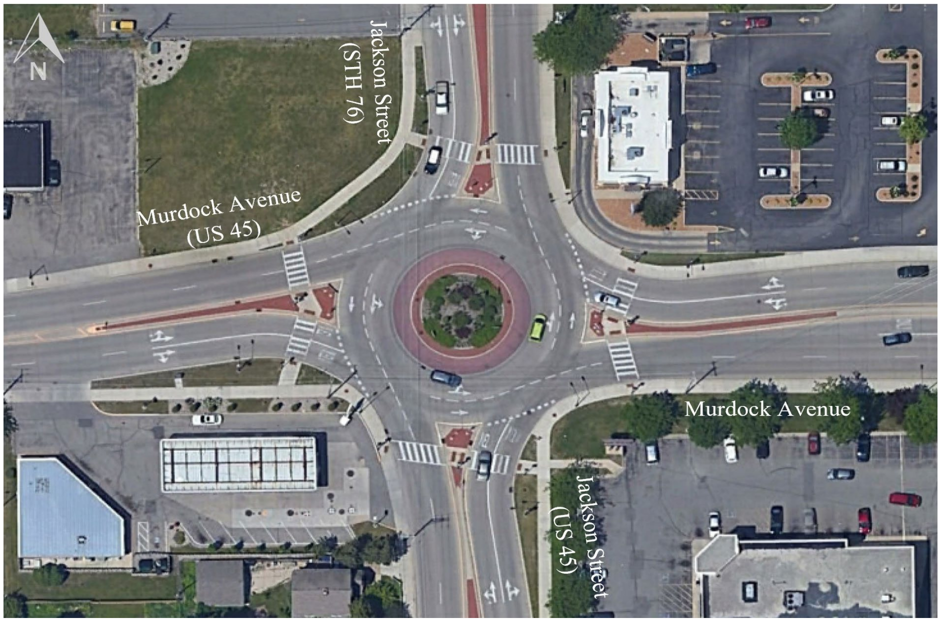
Intersection	Location	Lane Config.	ICD (ft)	Lane-Use Signing	Pavement Marking	AADT	Crash History
Wickham Rd. and Lake Andrew Blvd.	Melbourne, FL	2x2	200	Side-mounted	Fishhook arrows	25,000	182 crashes (2017–2019)
116th St. and Illinois St.	Carmel, IN	2x2	177	Side-mounted	Fishhook arrows	N/A[1]	192 crashes (2016–2019)
US 9/NY SR 67 and Dunning St.	Malta, NY	2x2; single lane exit, two legs	165	Side-mounted	Fishhook arrows, gore striping	26,500	116 crashes (2016–2019)
New Scotland Rd. and Cherry Ave. (alternate site)	Slingerlands, NY	2x2; single lane exit, two legs	198	Side-mounted	Fishhook arrows; gore striping	30,000	126 crashes (2016–2019)
Main St. and Cemetery Rd.	Hilliard, OH	2x2	159	Side-mounted	Fishhook arrows	32,000	231 crashes (2014–2016)
South 83 (North Wales Rd.) and US 18 (West Summit Ave.)	Wales, WI	2x2; Single lane exit, one leg	152	Overhead and side-mounted	Standard arrows, gore striping	34,000	104 crashes (2017–2019)

[1] AADT was not available at all sites at time of data collection/screening.

Aerial views illustrating each of the study sites are provided in figure 6 through figure 14.

Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: October 10, 2018. 39° 56′ 29.71″ N and 86° 09′ 40.36″ W.
Elevation 821 ft. Eye altitude 1,752 ft.

Figure 6. Photo. Carmel, IN—Aerial view of roundabout at 106th Street and Illinois Street.

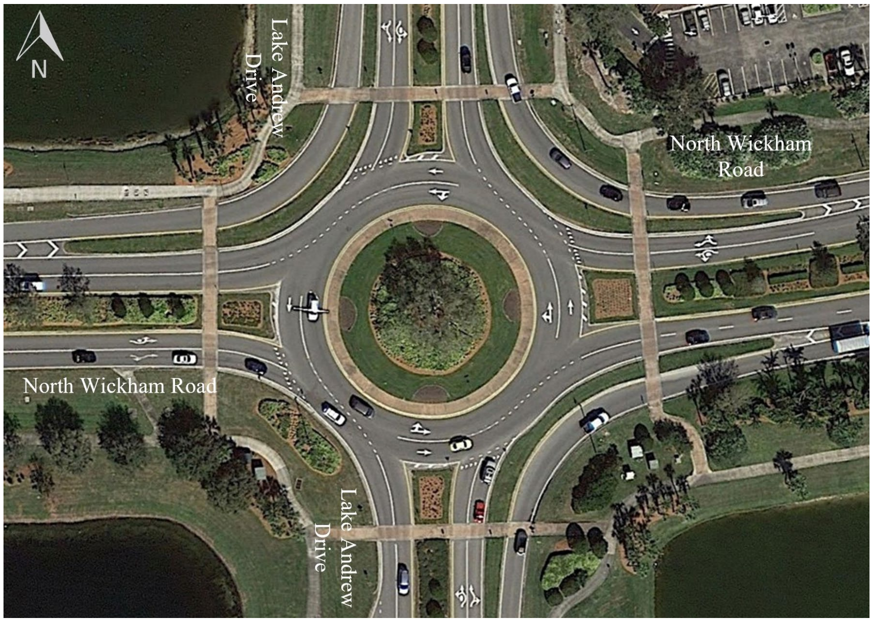


Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: April 13, 2015. 44° 02′ 21.52″ N and 88° 32′ 33.17″ W. Elevation 760 ft.
Eye altitude 1,539 ft.
STH = State Trunk Highway.

Figure 7. Photo. Oshkosh, WI—Aerial view of roundabout at Jackson Street (STH 76) and Murdock Avenue (US 45).

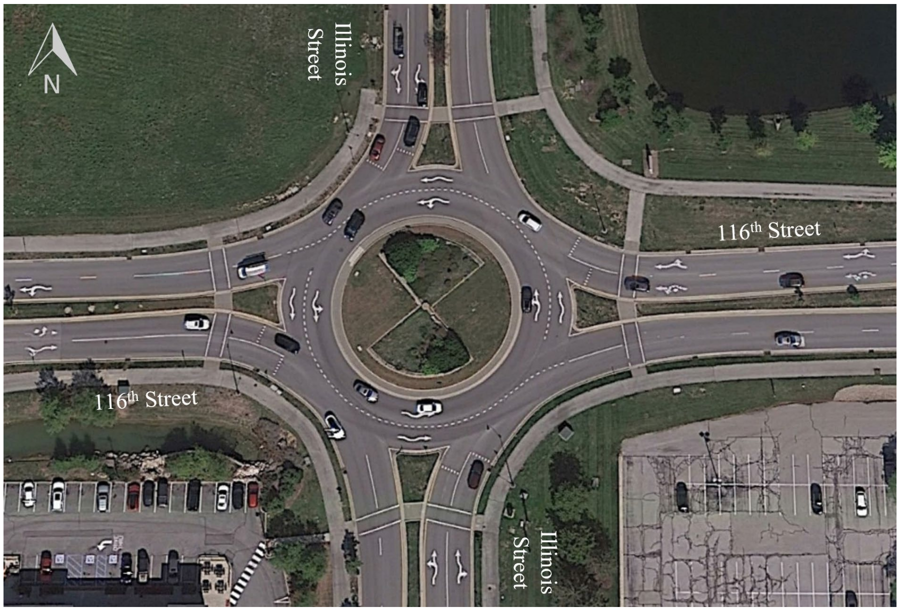
Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: May 17, 2018. 44° 25′ 57.57″ N and 88° 00′ 58.87″ W. Elevation 598 ft.
Eye altitude 1,485 ft.
CTH = County Trunk Highway.

Figure 8. Photo. De Pere, WI—Aerial view of roundabout at Monroe Road (CTH GV) and Dickinson Road (CTH G).



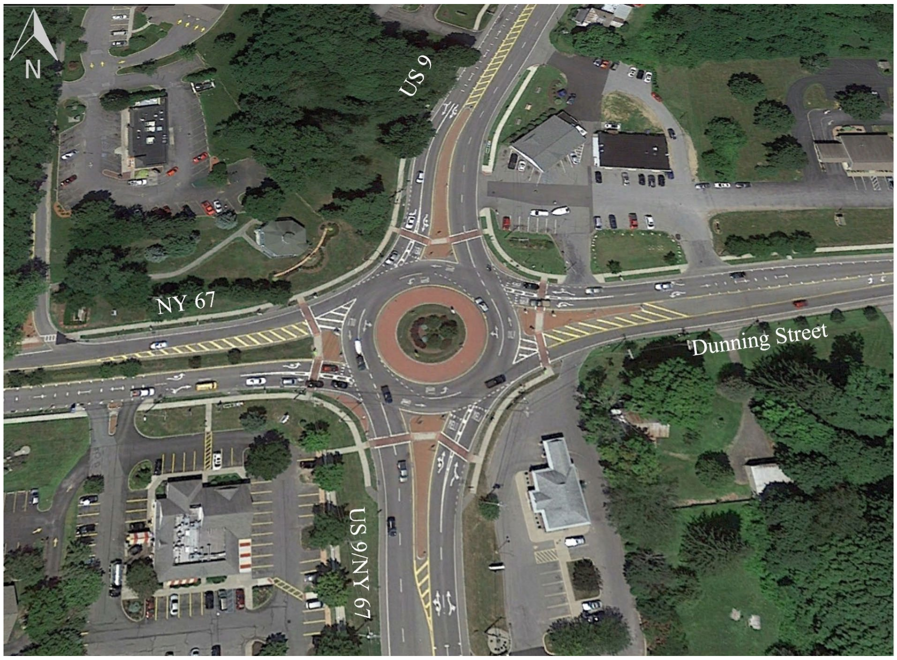
Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

Figure 9. Photo. Melbourne, FL—Aerial view of roundabout at Lake Andrew Drive and Wickham Road.



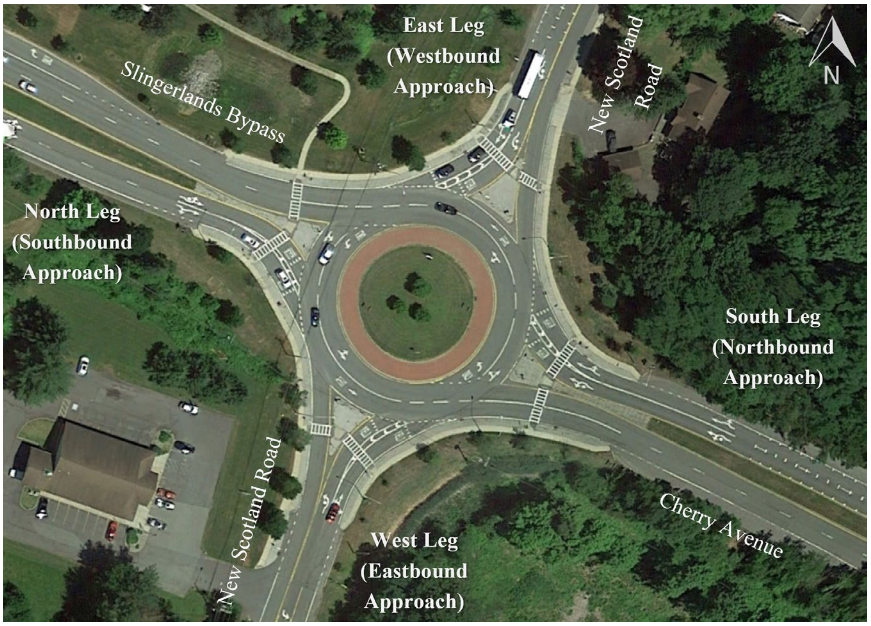
Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 10. Photo. Carmel, IN—Aerial view of roundabout at 116th Street and Illinois Street.



Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 11. Photo. Malta, NY—Aerial view of roundabout at US 9, NY 67, and Dunning Street.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 38′ 13.51″ N and 73° 51′ 21.50″ W. Elevation 217 ft.
Eye altitude 1,205 ft.

Figure 12. Photo. Slingerlands, NY—Aerial view of roundabout at New Scotland Road and Cherry Avenue.

Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 17, 2018. 40° 01′ 48.28″ N and 83° 09′ 40.58″ W. Elevation 937 ft.
Eye altitude 1,935 ft.

Figure 13. Photo. Hilliard, OH—Aerial view of roundabout at Main Street and Cemetery Road (as observed in May 2019).

Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: Imagery date: March 16, 2018. 43° 00′ 43.21″ N and 88° 23′ 02.71″ W. Elevation 987 ft. Eye altitude 2,450 ft.

Figure 14. Photo. Wales, WI—Aerial view of roundabout at South 83 (North Wales Road) at US 18 (West Summit Avenue).

Additional information related to the study's site lane configurations is summarized in table 4 and table 5.

Table 4. Control site lane configurations.

Intersection	SB Entry Lane Config.	NB Entry Lane Config.	WB Entry Lane Config.	EB Entry Lane Config.	Spiral Within Circulatory Roadway	Entries With Lane Additions	Single Lane Exits or Exit-Lane Merging
Carmel 106th	LT/TR	LT/TR	L/LTR	LT/TR	Painted	EB	Single lane WB exit
Oshkosh	LT/TR	LT/TR	LT/TR	LT/TR	—	—	Lane drop WB exit
De Pere	LT/TR	LT/TR	LT/TR	LT/TR	—	EB and WB	Lane merge EB and WB exits

—Not applicable.
EB = eastbound; NB= northbound; SB = southbound; WB = westbound.
L = exclusive left-turn lane; LT = shared left through lane; LTR = shared left through right lane; R = exclusive right-turn lane; TR = shared through right lane; RT bypass = right-turn bypass.

Table 5. Problem site lane configurations.

Intersection	SB Entry Lane Config.	NB Entry Lane Config.	WB Entry Lane Config.	EB Entry Lane Config.	Spiral Within Circulatory Roadway	Entries With Lane Additions	Single Lane Exits or Exit Lane Merging
Melbourne	LT/TR/R	LT/TR/R	LT/TR/R	LT/TR	—	RT bypass lanes on NB, SB, and WB entries	—
Carmel 116th	LT/TR	LT/TR	LT/TR	LT/TR	—	—	—
Malta	LT/TR	LT/TR	L/TR	L/TR	Painted	WB	Single lane EB and WB exits
Slingerlands	LT/TR	LT/TR	L/LTR	L/LTR	Painted	EB and WB	Single lane EB and WB exits
Hilliard	LT/TR	LT/TR	LT/TR	LT/TR	—	SB and WB	Lane merge on NB and EB exits
Wales	LT/TR	LT/TR	L/TR	LT/TR	Physical spiral built into central island curbline	WB	Single lane WB exit

—Not applicable.

Information regarding signing and pavement marking characteristics is summarized in table 6 through table 9. Table 6 summarizes signing characteristics at the selected control sites.

Table 6. Control site signing characteristics.

Intersection	Intersection Warning Sign Type (Speed Plaque Used?)	Advance Guide Signs	Lane-Use Signs Per Approach	Lane-Use Sign Placement and Arrow Type (Standard or Fishhook)	Yield Sign Placement (One Side, Both Sides)
Carmel 106th	Circular (N)	None	1 sign	Right side (fishhook)	Both
Oshkosh	W2-6 (Y)	Route assemblies	1 sign	Overhead (standard)	Both
De Pere	Circular (Y)	Route assemblies	1 sign	Right Side (fishhook)	Both

N = no; Y = yes.
W2-6 = Standard MUTCD Circular Intersection symbol sign.(6)

Table 7 summarizes signing characteristics at the selected problem sites.

Table 7. Problem site signing characteristics.

Intersection	Intersection Warning Sign Type (Speed Plaque Used?)	Advance Guide Signs	Lane-Use Signs Per Approach	Lane-Use Sign Placement and Arrow Type (Standard or Fishhook)	Yield Sign Placement (One Side, Both Sides)
Melbourne	—	Diagrammatic	1 set	EB and WB left side; NB and SB both sides (fishhook)	Both
Carmel 116th	Circular (Y)	—	1 sign	Right side (fishhook)	Both
Malta	W2-6 (Y)	Destination and route assemblies	1 sign	Right side (fishhook)	Both
Slingerlands	W2-6 (Y)	Destination and route assemblies	1 sign	Right side (fishhook)	Both
Hilliard	W2-6 (Y)	Route assemblies	1 sign	Right side (fishhook)	Both
Wales	Circular (Y)	Destination and route assemblies	2 sets	Overhead plus side mounted on both sides of approach (standard)	Both

—No sign provided

Table 8 summarizes information regarding pavement markings at the selected control sites.

Table 8. Control site pavement marking characteristics.

Intersection	Approach Lane-Use Arrow Type	Sets of Lane-Use Arrow Markings Per Approach	Yield Line, Yield Word Marking, or Both	Circulatory Roadway Lane Marking Style
Carmel 106th	Fishhook	1 set EB; 2 sets all other approaches	Yield line	Combination of solid and dotted lane lines
Oshkosh	Standard	2 sets	Yield word marking	Strong dash
De Pere	Standard	1 set	Yield word marking	Strong dash

Table 9 summarizes information regarding pavement markings at the selected control sites.

Table 9. Problem site pavement marking characteristics.

Intersection	Approach Lane-Use Arrow Type	Sets of Lane-Use Arrow Markings Per Approach	Yield Line, Yield Word Marking, or Both	Circulatory Roadway Lane Marking Style
Melbourne	Fishhook	1 set	Yield line	Combination of solid and dotted lane lines
Carmel 116th	Fishhook	2 sets	Yield line	Dotted
Malta	Fishhook	2 sets	Both	Combination of solid and dotted lane lines
Slingerlands	Fishhook	1 set EB; 2 sets on all other entries	Both	Combination of solid and dotted lane lines
Hilliard	Fishhook	1 set NB; 2 sets all other approaches	Yield line	Strong dash
Wales	Standard	3 sets SB; 2 sets all other approaches	Yield word marking	Strong dash

PROJECT DATA COLLECTION AND FIELD INVESTIGATIONS

For each of the study sites, the team coordinated with local agency partners to obtain key historical data, including the following:

- Historical AADT volume information and peak period intersection turning movement counts, if available.
- Historical crash data for 3 yr, with police reports or other narrative information sufficient to identify the crash type and location.
- Background information, including previous intersection studies, if applicable.

The team completed desktop reviews and analyses of each site to create an inventory as follows:

- Key dimensions and geometric characteristics.
- Crash locations and types using police report narratives for each individual crash.
- Summary graphics and tables of key crash trends by crash location.
- Crashes by severity, times of day, months of the year, and weather conditions. The team used time-of-day crash data in the selection of periods for further field investigations and analysis.
- Fastest path speeds for each site according to *NCHRP Report 672* procedures based on scaled aerial photography.(5)
- Inventory of signs and pavement markings on each roundabout approach and within the roundabout.

Information gleaned during the desktop screening process informed the data collection plan for field investigations. Based on available traffic volume and crash time-of-day data, the team identified 8 h throughout the day for video data collection to capture peak volume and crash periods as well as off-peak periods for comparison. Additionally, the team completed a full day of observations at each site over the course of the morning, midday, afternoon, and evening peak periods. During these sessions, the team recorded qualitative observations of traffic operations and driver behavior and times and locations for any observed vehicle conflicts and violations. Additionally, the team verified site geometric characteristics, including key dimensions and signing and pavement markings.

During field data collection, the team used a tethered drone to record 8 h of video footage for each site. The tether provides the drone with continuous power to allow for extended flight times. Continuous data collection for up to 4 h at a time was completed in the afternoon and evening hours at each site. Figure 15 shows the tethered drone in the process of collecting video data at the Hilliard site.

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Figure 15. Photo. Tethered drone collecting video data at Hilliard, OH site.

Figure 16 shows the drone operator and tethered cable management device, which maintains appropriate cable tensioning and spools excess cable.

Source: FHWA.

Figure 16. Photo. Drone operator and tethered cable management system.

Table 10 summarizes the dates for data collection at each site and the total hours of video data collected. Site observations and drone video data collection were completed on the same day to allow ground-level field observations to match with aerial drone footage to be analyzed later. At most sites, the collection of video data was completed on a single day. However, the Malta and Melbourne sites had data collection split up over multiple days due to adverse weather conditions.

Table 10. Field investigation and video data collection dates.

Intersection	Field Investigation Date	Hours of Video Data Collected
Carmel 116th	May 13, 2019	8
Hilliard	May 14, 2019	8
Carmel 106th	May 15, 2019	8
Malta	October 29–October 30, 2019	8
Slingerlands	October 30, 2019	3
Melbourne	September 15–September 17, 2020	8
De Pere	October 19, 2020	8
Oshkosh	October 20, 2020	8
Wales	October 21, 2020	8

The Slingerlands site was the alternate New York site and not intended as part of primary data collection. The study team completed field observations and gathered supplemental video there due to flexibility in travel schedule and its close proximity to Malta, the chosen New York site. Thus, even though only 3 h of video were captured at Slingerlands, site observations and crash data for the site are incorporated throughout the rest of this report.

For each site, the team reduced 4 h of video data, generally into four 1-h blocks, for further analysis and comparison of hourly data across sites. The team completed video data reduction and analysis in two parts, as follows:

- Lane-by-lane volume reduction and analysis: The team logged passenger cars, heavy vehicles, pedestrians, and bicycle users in 1-min intervals to provide information regarding volume profiles throughout each hour. The team logged vehicular turning movements (left, through, right, and U-turn) on a lane-by-lane basis corresponding to the lane the vehicle was in when it crossed the yield line entering the roundabout. The lane-by-lane breakdown of vehicle data allowed for further analysis of lane utilization and frequency of vehicles making turning movements from incorrect lanes. Summarized volume information is incorporated into chapters 3 through 6.
- Conflict analysis: On an approach-by-approach basis, the team reviewed video data and logged timestamps and details corresponding to various violation types. Violations were further categorized by severity including violation only, potential conflict, incident, near-crash, and crash. Further information regarding the violation types recorded and analysis results is presented in chapter 4.

The team prepared individual field investigation reports for each site to document findings from the desktop screening activities, field observations, and follow-up volume and conflict analyses. The field investigation reports provide additional detail regarding site-specific observations as well as more detailed volume and conflict analysis results.

CHAPTER 3. SAFETY ANALYSIS

The project team conducted a safety analysis of the control and problem sites as one component of investigating the root causes of crashes at multi-lane roundabouts. The team studied three consecutive years of crash history at each identified site. This analysis included review of detailed crash reports to verify information such as crash types and locations. The team aggregated crash data for the control and problem sites by crash frequency, severity, and type to allow for comparisons across sites. For selected crash types, the team performed supplemental analysis to review approach-level crash trends based on observed entering and circulating volume levels. At each site, the team verified that adjustments had not been made to the roundabout during the period covering 3 yr of reviewed crash data through the date of field observations.

Table 11 shows the total crashes at each of the reviewed control sites the during selected 3 yr periods.

Table 11. Total crashes at reviewed control sites during selected 3 yr periods.

Intersection	Site Code	Total Crashes	Period of Reviewed Crashes
106th St./North Illinois St., Carmel, IN	Carmel 106th	44	August 1, 2016–July 31, 2019
Murdock Ave./Jackson St., Oshkosh, WI	Oshkosh	39	January 1, 2017–December 31, 2019
Monroe Rd. (CTH GV)/Dickinson Rd. (CTH G), De Pere, WI	De Pere	23	January 1, 2017–December 31, 2019
Total crashes at all control sites over 3 yr	—	106	—
Average crashes per control site over 3 yr	—	35.3	—
Average crashes per control site per year	—	11.8	—

—No data.

Table 12 shows the total crashes at each of the reviewed problem sites the during selected 3 yr periods.

Table 12. Total crashes at reviewed problem sites during selected 3 yr periods.

Intersection	Site Code	Total Crashes	Period of Reviewed Crashes
Main St./Cemetery Rd., Hilliard, OH	Hilliard	231	January 1, 2014–December 31, 2016
116th St./North Illinois St., Carmel, IN	Carmel 116th	192	October 1, 2016–September 30, 2019
North Wickham Rd./Lake Andrew Dr., Melbourne, FL	Melbourne	182	January 1, 2017–December 31, 2019
New Scotland Rd./Cherry Ave., Slingerlands, NY	Slingerlands	126	May 1, 2016–April 30, 2019
US 9/NY SR 67/Dunning St., Malta, NY	Malta	116	May 1, 2016–April 30, 2019
North Wales Rd. (STH 83)/West Summit Ave. (US 18), Wales, WI	Wales	104	January 1, 2017–December 31, 2019
Total crashes at all problem sites over 3 yr	—	951	—
Average crashes per problem site over 3 yr	—	158.5	—
Average crashes per problem site per year	—	52.8	—

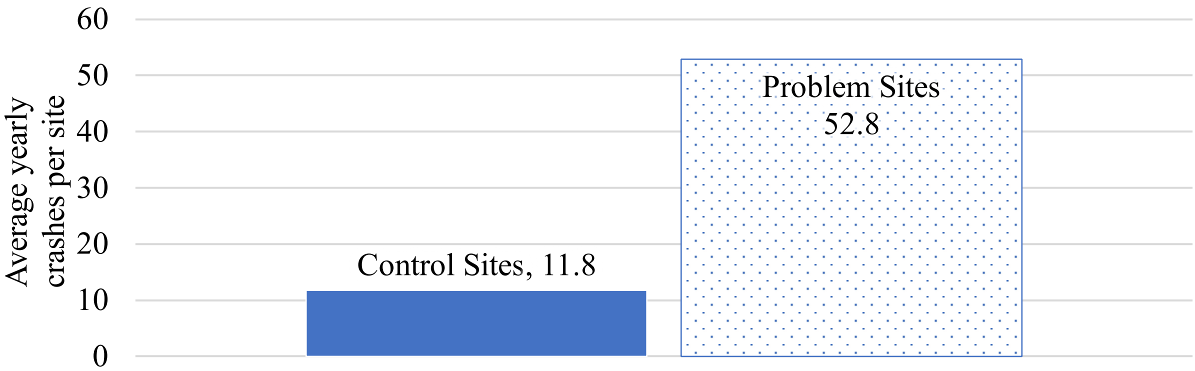
—No data.

Table 13 summarizes crashes across all the sites. As shown, the 3 control sites experienced a total of 106 crashes over 3 yr, an average of 35.3 crashes per control site over 3 yr. The 6 problem sites experienced a total of 951 crashes over 3 yr, an average of 158.5 crashes per problem site over 3 yr. These totals represent approximately 4.5 times more crashes per problem site than control site.

Table 13. Reviewed crashes at all sites.

Intersection Type	Control Sites	Problem Sites	All Sites
Total crashes over 3 yr	106	951	1,057
Average crashes per site over 3 yr	35.3	158.5	117.4
Average crashes per site per year	11.8	52.8	39.1

Figure 17 displays the average total crashes by site type.



Source: FHWA.

Figure 17. Graph. Average yearly crashes per site by site type.

The team further investigated the crashes at the control and problem sites by performing a deeper examination of the crash severity and type at each type of intersection. The results of this investigation are provided in the next two sections.

CRASH SEVERITY

Using the Federal KABCO crash severity scale, the severity of the crashes at each intersection was reviewed. For the review, the following common definitions were used to define each level of crash severity:

- K—Fatal.
- A—Incapacitating/Serious Injury.
- B—Nonincapacitating/Visible Injury.
- C—Possible Injury/Complaint.
- O—No Injury.

At five sites (Oshkosh, De Pere, Wales, Hilliard, and Melbourne), the crash severities were provided in a format directly compatible with the five crash severity levels associated with the KABCO scale. At the remaining four sites, the numbers of fatal (K), incapacitating/serious injury (A), and no injury (O) crashes were known, but the numbers of nonincapacitating/visible injury (B) and possible injury/complaint (C) crashes were not consistently known. Thus, the team reviewed the crash descriptions and police reports associated with all unspecified B and C crashes at these four sites to classify them as B crashes or C crashes in cases where the description clearly indicated the crash severity. However, 21 crashes among the 4 sites were not able to be classified as definitively either B crashes or C crashes, and these crashes were left as unspecified "B or C" crashes.

Table 14 summarizes the total crashes by crash severity at the control sites.

Table 14. Total crashes by crash severity at control sites.

Intersection	K	A	B	B or C	C	O	Total Crashes
Carmel 106th	0	0	0	2	0	42	44
Oshkosh	0	0	2	0	3	34	39
De Pere	0	0	1	0	2	20	23
Total crashes at all control sites	0	0	3	2	5	96	106
Average crashes per control site	0	0	1	0.7	1.7	32	35.3

Table 15 summarizes the total crashes by crash severity at the problem sites.

Table 15. Total crashes by crash severity at problem sites.

Intersection	K	A	B	B or C	C	O	Total Crashes
Hilliard	0	0	7	0	16	208	231
Carmel 116th	0	0	0	3	2	187	192
Melbourne	0	0	8	0	11	163	182
Slingerlands	0	1	0	7	10	108	126
Malta	0	0	0	9	1	106	116
Wales	0	0	3	0	6	95	104
Total crashes at all problem sites	0	1	18	19	46	867	951
Average crashes per problem site	0	0.2	3	3.2	7.7	144.5	158.5

Table 16 summarizes the total crashes by severity across all sites.

Table 16. Total crashes by crash severity at all sites.

Site Group	K	A	B	B or C	C	O	Total Crashes
Total crashes at all control sites	0	0	3	2	5	96	106
Average crashes per control site	0	0	1	0.7	1.7	32	35.3
Total crashes at all problem sites	0	1	18	19	46	867	951
Average crashes per problem site	0	0.2	3	3.2	7.7	144.5	158.5
Total crashes at all sites	0	1	21	21	51	963	1,057
Average crashes at all sites	0	0.1	2.3	2.3	5.7	107	117.4

As shown in table 16, there were no fatal crashes at any of the sites reviewed, and there was one incapacitating/serious injury crash at the problem site in Slingerlands. Crashes involving no injury were the predominant crash type at both the control and problem sites, representing

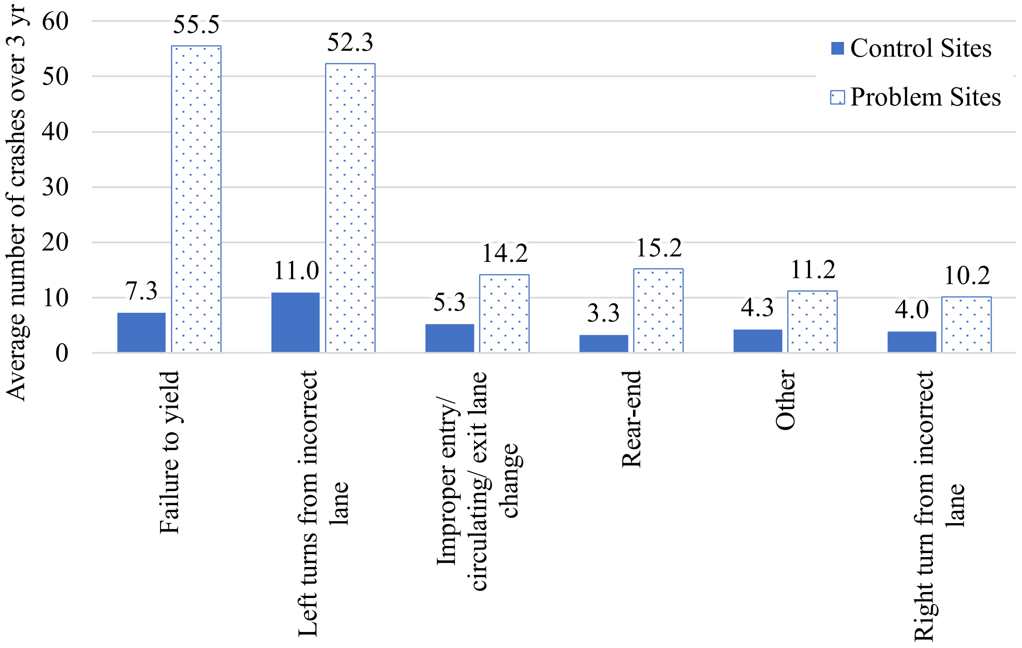
90.6 percent (96 of 106) of the crashes at the control sites and 91.2 percent (867 of 951) of the crashes at the problem sites. While both the control and problem sites had similar percentages of crashes at each crash severity level, because the problem sites had approximately 4.5 times more overall crashes per site, the numbers of B, unspecified B or C, and C crashes were higher at the problem sites than at the control sites. The average numbers of B crashes were three times higher at the problem sites than at the control sites (three crashes per problem site versus one crash per control site). The average of unspecified B or C crashes was 4.8 times higher at the problem sites than at the control sites (3.2 crashes per problem site versus 0.7 crashes per control site). The average of C crashes was 4.6 times higher at the problem sites than at the control sites (7.7 crashes per problem site versus 1.7 crashes per control site).

CRASH TYPE

The team reviewed crashes by type to identify trends related to crash type and intersection characteristics. The five most common crash types identified for further review are as follows:

a. Failure to yield.
b. Left turn from incorrect lane.
c. Improper entry/circulating/exit lane change.
d. Rear-end.
e. Right turn from incorrect lane.

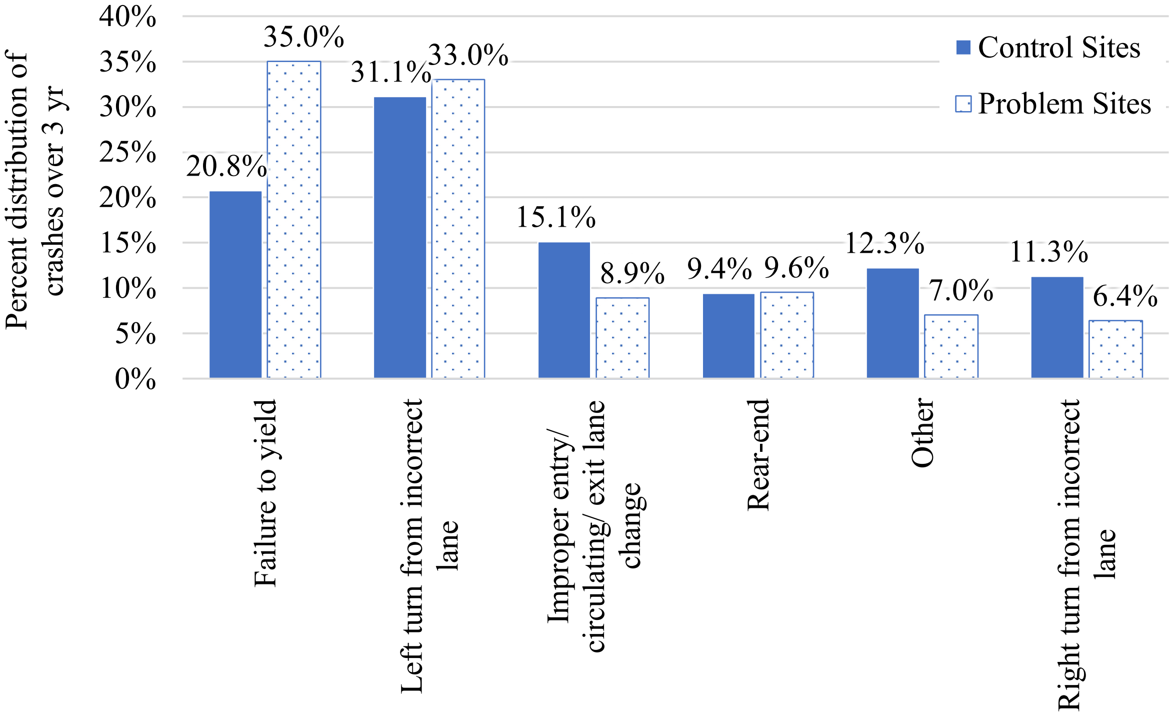
Figure 18 displays the average number of crashes by crash type per site, by site type. As shown, crashes involving failure to yield and crashes involving left turns from incorrect lanes account for the majority of crashes across all sites (51.9 percent of the control site crashes and 68 percent of the problem site crashes).



Source: FHWA.

Figure 18. Graph. Average number of each crash type over 3 yr.

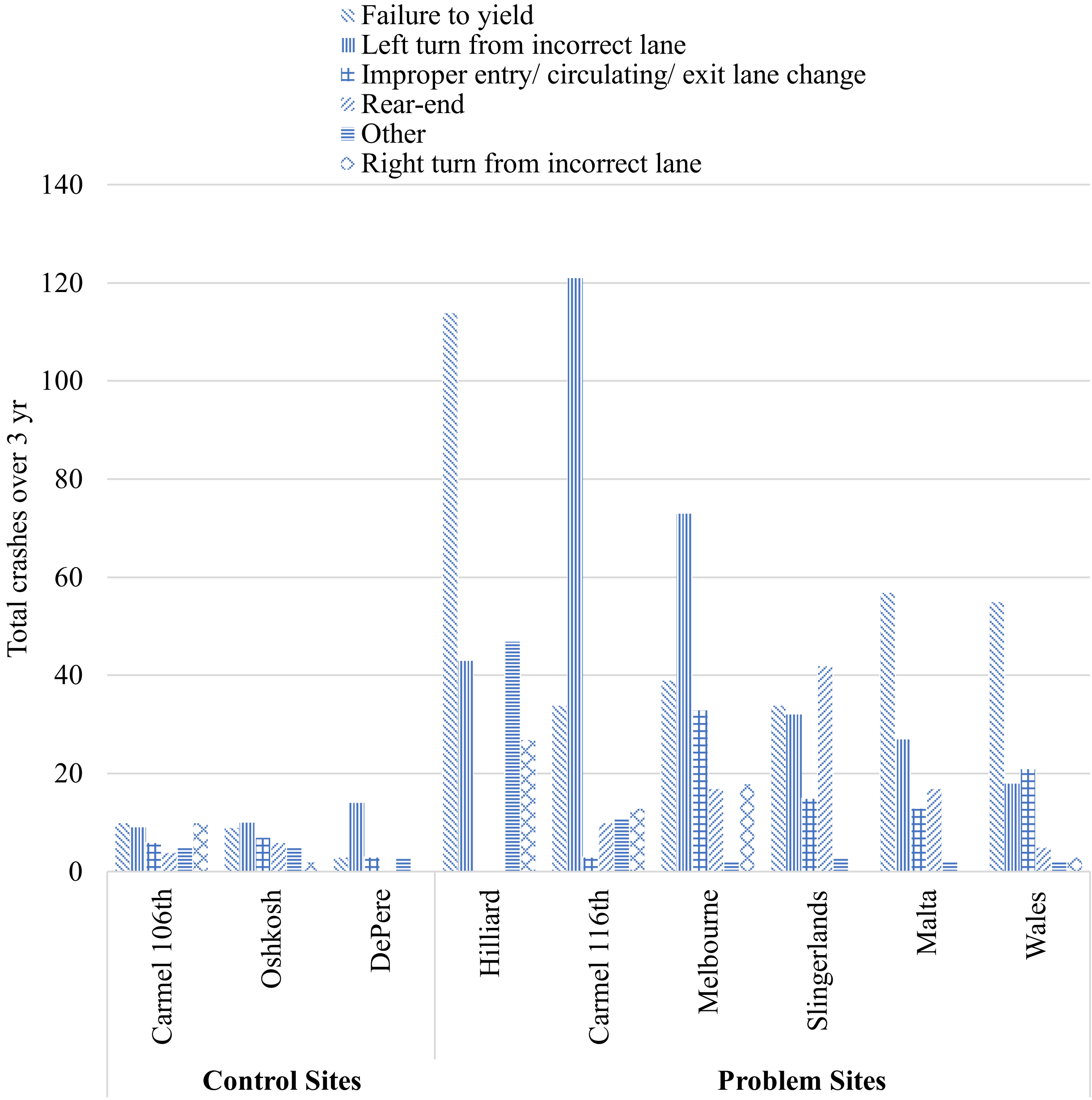
Figure 19 compares the distribution of crashes at problem versus control sites by crash type. At problem sites, failure-to-yield crashes represent 35 percent of total crashes, compared to 20.8 percent at problem sites. At control sites, crashes due to lane changes, right turns from incorrect lanes, and "other" types reflect a higher proportion of the total crashes compared to problem sites. The proportion of crashes due to left turns from incorrect lanes and rear-ending are comparable at control and problem sites.



Source: FHWA.

Figure 19. Graph. Percent distribution of crashes at control sites and problem sites by crash type over 3 yr.

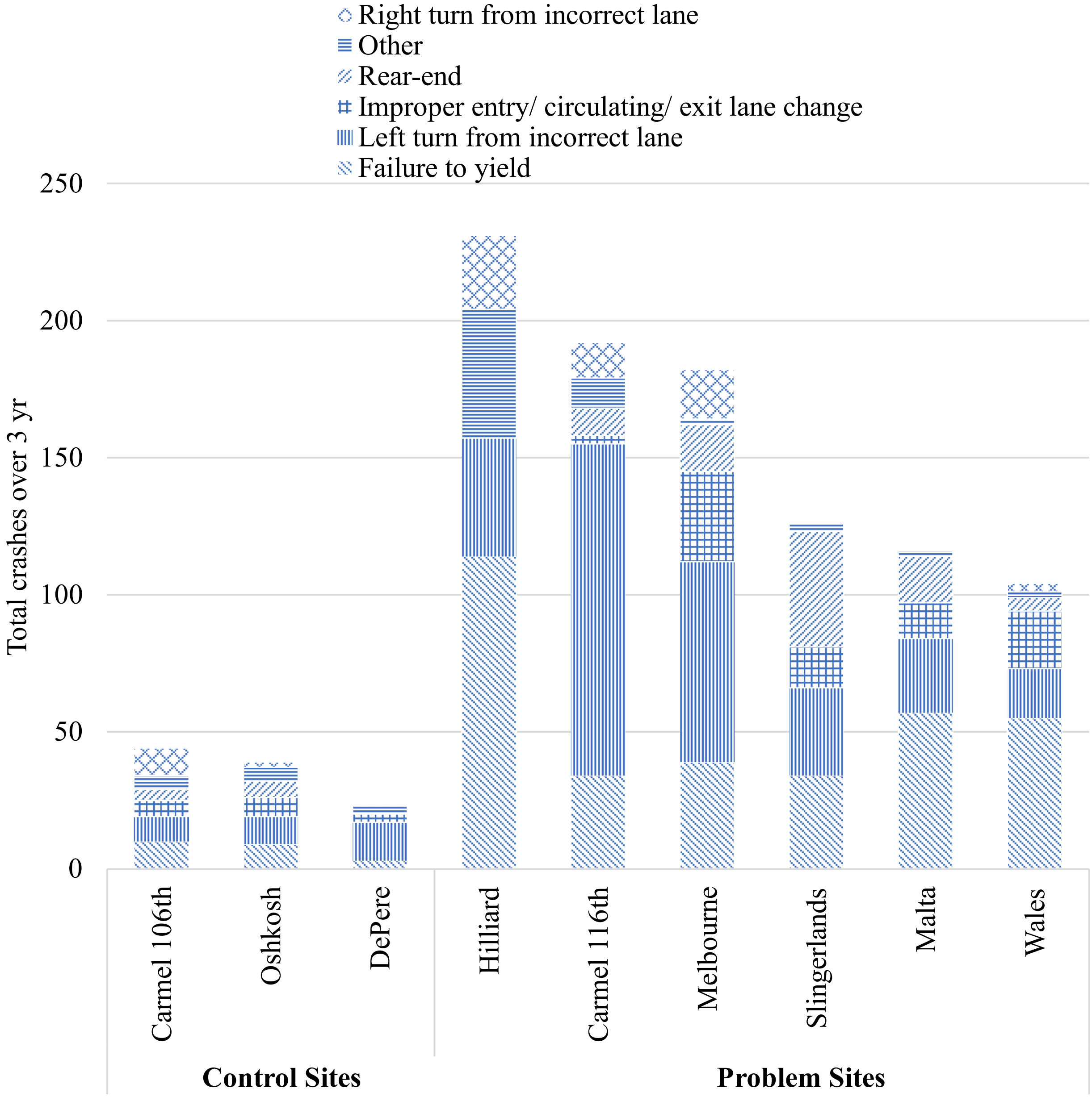
The team broke down the number of crashes by type by intersection, as seen in figure 20.



Source: FHWA.

Figure 20. Graph. Total crashes over 3 yr by intersection and crash type.

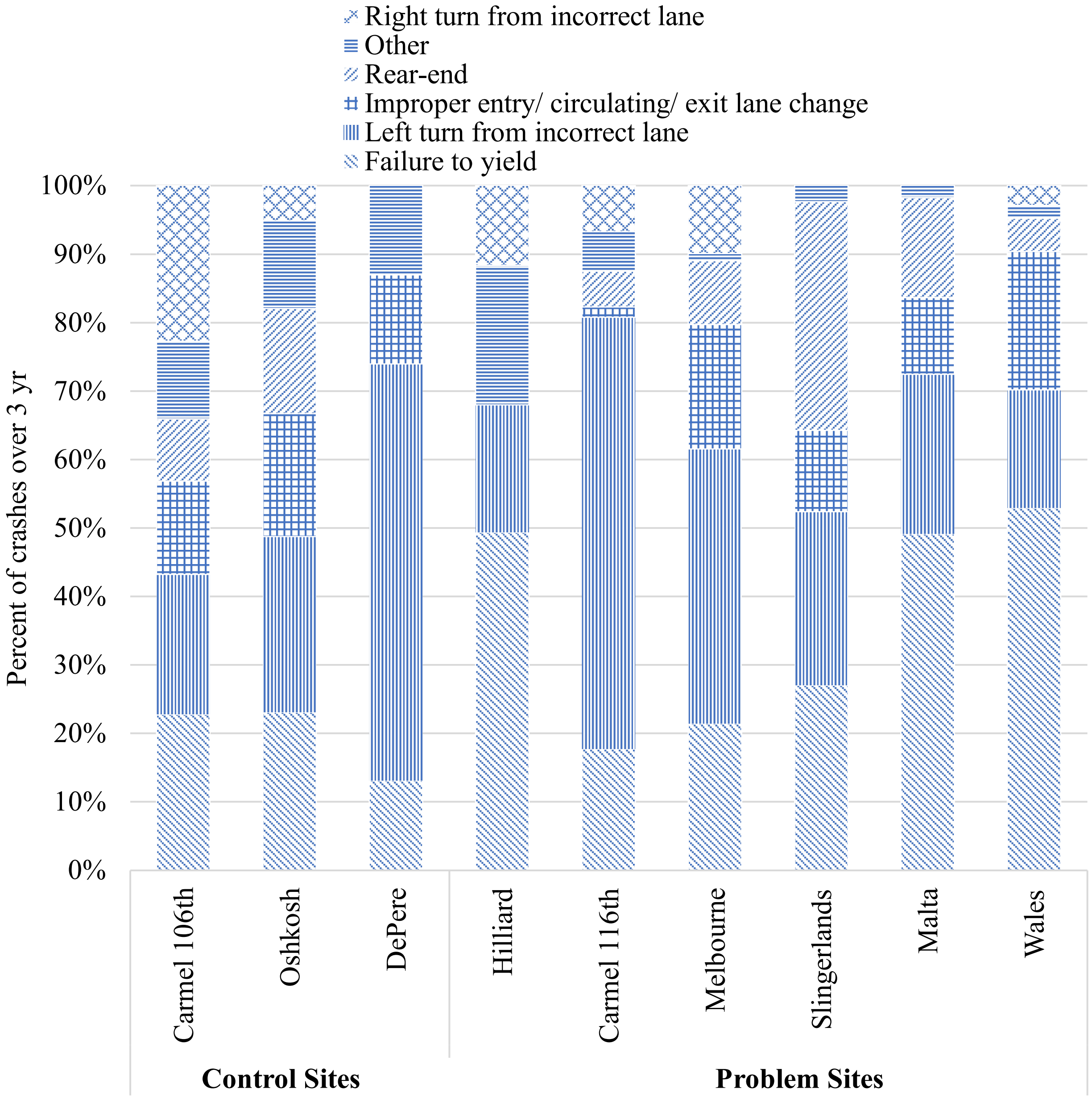
Figure 21 shows the same information in a stacked format.



Source: FHWA.

Figure 21. Graph. Stacked total crashes over 3 yr by intersection and crash type.

Figure 22 shows the same information as the percentage of crashes by crash type at each intersection. Failure-to-yield crashes make up about half of the total number of all crash types at the Hilliard, Malta, and Wales intersections. In contrast, crashes involving left turns from incorrect lanes surpass all other crash types at Carmel 116th and comprise most of the crashes at Melbourne. The numbers of crashes involving failure to yield, left turns from incorrect lanes, and rear-ending are all approximately the same at Slingerlands.



Source: FHWA.

Figure 22. Graph. Percent of crashes over 3 yr by crash type per intersection.

Table 17 summarizes the crashes by crash type and site type per intersection for the control sites.

Table 17. Crashes by crash type and site type per intersection for control sites.

Intersection	Failure To Yield	Left Turn From Incorrect Lane	Improper Entry/ Circulating/ Exit Lane Change	Rear-End	Other	Right Turn From Incorrect Lane	Total Crashes
Carmel 106th	10 (22.7%)	9 (20.5%)	6 (13.6%)	4 (9.1%)	5 (11.4%)	10 (22.7%)	44 (100%)
Oshkosh	9 (23.1%)	10 (25.6%)	7 (17.9%)	6 (15.4%)	5 (12.8%)	2 (5.1%)	39 (100%)
De Pere	3 (13%)	14 (60.9%)	3 (13%)	0 (0%)	3 (13%)	0 (0%)	23 (100%)
Average number of crashes by site and percent of total crashes at control sites	7.3 (20.8%)	11 (31.1%)	5.3 (15.1%)	3.3 (9.4%)	4.3 (12.3%)	4 (11.3%)	35.3 (100%)

Table 18 summarizes the crashes by crash type and site type per intersection for the problem sites.

Table 18. Crashes by crash type and site type per intersection for problem sites.

Intersection	Failure To Yield	Left Turn From Incorrect Lane	Improper Entry/ Circulating/ Exit Lane Change	Rear-End	Other	Right Turn From Incorrect Lane	Total Crashes
Hilliard	114 (49.4%)	43 (18.6%)	0 (0%)	0 (0%)	47 (20.3%)	27 (11.7%)	231 (100%)
Carmel 116th	34 (17.7%)	121 (63%)	3 (1.6%)	10 (5.2%)	11 (5.7%)	13 (6.8%)	192 (100%)
Melbourne	39 (21.4%)	73 (40.1%)	33 (18.1%)	17 (9.3%)	2 (1.1%)	18 (9.9%)	182 (100%)
Slingerlands	34 (27%)	32 (25.4%)	15 (11.9%)	42 (33.3%)	3 (2.4%)	0 (0%)	126 (100%)
Malta	57 (49.1%)	27 (23.3%)	13 (11.2%)	17 (14.7%)	2 (1.7%)	0 (0%)	116 (100%)
Wales	55 (52.9%)	18 (17.3%)	21 (20.2%)	5 (4.8%)	2 (1.9%)	3 (2.9%)	104 (100%)
Average number of crashes by site and percent of total crashes at problem sites	55.5 (35%)	52.3 (33%)	14.2 (8.9%)	15.2 (9.6%)	11.2 (7%)	10.2 (6.4%)	158.5 (100%)

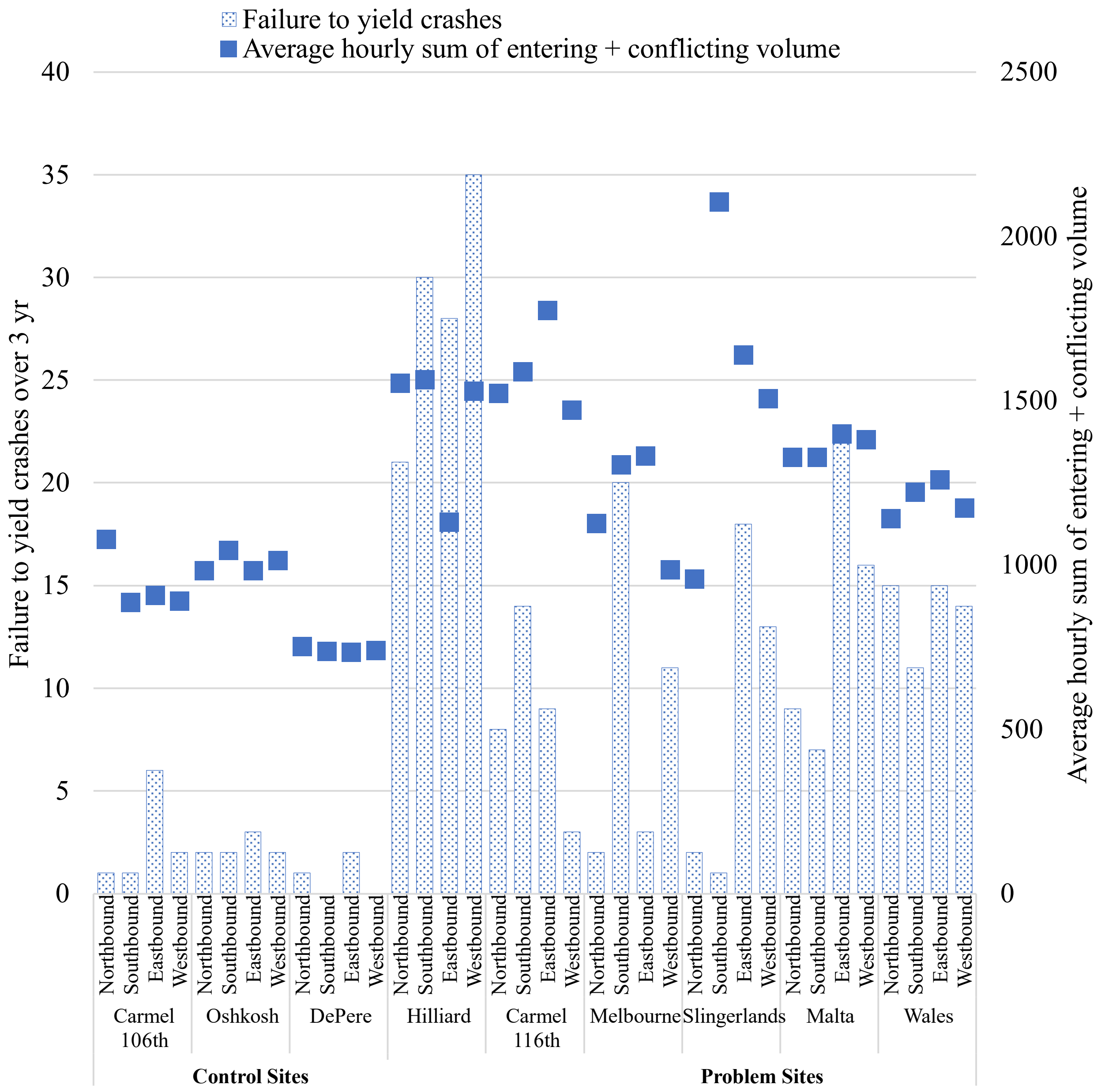
As shown in table 17 and table 18, the number of crashes involving failure to yield comprises an average of 20.8 percent of all crashes at the control sites, compared to 35 percent of all crashes at the problem sites. However, the average of crashes involving left turns from incorrect lanes comprises a similar proportion of crashes at control sites (31.1 percent) compared to problem sites (33 percent). The average proportion of crashes involving improper entry, circulating, or exit lane changes is higher at the control sites (15.1 percent) compared to the problem sites (8.9 percent). Meanwhile, the average proportion of rear-end crashes is similar at the control sites (9.4 percent) and the problem sites (9.6 percent). The average number of crashes involving right turns from incorrect lanes is higher at the control sites (11.3 percent) compared to the problem sites (6.4 percent).

Three crash types (failure to yield, left turn from incorrect lane, and right turn from incorrect lane) were identified for further review. These crash types were targeted because of their relationship to exit crashes and the likelihood of interventions reducing the numbers of these types of crashes. These three crash types are explored further in the subsequent sections.

Crashes Involving Failure To Yield

As shown in table 17, the problem sites experienced 55.5 crashes involving failure to yield on average over 3 yr, but the control sites experienced 7.3 crashes of this type over 3 yr. The number of crashes involving failure to yield at the problem sites ranged from 34 crashes over 3 yr at Melbourne to 114 crashes over 3 yr at Hilliard.

The project team investigated possible explanations for the higher-than-desired number of failure-to-yield crashes at the problem sites. When looking at the entering and conflicting volumes, the control sites generally had lower volumes, both entering and conflicting, than the problem sites. These data emerged as one potential explanation for the number of failure-to-yield crashes. Figure 23 shows the number of failure-to-yield crashes by intersection approach and the 1-h average of the entering and conflicting volume sum on the same approach. As shown, the 1-h average sum of the entering and conflicting volumes is relatively uniform and consistently between 600 vehicles per hour and 1,200 vehicles per hour for the control sites. However, the problem sites have 1-h average sums of entering and conflicting volumes ranging between 900 vehicles per hour and just over 2,100 vehicles per hour, with less uniformity across the intersection approaches.



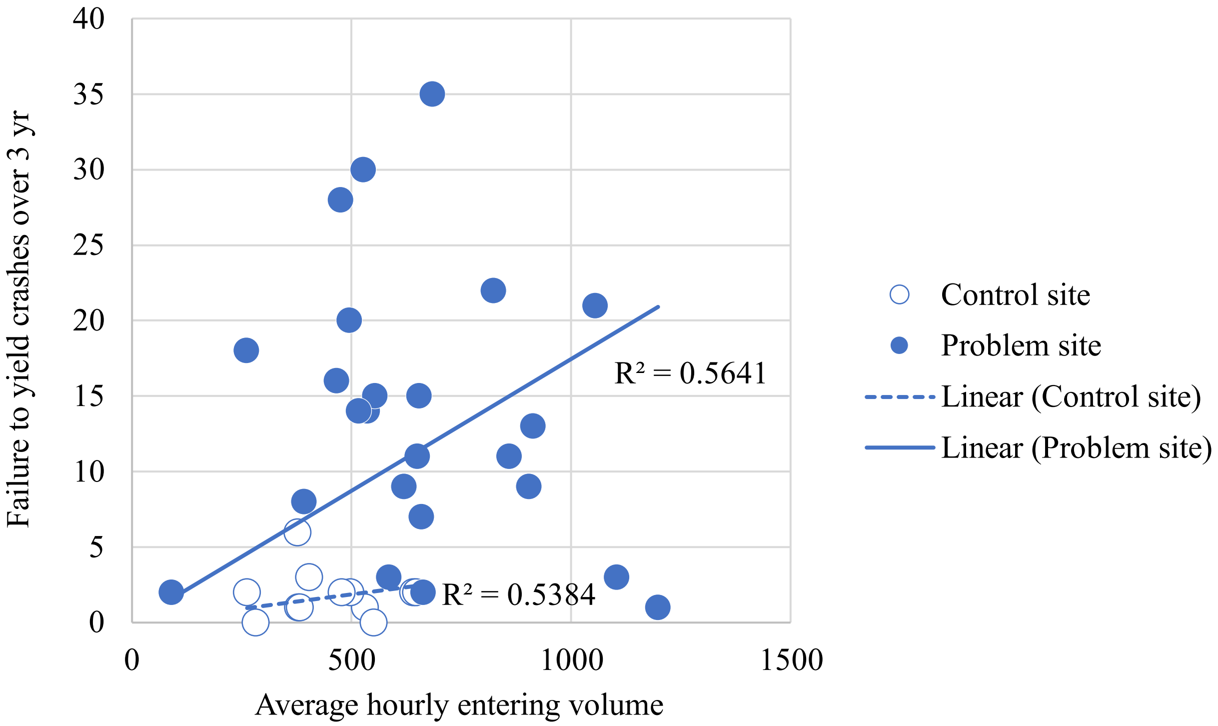
Source: FHWA.

Figure 23. Graph. Number of crashes over 3 yr involving failure to yield and sum of entering plus conflicting volume, by intersection approach.

To further investigate potential relationships between traffic volume and number of failure-to-yield crashes, the project team produced three plots, as follows:

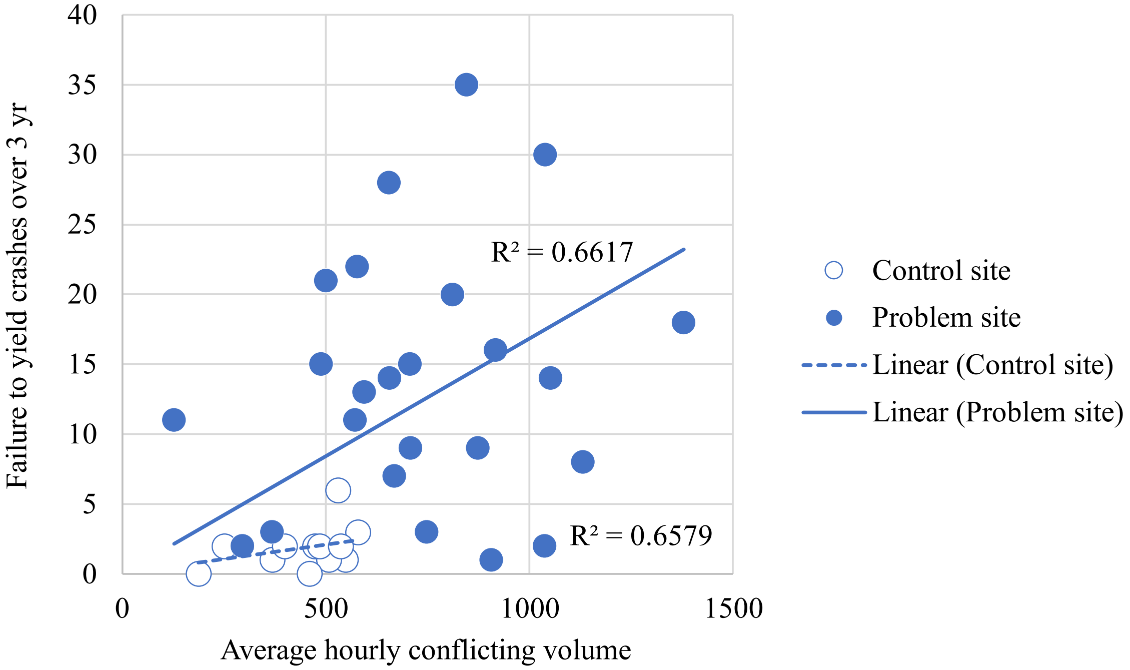
- The average 1-h entering volume versus the number of failure-to-yield crashes by intersection approach, shown in figure 24.
- The average 1-h conflicting volume versus the number of failure-to-yield crashes by intersection approach, shown in figure 25.
- The average 1-h entering plus conflicting volume versus the number of failure-to-yield crashes by intersection approach, shown in figure 26.

No notable relationship is apparent between any of the three volume-metric combinations and failure-to-yield crashes, especially for the problem sites, due to the large spread in data.



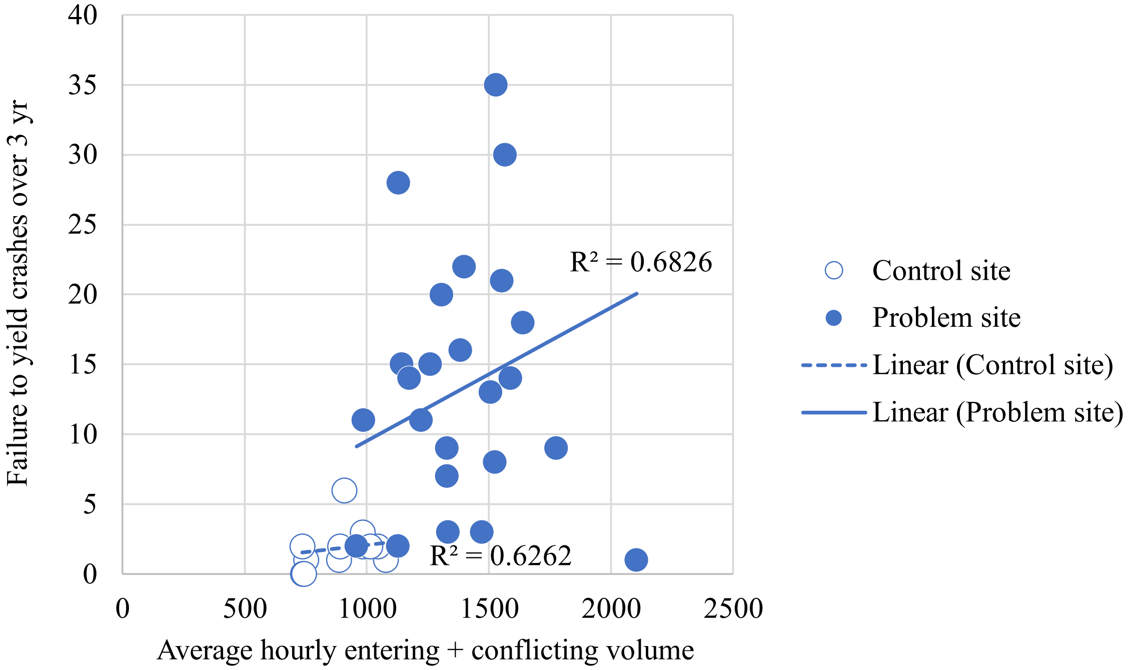
Source: FHWA.

Figure 24. Graph. Number of crashes over 3 yr involving failure to yield by average 1-h entering volume.



Source: FHWA.

Figure 25. Graph. Number of crashes over 3 yr involving failure to yield by average 1-h conflicting volume.



Source: FHWA.

Figure 26. Graph. Number of crashes over 3 yr involving failure to yield by average 1-h entering plus conflicting volume.

The problem sites, in aggregate, had over seven times as many failure-to-yield crashes as the control sites, but these crashes at the problem sites varied by approach. On the low end, the southbound approach at Slingerlands had one crash over 3 yr involving failure to yield. Conversely, on the high end, the westbound approach at Hilliard had 35 crashes over 3 yr involving failure to yield. To draw a further distinction between the approaches with higher numbers of these types of crashes, the project team investigated the intersection entries with more than 15 failure-to-yield crashes over 3 yr, which included the following 8 (out of 24 total) entries:

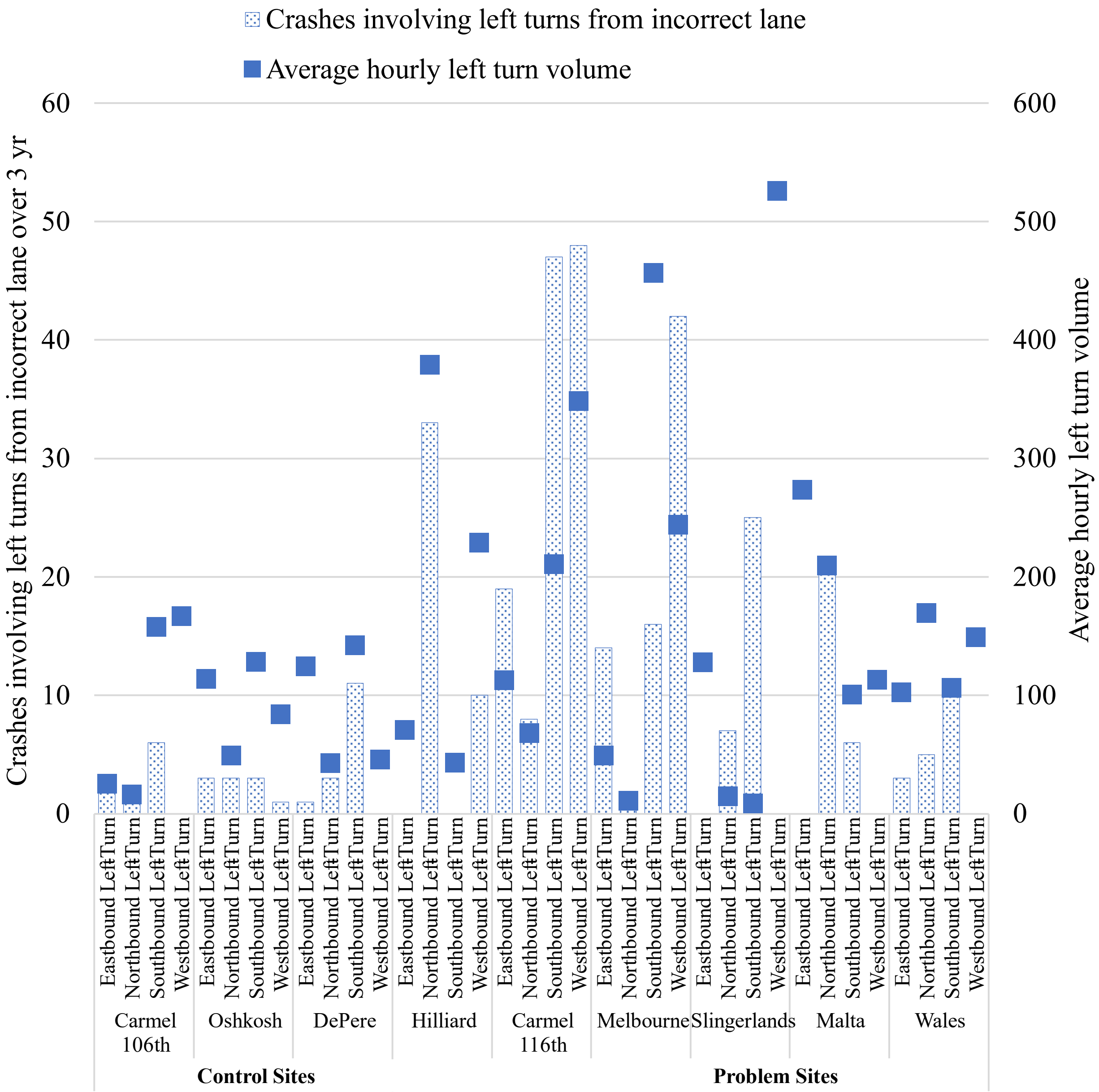
- All four entries at Hilliard.
- The southbound entry at Melbourne.
- The eastbound entry at Slingerlands.
- The eastbound and westbound entries at Malta.

These eight entries were adjacent to two conflicting lanes that each allowed for a through exiting movement. This configuration requires the outside lane to exit the roundabout because vehicles in the inside circulating lane are given the option of exiting or continuing to circulate. These eight entries generally had a large imbalance in lane use, with high percentages of vehicles using the right/outside lane. For instance, 85.4 percent of the volume was in the right/outside lane at the eastbound entry at Slingerlands.

Crashes Involving Left Turns From Incorrect Lanes

As shown in table 17, the problem sites experienced an average of 52.3 crashes over 3 yr involving left turns from incorrect lanes, compared to 11 crashes over 3 yr of this type at the control sites. The total number of crashes involving left turns from incorrect lanes at the problem sites ranged from 18 crashes at Wales to 116 crashes at Carmel 116th. The project team investigated possible explanations for these crashes. When looking at the left-turn volumes, the control sites generally had lower volumes than the problem sites, and these data emerged as one potential explanation for these types of crashes.

Figure 27 shows the number of crashes involving left turns from incorrect lanes by left-turn movement and the 1-h average of the left-turn volumes for the same movement. As shown, the 1-h average of the left-turn volumes is relatively uniform and consistently under 200 for the control sites. However, the problem sites have 1-h average left-turn volumes ranging between 9 vehicles per hour and 526 vehicles per hour, with less uniformity across the left-turn movements. The entry with nine left turns (the southbound left turn at Slingerlands) reflected only 1 h of data. This approach had 25 crashes involving left turns from incorrect lanes, which may be due to higher left-turn volumes during other hours. In comparison, the entry with 526 left turns (the westbound left turn at Slingerlands) had zero crashes involving left turns from incorrect lanes.



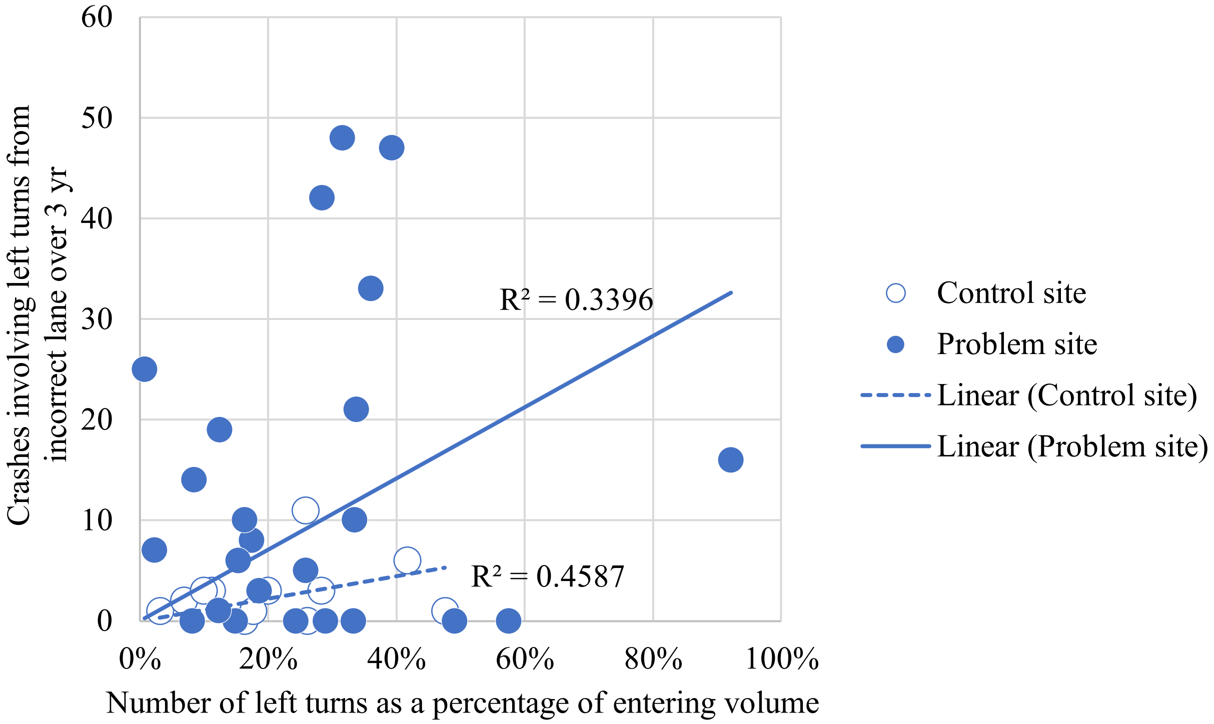
Source: FHWA.

Figure 27. Graph. Number of crashes over 3 yr involving left turns from incorrect lanes and average 1-h left turn volumes, by left-turn movement.

To further investigate potential relationships between left-turn volumes and the number of crashes involving left turns from incorrect lanes, the team produced two plots, as follows:

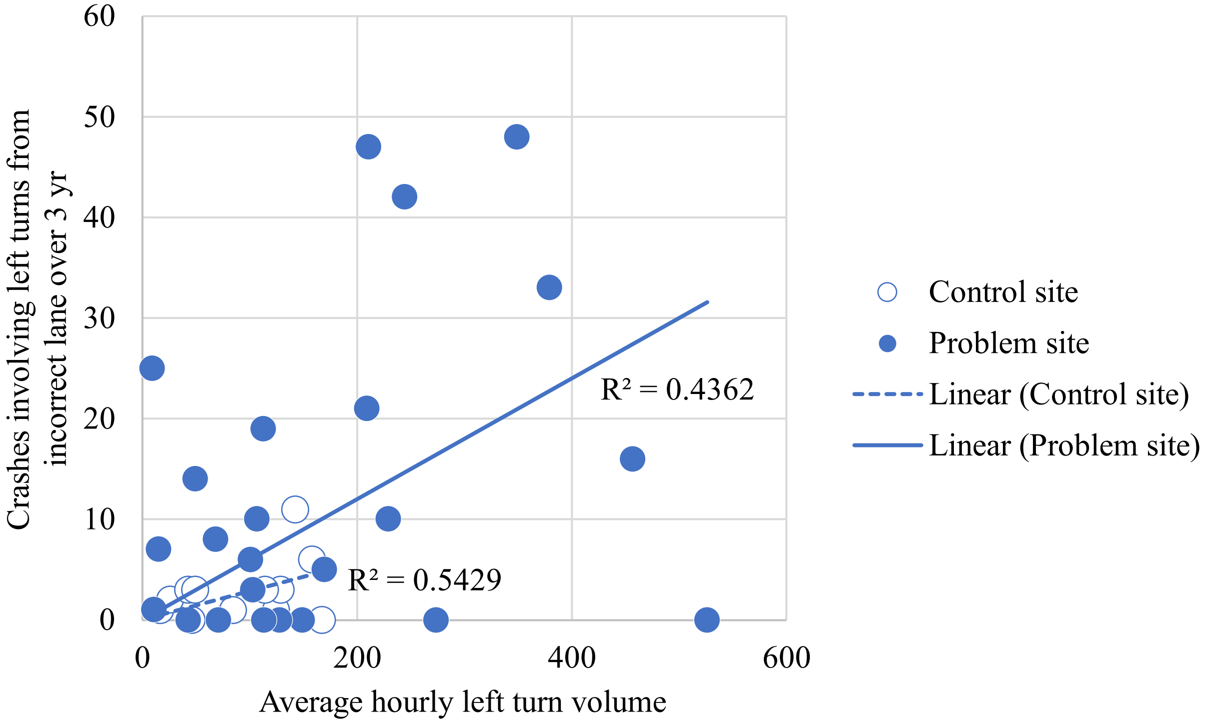
- The number of crashes over 3 yr involving left turns from incorrect lanes versus the number of left turns as a percentage of entering volume is shown in figure 28.
- The number of crashes over 3 yr involving left turns from incorrect lanes versus the average 1-h left-turn volume is shown in figure 29.

Neither of these plots supported a strong relationship between left-turn movement volumes and the number of left-turn crashes.



Source: FHWA.

Figure 28. Graph. Number of crashes over 3 yr involving left turns from incorrect lanes by number of left turns as a percentage of entering volume.



Source: FHWA.

Figure 29. Graph. Number of crashes over 3 yr involving left turns from incorrect lanes by average 1-h left-turn volumes.

The problem sites, in aggregate, had over four times as many crashes involving left turns from incorrect lanes as the control sites, but crash numbers varied considerably among problem sites. Seven of the 24 left-turn movements had zero crashes over 3 yr associated with left turns from incorrect lanes. Conversely, on the high end, three approaches had over 40 crashes of this type over 3 yr, including 42 crashes over 3 yr at the westbound left-turn movement at Melbourne, and 48 and 47 crashes over 3 yr on the westbound and southbound left turns, respectively, at Carmel 116th.

The 6 left-turn movements (out of a total of 24) with more than 20 crashes over 3 yr involving left turns from incorrect lanes are as follows:

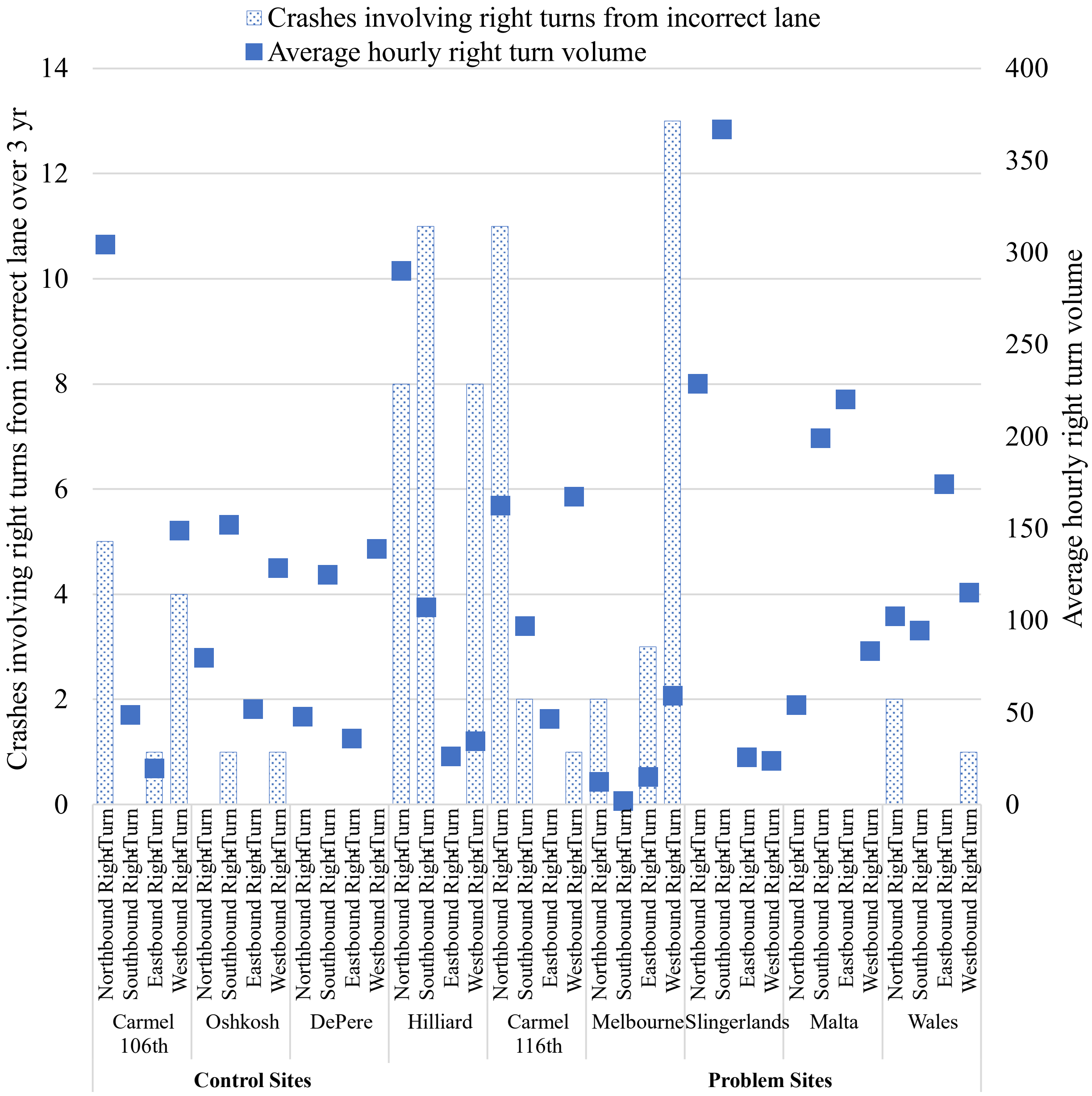
- The westbound and southbound left-turn movements at Carmel 116th (48 and 47 crashes over 3 yr, respectively).
- The westbound left-turn movement at Melbourne (42 crashes over 3 yr).
- The northbound left-turn movement at Hilliard (33 crashes over 3 yr).
- The southbound left-turn movement at Slingerlands (25 crashes over 3 yr).
- The northbound left-turn movement at Malta (21 crashes over 3 yr).

Crashes Involving Right Turns From Incorrect Lanes

As shown in table 17, the problem sites experienced an average of 10.2 crashes over 3 yr involving right turns from incorrect lanes, compared to 4 crashes of this type over 3 yr at the control sites. The number of crashes of this type at the problem sites ranged from zero crashes over 3 yr at Slingerlands and Malta to 27 crashes over 3 yr at Hilliard.

The project team investigated possible explanations for these types of crashes at the problem sites by investigating potential links between right-turn volumes and the number of crashes involving right turns from incorrect lanes. Figure 30 shows the number of crashes involving right turns from incorrect lanes by right-turn movement and the 1-h average of the right-turn volumes on the same movement.

When looking at the right-turn volumes, except for the northbound right-turn movement at Carmel 106th, the average 1-h volumes at the control sites were all lower than 160 vehicles per hour. In contrast, the problem sites had eight approaches, over six sites, with average 1-h right-turn volumes exceeding 160 vehicles per hour. The problem sites generally had more individual entries with higher right-turn movement volumes and a wider range in average 1-h right-turn movement volumes. However, the project team did not find any clear trends between the right-turn movement volumes and the number of crashes involving right turns from incorrect lanes.



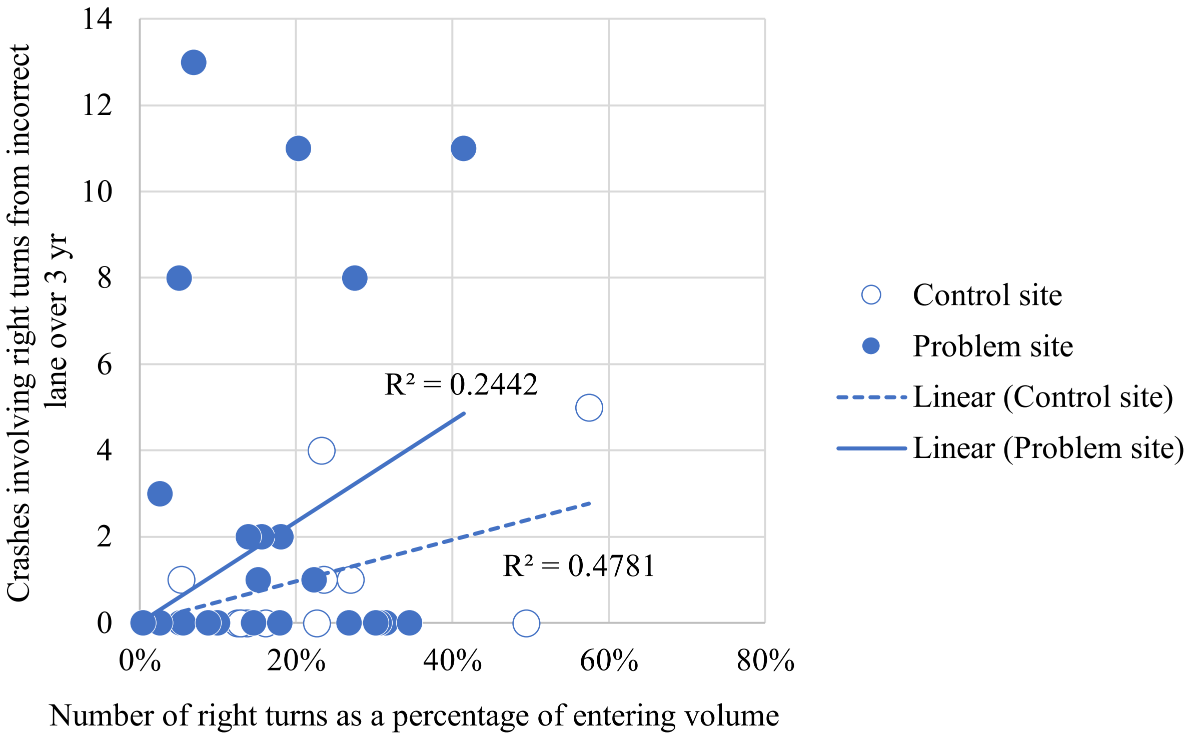
Source: FHWA.

Figure 30. Graph. Number of crashes over 3 yr involving right turns from incorrect lanes and average 1-h right-turn volumes, by right-turn movement.

The project team also generated two plots, as follows:

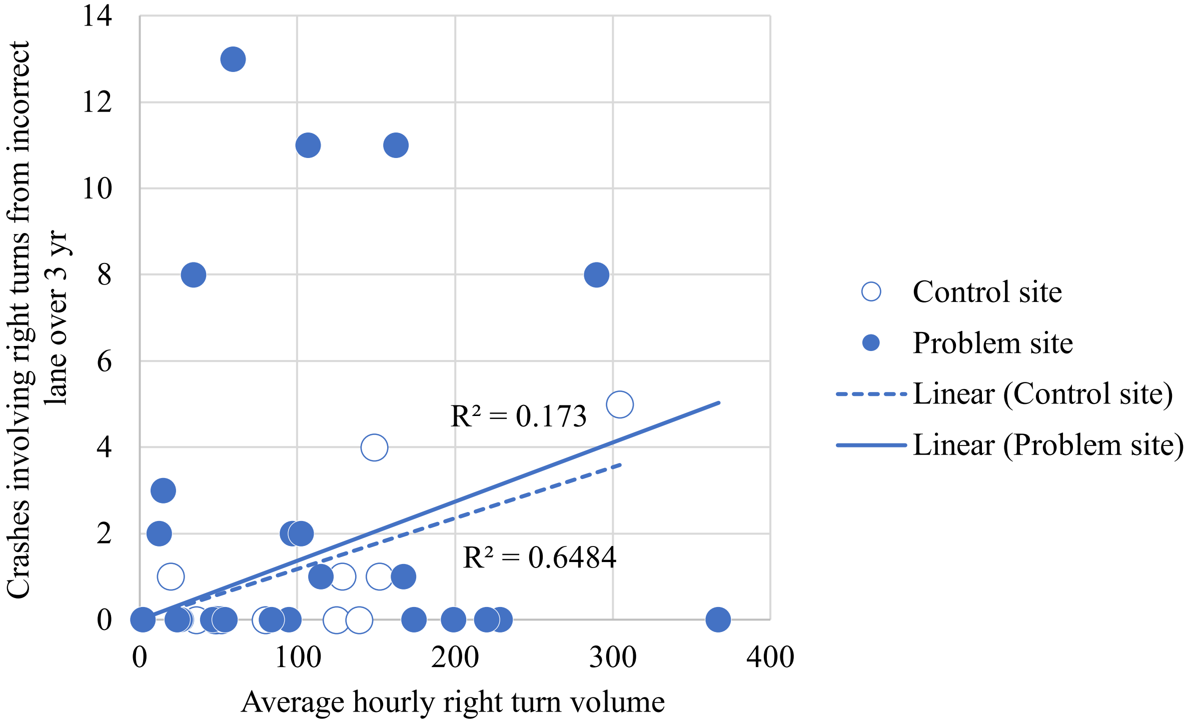
- The number of crashes over 3 yr involving right turns from incorrect lanes versus the number of right turns as a percentage of entering volume is shown in figure 31.
- The number of crashes over 3 yr involving right turns from incorrect lanes versus the average 1-h right-turn volume is shown in figure 32.

Neither of these plots supported a strong relationship between right-turn movement volumes and the number of right-turn crashes.



Source: FHWA.

Figure 31. Graph. Number of crashes over 3 yr involving right turns from incorrect lanes and number of right turns as a percentage of entering volume, by right-turn movement.



Source: FHWA.

Figure 32. Graph. Number of crashes over 3 yr involving right turns from incorrect lanes and average 1-h right-turn volumes, by right-turn movement.

While the problem sites, in aggregate, had twice as many crashes over 3 yr involving right turns from incorrect lanes as the control sites, the problem sites had a range of crashes of this type. Thirteen of the 24 right-turn movements had zero crashes of this type over 3 yr. Conversely, on the high end, 5 approaches had 8 or more crashes of this type over 3 yr, including 13 crashes over 3 yr at the westbound right-turn movement at Melbourne.

The 5 right-turn movements (out of a total of 24) with 8 or more crashes over 3 yr involving right turns from incorrect lanes are as follows:

- The westbound right-turn movement at Melbourne (13 crashes over 3 yr).
- The northbound right-turn movement at Carmel 116th (11 crashes over 3 yr).
- The southbound, northbound, and westbound right-turn movements at Hilliard (11, 8, and 8 crashes over 3 yr, respectively).

CHAPTER 4. CONFLICT ANALYSIS

The project team reviewed video footage collected by the tethered drone and used the footage to track violations and conflicts at each roundabout. The team logged information about each event, including the time of the event, where the offending vehicle entered and exited the roundabout, where the event occurred, and what violation was committed, among others.

EVENT TYPES

The project team categorized events into five types based on their severity. These types included the following:

- Violation—An event in which a single vehicle violated a rule while traveling through the roundabout, and no other vehicles were affected.
- Potential conflict—A violation event that had the potential to create a conflict due to the proximity of another vehicle (i.e., another vehicle was within approximately two car lengths of the violating vehicle at the time of the violation).
- Conflict: Incident—A conflict between two or more vehicles in which at least one vehicle had to brake or steer to avoid another vehicle.
- Conflict: Near-crash—A conflict between two or more vehicles in which at least one vehicle had to perform a hard or abrupt braking or steering maneuver to narrowly avoid colliding with another vehicle.
- Conflict: Crash—A conflict in which two or more vehicles collided with each other.

VIOLATION TYPES

The project team categorized 15 violation types based on definitions by Richfield and Hourdos, which are illustrated in figure 33.(10) Additionally, an “other” category was added as a catch-all for violations that did not fit into these categories. Each violation type is listed as follows:

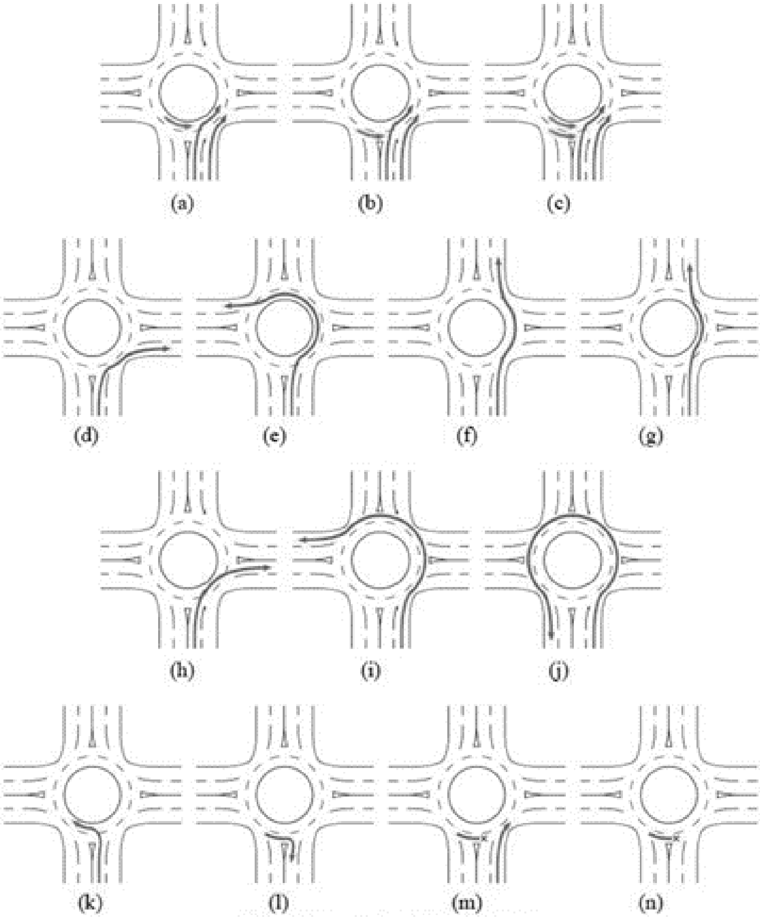
- Yield violations:
  a. Failure to yield to vehicle in inner lane.
  b. Failure to yield to vehicle in outer lane.
  c. Failure to yield to vehicles in both lanes.

- Lane change violations:
  a. Entrance lane—entering the inside circulating lane from the outside entry lane or vice versa.
  b. Exit lane—exiting from the inside circulating lane into the outside exit lane or vice versa.
  c. Occupying or straddling both lanes.
  d. Cutting lanes when going straight through.

- Turn violations:
    e. Turning right from the inner lane.
    f. Turning left from the outer lane.
    g. Turning more than 270 degrees from the outer lane.

- Wrong way and stop violations:
    d. Wrong-way violation—entering the roundabout against traffic.
    e. Wrong-way violation—exiting the roundabout through entrance lanes.
    f. Stop violation—vehicle in circle stopping to yield to vehicles entering roundabout.
    g. Stop violation—general unjustified stopping.

- Other violations:
    a. Other.



© 2013 Richfield and Hourdos. Modified by FHWA to remove color.

Figure 33. Illustration. 'Categories of Violations.'[10]

EVENTS BY LOCATION

Table 19 shows the total number of events by type for each roundabout. While roundabouts with the highest number of each event type fell within the problem group, roundabouts in the control group still had high numbers of violations. The Carmel 106th roundabout also had a relatively high number of conflicts, although still fewer than its counterpart, Carmel 116th.

Table 19. Number of events by event type and roundabout location.

Site Type	Roundabout Location	Violations	Potential Conflicts	Conflicts: Incidents	Conflicts: Near-Crashes	Total
Control	Carmel 106th	1,185	26	16	3	1,230
Control	Oshkosh	898	12	8	1	919
Control	De Pere	419	14	2		435
Problem	Melbourne	1,247	63	16	4	1,330
Problem	Malta	1,289	15	12	1	1,317
Problem	Carmel 116th	769	23	21	6	819
Problem	Wales	582	17	5	2	606
Problem	Hilliard	168	17	14	6	205
Problem	Slingerlands	155	37	8	1	201

The team extracted data and completed analysis for 4 h of video for each roundabout except for the New York roundabouts, which had a total of 4 h between the two locations (3 h at Malta and 1 h at Slingerlands). In total, the team evaluated 12 h of video for control sites and 20 h for problem sites. Table 20 shows the average hourly events for each event type for control and problem sites. Problem sites had higher rates of conflicts and potential conflicts, but the rate of violations was similar between the two groups.

Table 20. Average hourly events by event type and site type.

Site Type	Conflicts: Near-Crashes	Conflicts: Incidents	Potential Conflicts	Violations	Total
Control	0.33	2.17	4.33	208.50	215.33
Problem	1	3.80	8.60	210.50	223.90

Table 21 shows the average hourly events by violation type for each location. Lane-change violations accounted for most events, particularly lane-straddling and exit lane violations. Two control sites, Carmel 106th and Oshkosh, had some of the highest numbers of these violations. The Melbourne roundabout was the only location that had a higher number of turn violations than lane-change violations.

Table 21. Average hourly events by violation type and roundabout location.

Violation Type	Carmel 106th (C)	De Pere (C)	Oshkosh (C)	Carmel 116th (P)	Hilliard (P)	Malta (P)	Melbourne (P)	Slingerlands (P)	Wales (P)	Average for All Sites
a. Yield violation—failure to yield to vehicle in inner lane	4	0	2	7	4	1	2	18	2	4
b. Yield violation—failure to yield to vehicle in outer lane	2	0	1	1	2	2	1	10	1	2
c. Yield violation—failure to yield to vehicles in both lanes	0	0	0	1	1	1	0	3	0	1
d. Lane change violation—entrance lane	9	4	1	8	3	10	14	13	2	7
e. Lane-change violation—exit lane	103	23	38	109	15	123	59	31	43	60
f. Lane-change violation—occupying or straddling both lanes	166	68	179	35	16	267	40	104	80	106
g. Lane-change violation—cutting lanes when going straight through	13	11	7	4	1	7	15	18	16	10
h. Turn violation—turning right from the inner lane	2	0	1	2	2	0	1	0	0	1
i. Turn violation—turning left from the outer lane	5	3	1	33	6	25	200	2	8	31
j. Turn violation—turning more than 270 degrees from the outer lane	1	0	0	4	1	2	2	1	1	1
m. Stop violation—vehicle in circle stopping to yield to entering vehicle	0	0	0	0	0	0	0	0	0	0
n. Stop violation—general unjustified stopping	1	0	0	0	0	0	0	1	0	0
o. Other	3	0	0	2	1	0	0	0	0	1

C = control site; P = problem site.

Table 22 shows the average hourly events by violation type and site type. Control sites had a higher rate of lane-straddling and lane-cutting violations but lower rates of yield violations and turn violations.

Table 22. Average hourly events by violation type and site type.

Violation Type	Control	Problem
a. Yield violation—failure to yield to vehicle in inner lane	2.08	4.05
b. Yield violation—failure to yield to vehicle in outer lane	0.92	1.70
c. Yield violation—failure to yield to vehicles in both lanes	0	0.70
d. Lane change violation—entrance lane	4.58	7.35
e. Lane change violation—exit lane	54.67	65.15
f. Lane change violation—occupying or straddling both lanes	137.42	79.40
g. Lane change violation—cutting lanes when going straight through	10.17	8.95
h. Turn violation—turning right from the inner lane	0.92	1
i. Turn violation—turning left from the outer lane	2.75	53.20
j. Turn violation—turning more than 270 degrees from the outer lane	0.50	1.75
m. Stop violation—vehicle in circle stopping to yield to entering vehicle	0.08	0
n. Stop violation—general unjustified stopping	0.25	0.10
o. Other	1	0.55

Table 23 shows average hourly conflicts by violation type and roundabout location. When looking only at events that resulted in a conflict (incident or near-crash), yield violations were the most common cause. Failure to yield to a vehicle in the inner lane was the most common cause of conflicts (42 events) followed by failure to yield to a vehicle in the outer lane (21 events). The next most common cause of conflicts was turning left in the outer lane (18 events), for which the Melbourne roundabout was the most problematic.

Table 23. Average hourly conflicts by violation type and roundabout location.

Violation Type	Carmel 106th (C)	De Pere (C)	Oshkosh (C)	Carmel 116th (P)	Hilliard (P)	Malta (P)	Melbourne (P)	Slingerlands (P)	Wales (P)	Average for All Sites
a. Yield violation—failure to yield to vehicle in inner lane	0.8	0	1	3.3	2	0.7	1.8	3	0.5	1.4
b. Yield violation—failure to yield to vehicle in outer lane	0.5	0	0.8	0.5	1.3	1	0.8	2	0.3	0.8
c. Yield violation—failure to yield to vehicles in both lanes	0	0	0	0.8	0.5	0.7	0	2	0.3	0.5
d. Lane-change violation—entrance lane	0.3	0	0	0	0.3	0	0	0	0	0.1
e. Lane-change violation—exit lane	1.8	0	0	0.8	0	0.7	0.3	2	0.3	0.6
f. Lane-change violation—occupying or straddling both lanes	0	0	0	0	0	0.3	0	0	0.5	0.1
g. Lane-change violation—cutting lanes when going straight through	0	0.3	0	0	0	0	0.5	0	0	0.1
h. Turn violation—turning right from the inner lane	0.5	0	0	0.3	0.5	0	0	0	0	0.1
i. Turn violation—turning left from the outer lane	0.8	0.3	0.3	0.5	0.3	1	1.8	0	0	0.5
j. Turn violation—turning more than 270 degrees from the outer lane	0	0	0.3	0.8	0.3	0	0	0	0	0.1
n. Stop violation—general unjustified stopping	0.3	0	0	0	0	0	0	0	0	0
o. Other	0	0	0	0	0	0	0	0	0	0

C = control site; P = problem site.

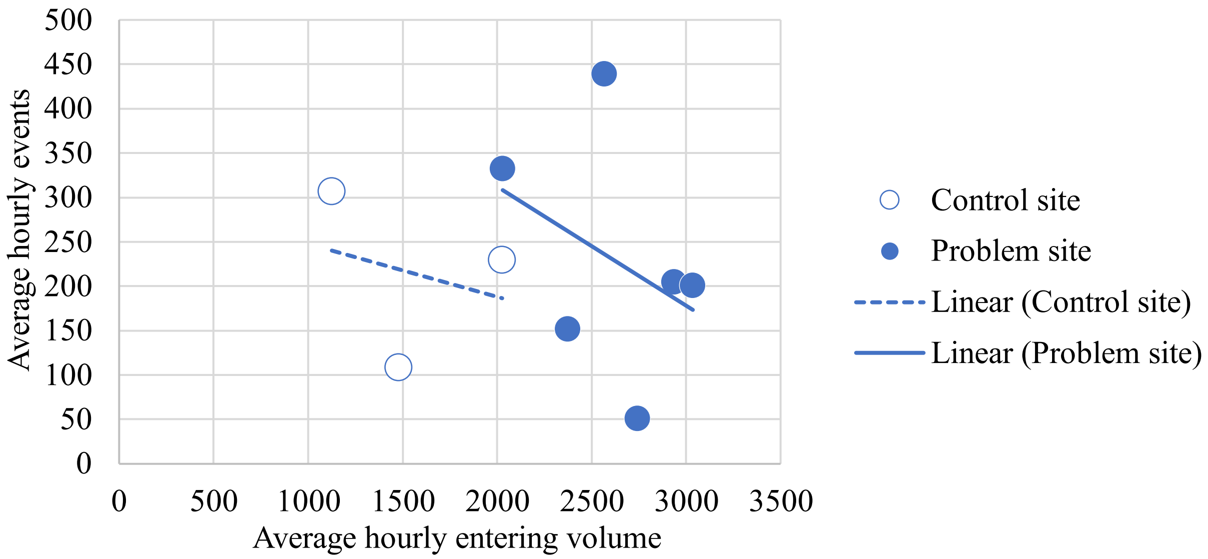
Table 24 shows the average hourly conflicts by violation type and site type. Problem sites had a much higher rate of yield violations that resulted in a conflict. Problem sites also had slightly higher rates of turn violations resulting in conflicts. The rates of all other violation types that resulted in a conflict were similar between problem and control sites.

Table 24. Rate of conflicts per hour by violation type and site type.

Violation Type	Control	Problem
Yield violation—failure to yield to vehicle in inner lane	0.58	1.75
Yield violation—failure to yield to vehicle in outer lane	0.42	0.80
Yield violation—failure to yield to vehicles in both lanes	0	0.50
Lane-change violation—entrance lane	0.08	0.05
Lane-change violation—exit lane	0.58	0.45
Lane-change violation—occupying or straddling both lanes	0	0.15
Lane-change violation—cutting lanes when going straight through	0.08	0.10
Turn violation—turning right from the inner lane	0.17	0.15
Turn violation—turning left from the outer lane	0.42	0.65
Turn violation—turning more than 270 degrees from the outer lane	0.08	0.20
Stop violation—general unjustified stopping	0.08	0
Other	0	0

EVENTS BY VOLUME

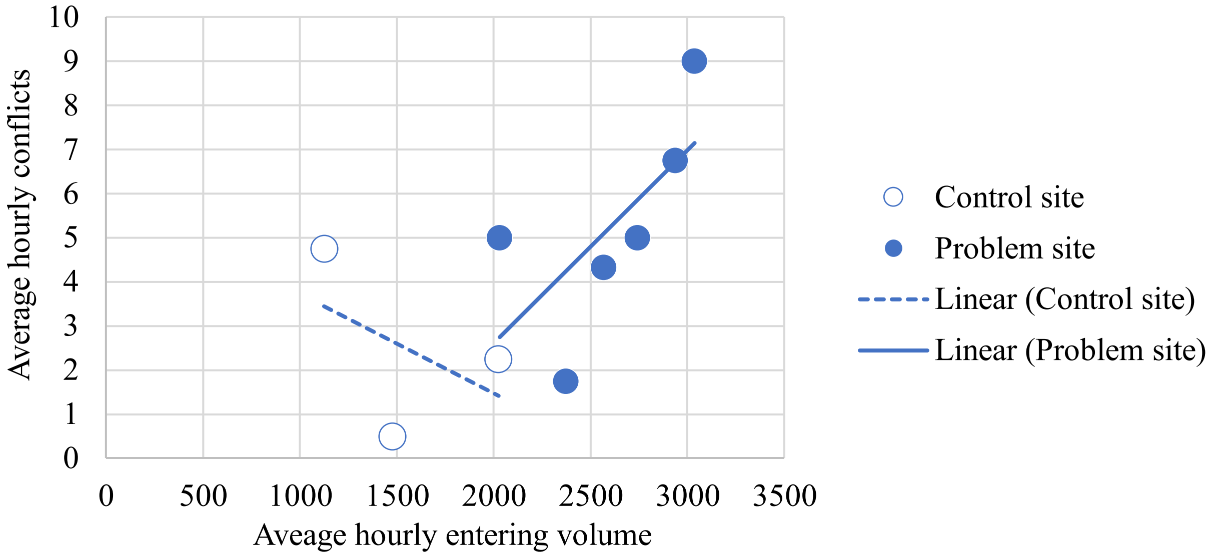
Figure 34 shows the average hourly number of events by the average hourly entering traffic volume for control and problem sites. For both control and problem sites, there is a slight trend in which the number of events decreases as the volume increases. Because lane-change violations caused most events, it may be that an increase in volume makes these types of violations less likely to occur because there is less room to maneuver within the roundabout.



Source: FHWA.

Figure 34. Graph. Average hourly events by entering volume.

Figure 35 shows the average hourly conflicts by the average hourly entering traffic. For the control sites, the number of conflicts decrease as the volume increases. However, at the problem sites, the number of conflicts increase as volume increases. Conflicts were more likely to occur as the result of failure-to-yield violations, which were more common for problem sites. As volume increases, these types of violations may be more likely to occur, as entering drivers have fewer opportunities to enter and may take more risks.



Source: FHWA.

Figure 35. Graph. Average hourly conflicts by entering volume.

CHAPTER 5. DESIGN INFLUENCES

This section summarizes observations related to potential design influences on observed crash and conflict patterns. Design influences encompass both geometric design and traffic control devices. This section focuses on design influences at the roundabout itself; network influences away from the roundabout are discussed in Chapter 6.

The research team identified the following 10 general categories of geometric design and traffic control device influences at the roundabout:

1. Large conflict areas: Large conflict areas appear to be associated with failure-to-yield crashes and may contribute to other crashes and violations related to lane changes through the entry or exit. At study sites, large conflict areas resulted from use of large ICDs, skewed angles between legs, and other factors.
2. Mandatory turn lanes: Approach lanes that are designated at the roundabout as mandatory left- or right-turn lanes appear to influence turning movements from incorrect lanes and lane changes within the roundabout.
3. Alignment of entry lane additions and exit merging: The taper design used to add entry lanes appears to affect driver lane selection and subsequently influence turning movements from incorrect lanes.
4. Reverse curves through exits: Reverse curves without a tangent section between curves appear to increase lane changes through the exit area.
5. Small diameters: Sites with small ICDs had increased violations related to maintaining lanes through the roundabout.
6. Entry alignment: The alignment of entering lanes with corresponding circulating lanes affects entry lane changes and the likelihood that drivers straddle lanes.
7. Circulatory roadway striping: For roundabouts where painted spirals are used, drivers often follow the central island curb and then change lanes abruptly to exit.
8. Yield signs and markings: The roundabouts in this study had a variety of signing and pavement marking treatments in the yielding area. However, no clear pattern emerged to distinguish failure-to-yield crash patterns as a function of yield signing and markings.
9. Advance lane-use signs and pavement arrows: The roundabouts in this study had a variety of signing and pavement-marking treatments to convey lane use in advance of the roundabout. Overhead lane control signs were anecdotally found to be more visible and simpler to read at a glance. However, the effect of signing and marking differences on driver lane selection could not be isolated in this analysis.
10. Circulating lane-use pavement arrows: The roundabouts in this study had a variety of signing and pavement-marking treatments to convey lane use within the circulatory roadway of the roundabout. No clear pattern emerged to distinguish crash patterns as a function of pavement arrow style or placement configurations.

Table 25 through table 28 summarize information related to the 10 generalized categories of design influences for each of the control sites and problem sites, respectively. Design influences were identified at each of the study sites. The relative magnitude of design impact on vehicle conflicts and historical crashes varies by site with other contributing factors, including overall volumes and turning movement patterns during peak hours.

Table 25. Geometric design influences for control sites.

Intersection	Large Conflict Areas or Large ICD	Mandatory Turn Lanes	Lane Additions or Lane Merge	Exit Reverse Curves	Small ICD	Entry Misalignment
Carmel 106th	Northeast quadrant	WB left	EB entry	—	—	EB and WB entries
Oshkosh	—	—	EB entry	—	135 ft ICD	Minor; all entries
De Pere	NB and SB entries	—	EB and WB entries; EB and WB exits	—	—	Minor; all entries

—No data.

Table 26. Summary of design influences for problem sites.

Intersection	Large Conflict Areas or Large ICD	Mandatory Turn Lanes	Lane Additions or Lane Drops	Exit Reverse Curves	Small ICD	Entry Misalignment
Carmel 116th	All quadrants	—	—	Yes	—	All entries
Hilliard	—	—	SB and WB entry; EB and NB exit	—	—	—
Melbourne	All entries. 200 ft ICD.	WB right	Added right-turn bypass lanes on SB and NB entry	All exits	—	All entries
Slingerlands	198 ft ICD. EB and WB entries.	EB and WB left	EB and WB entry	—	—	—
Malta	EB and WB entries	EB and WB left	WB entry	—	—	Varies by entry
Wales	—	WB left	WB entry	SB exit	—	Minor; all entries

—No data.

Table 27. Traffic control influences for control sites.

Intersection	Circulatory Roadway Striping	Yield Signs and Markings	Advance Lane Control Signs and Pavement Arrows	Circulating Lane-Use Arrow Type and Position
Carmel 106th	Combination of solid and dotted lane line	Dual yield signs; yield lines	One roadside sign; 1–2 sets of fishhook arrows	Standard; centered
Oshkosh	Dotted lane line	Dual yield signs with plaques; YIELD word markings	Overhead signs; two sets of standard arrows	Standard; centered
De Pere	Dotted lane line	Dual yield signs with plaques; YIELD word markings	One roadside sign; one set of standard arrows	Standard; centered

Table 28. Traffic control influences for problem sites.

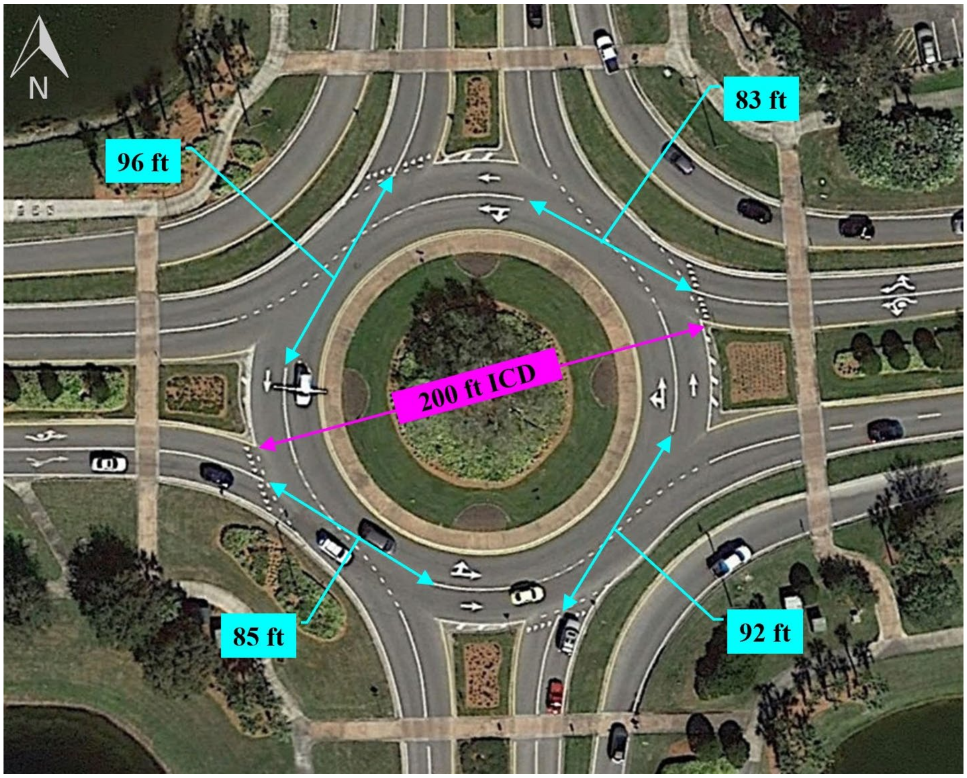
Intersection	Circulatory Roadway Striping	Yield Signs and Markings	Advance Lane Control Signs and Pavement Arrows	Circulating Lane-Use Arrow Type and Position
Carmel 116th	Dotted lane line; partially concentric markings in NE and SW quadrants	Dual yield signs; yield lines	One roadside sign; 1–2 sets of fishhook arrows	Fishhook; centered
Hilliard	Dotted lane line	Dual yield signs with plaques; yield lines	One roadside sign; 1–2 sets of fishhook arrows	Standard; start of lane line
Melbourne	Combination of solid and dotted lane line	Dual yield signs with plaques; yield lines	One set of roadside signs, one set of fishhook arrows	Standard; centered
Slingerlands	Combination of solid and dotted lane line	Dual yield signs with plaques; YIELD word markings and yield lines	One roadside sign; 1–2 sets of fishhook arrows	Standard with "ONLY"; start of lane line
Malta	Combination of solid and dotted lane line	Dual yield signs with plaques; YIELD word markings and yield lines	One roadside sign; two sets of fish-hook arrows	Standard with "ONLY"; varies
Wales	Dotted lane line	Dual yield signs with plaques; YIELD word markings	Overhead plus roadside signs; 2–3 sets of standard arrows	Standard; start of raised splitter

LARGE CONFLICT AREAS

One of the geometric elements associated with crashes involving failure of entering vehicles to yield to both circulating lanes is the presence of a large conflict area. A large conflict area is one where there is separation between an entry and the immediate downstream exit, creating an alignment where the entering and exiting paths become coincident over a given length. A small conflict area, by contrast, has entering and exiting paths crossing one another without a coincident segment. The size of the conflict area is influenced by a combination of several interrelated geometric elements, described as follows:

- Angles between legs greater than 90 degrees.
- Large ICDs (especially 200 ft or larger), even for sites with 90-degree angles between legs.
- Approach alignments and corresponding entry angle: Overly deflected entries with small entry angles have the potential to result in larger conflict areas.
- Exit radius and alignment of the adjacent exit: Small exit radii and reversing curves through the exit can result in increased separation between an entry and an adjacent exit.
- Design of spiral curves within the circulatory roadway.

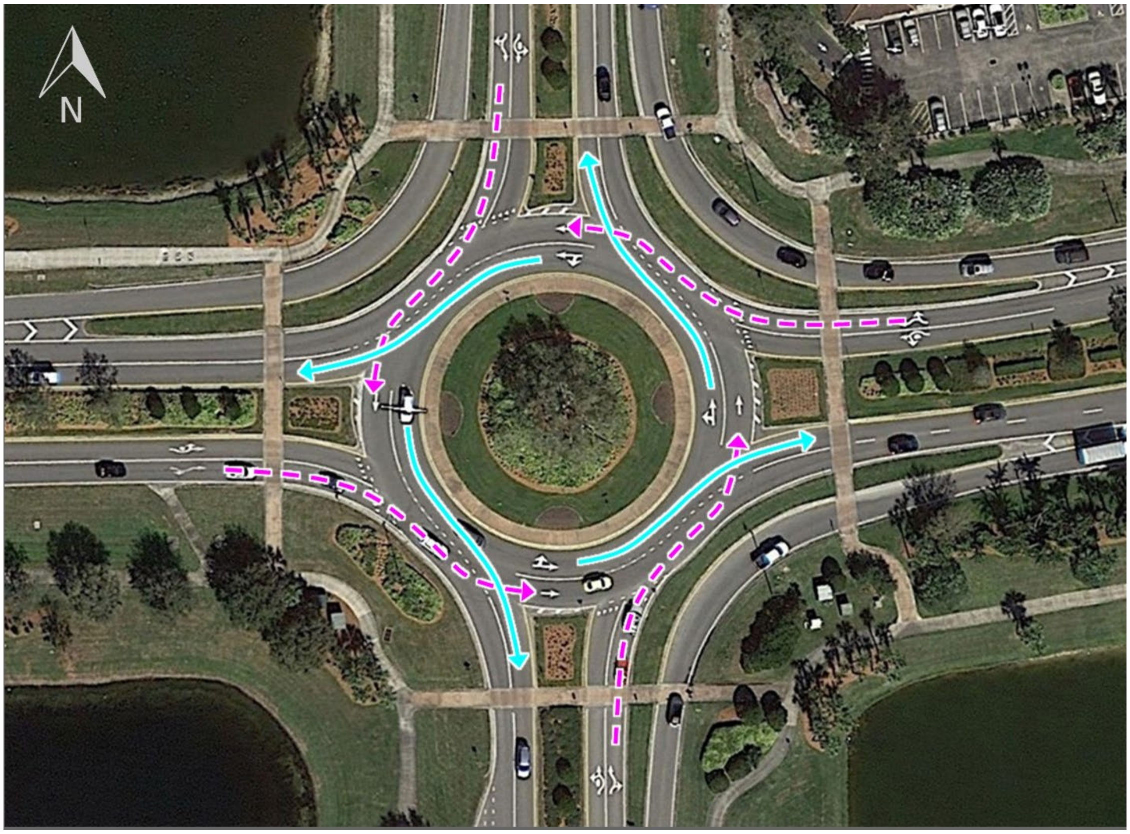
As illustrated in figure 36, the Melbourne site has large conflict areas in each of the four quadrants. The large conflict areas are the result of a large ICD of 200 ft, relatively small exit radii, and entry and exit alignments that combine to create over 50 ft of separation (measured along the outside curb) between each entry and the adjacent exit to the right.



Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft. Eye altitude 1,013 ft.

Figure 36. Photo. Melbourne—conflict areas.

The distance from the yield line to the start of the circulating lane lines is another indication of the size of the conflict area. The longer the distance of travel through the conflict area, the more likely a driver may be to enter beside another vehicle, as illustrated in figure 37.

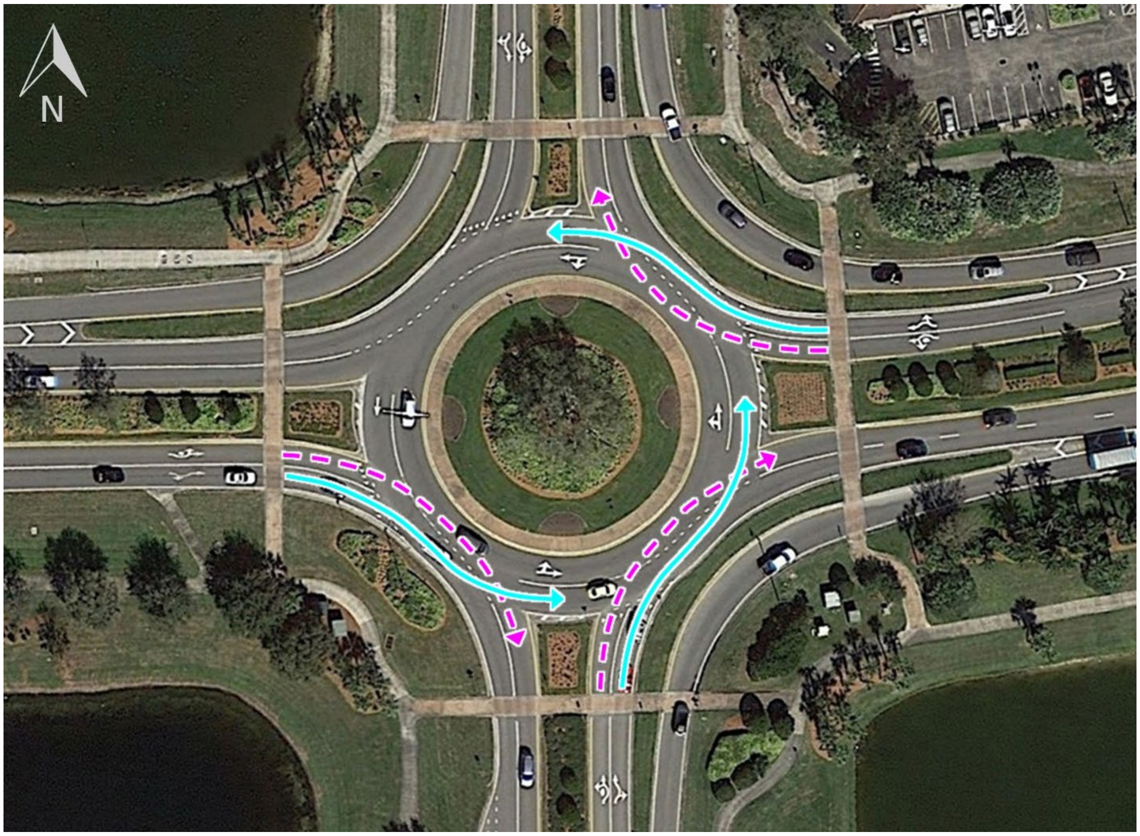


Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

Figure 37. Photo. Melbourne—Failure-to-yield crash patterns associated with large conflict areas.

Longer distances also make it more difficult for drivers to maintain alignment with the correct circulating lane, which increases the potential for lane changing through the entry. The distances from the yield line to the start of the circulating lane line range from 83 to 96 ft (figure 36). Failure of entering vehicles to yield to both circulating lanes resulted in 37 crashes over 3 yr (20 percent of the intersection total), with the crashes predominantly on the southbound and westbound entries.

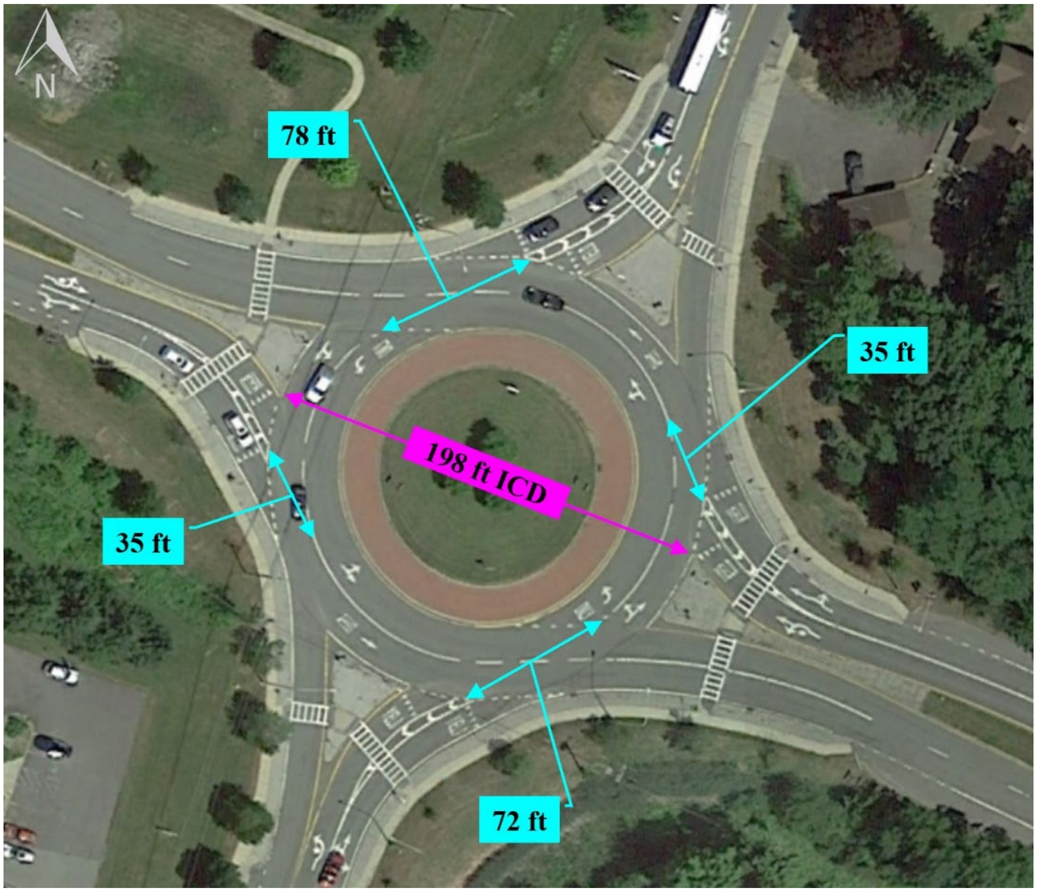
The large size of the Melbourne roundabout also appears to influence crashes related to lane changes within the roundabout, right turns from incorrect lanes, and left turns from incorrect lanes. In particular, the large size and exit geometry result in smooth paths for left turns and right turns from incorrect lanes, which may lead to some drivers navigating the roundabout incorrectly without realizing it. Left turns from incorrect lanes account for 40 percent of the intersection crashes and are discussed in more detail in other sections of chapter 5 and chapter 6. Figure 38 illustrates observed locations of crashes related to right turns from incorrect lanes, accounting for 10 percent of the intersection total.



Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

Figure 38. Melbourne—Crash patterns for right turns from incorrect lanes associated with large conflict areas.

The Slingerlands site has an ICD of 198 ft with exclusive left-turn lanes and corresponding single-lane exits on two legs, as illustrated in figure 39.

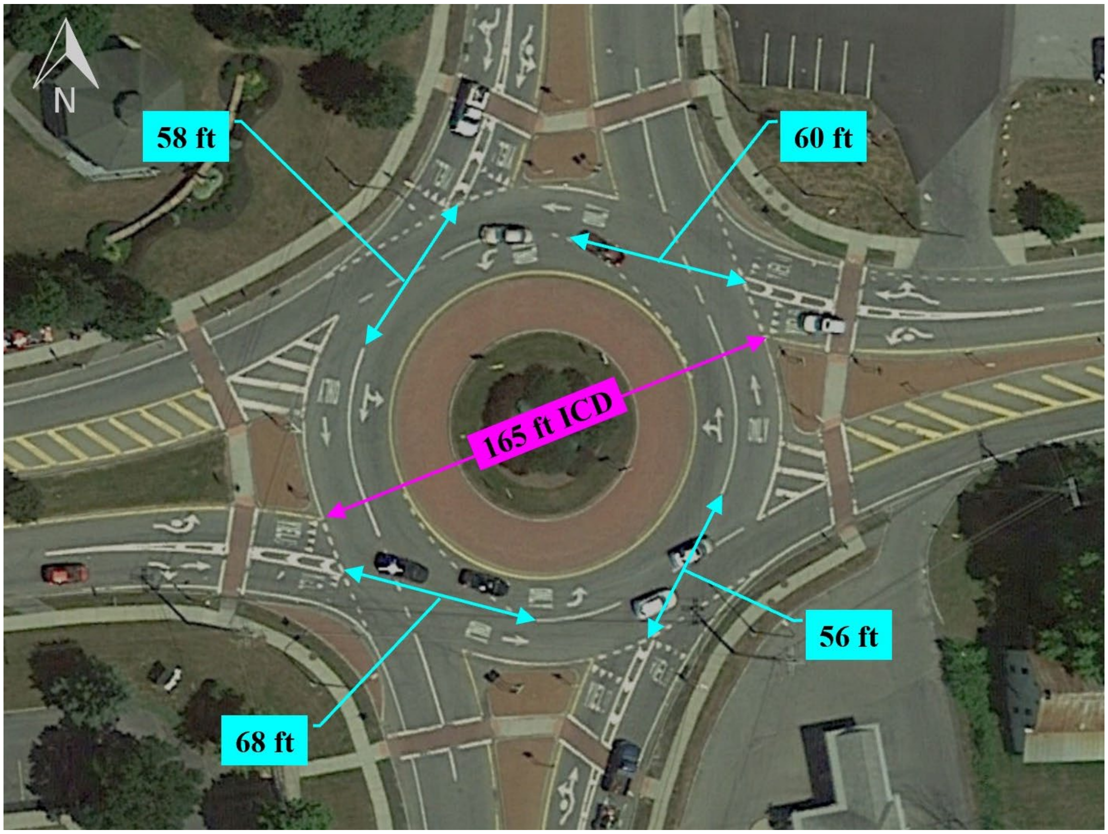


Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 38′ 13.51″ N and 73° 51′ 21.50″ W. Elevation 217 ft.
Eye altitude 1,205 ft.

Figure 39. Photo. Slingerlands—conflict areas.

However, despite the similar size, the relative alignments of each entry and exit reduce the separation between entries and adjacent exits compared to the Melbourne site. Still, Slingerlands has large conflict areas at two entries, which are influenced by the large ICD in combination with painted spiral markings that result in 72–78 ft of distance between the yield line and the start of the circulating lane line. These 2 entries with the large conflict areas corresponded to the locations with the majority of crashes related to failure of entering vehicles to yield to both circulating lanes (32 crashes over 3 yr).

Malta, with an ICD of 165 ft, has a more compact size than the nearby Slingerlands site. However, as part of a previous retrofit, the eastbound and westbound approaches were modified to be exclusive left-turn lanes with single-lane exits, as illustrated in figure 40.

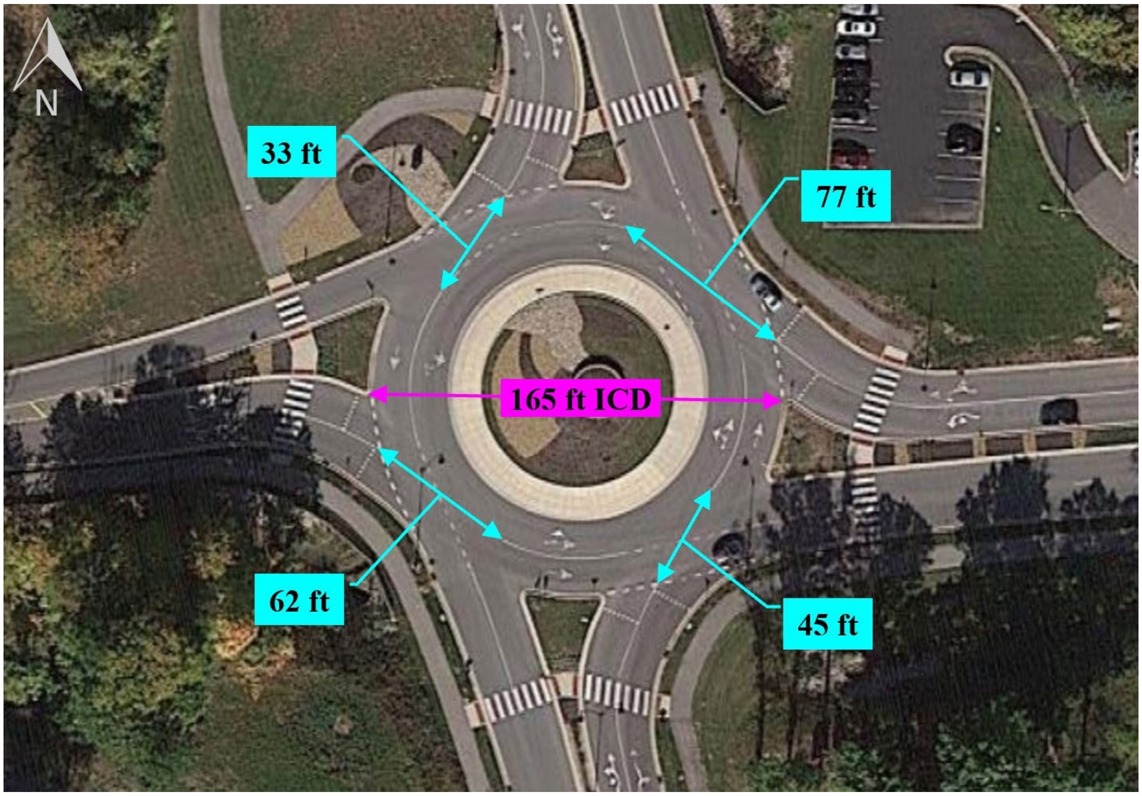


Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 40. Photo. Malta—conflict areas.

Painted spirals were added to the circulatory roadway to support the modified lane configurations. However, due to the retrofit conditions, the addition of the painted spirals increased the length of conflict areas adjacent to the eastbound and westbound entries to 68 ft and 60 ft, respectively. This increase was observed to adversely affect vehicle alignment and increase lane straddling.

At Carmel 106th, which has an ICD of 165 ft, the size of the conflict areas varies. Key dimensions are illustrated in figure 41.

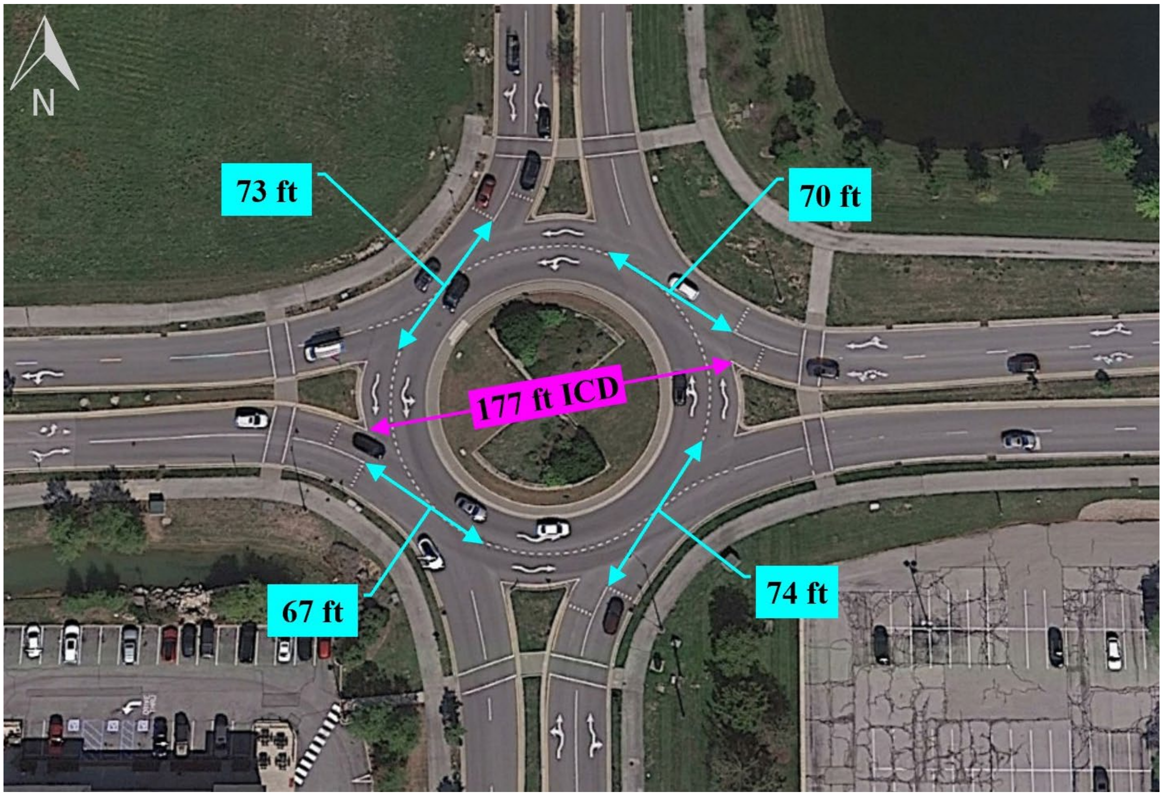


Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: October 10, 2018. 39° 56′ 29.71″ N and 86° 09′ 40.36″ W. Elevation 821 ft.
Eye altitude 1,752 ft.

Figure 41. Photo. Carmel 106th—conflict areas.

At this location, other factors—the angle between legs and the alignment of the entries and exits—appear to have a greater impact on the size of the conflict areas than the ICD. The largest conflict area is adjacent to the westbound entry, which has a distance of 77 ft from the yield line to the start of the circulating lane line. The width of this conflict area is created by a combination of the design of the spiral within the circulatory roadway, the skew angle between legs, and the alignment of the east leg being heavily offset to the left of the roundabout center. The size of the conflict area is likely contributing to observed violations of vehicles crossing and straddling lanes westbound. The two largest conflict areas correspond to the locations of the highest numbers of crashes related to entering drivers failing to yield to both circulating lanes, with six crashes at the eastbound entry and two crashes at the westbound entry. Traffic patterns and network influences also have a major impact on crash patterns at this location; these patterns are further discussed in chapter 6.

Carmel 116th has an ICD of 177 ft, which is larger than that for Carmel 106th. The conflict areas at Carmel 116th, illustrated in figure 42, are also larger than those at Carmel 106th, ranging from 67 to 74 ft when measured from the entrance line to the start of the circulating lane lines.

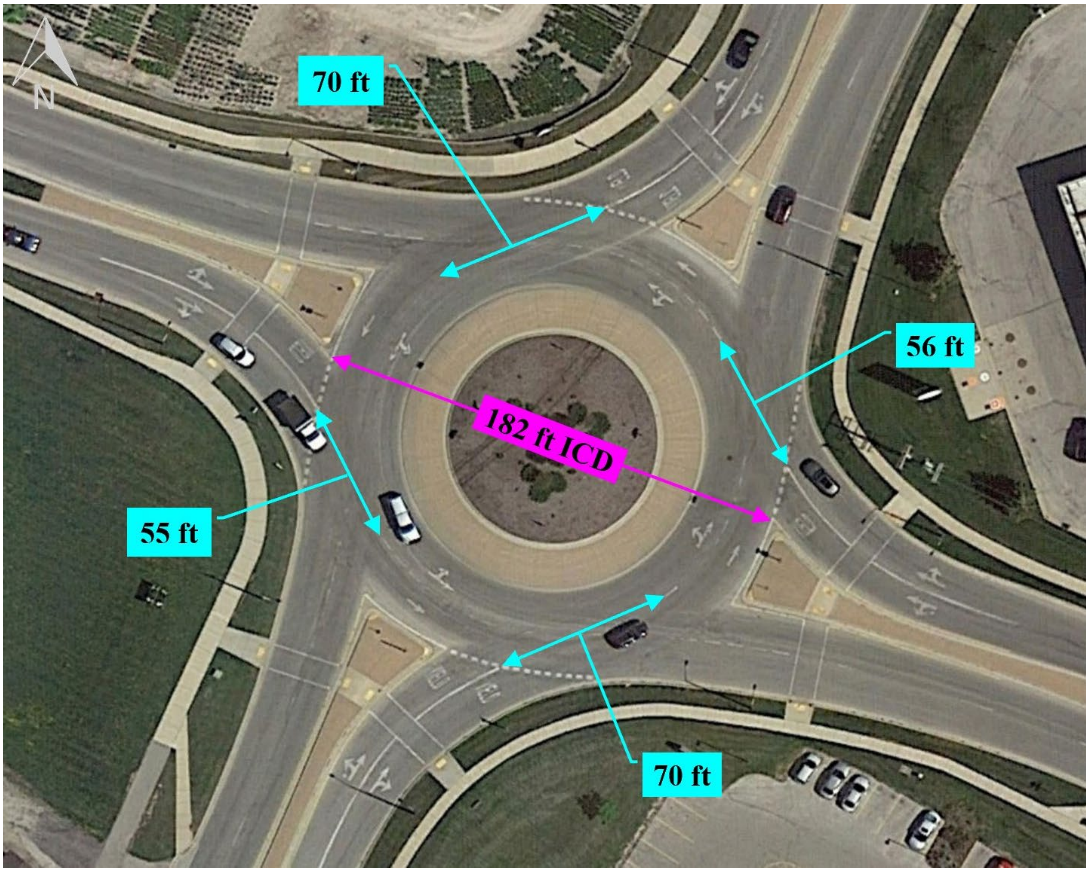


Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 42. Photo. Carmel 116th—conflict areas.

For the northeast and southwest corners of the roundabout, concentric lane markings are present. In these corners, the conflict area was measured to coincide with the edge of the splitter island. The exit geometry influences the size of the conflict areas at this location. Carmel 116th has a higher number of crashes related to failure of entering vehicles to yield to both circulating lanes, with 31 crashes of this type over 3 yr compared to 10 crashes over 3 yr at Carmel 106th. However, this crash type represented 16–20 percent of the total intersection crashes at both locations. At Carmel 116th, the failure-to-yield crashes were distributed between the northbound, southbound, and eastbound entries, with 8–12 crashes over 3 yr per entry. These crashes were also influenced by traffic volume patterns and network considerations, which are discussed further in chapter 6.

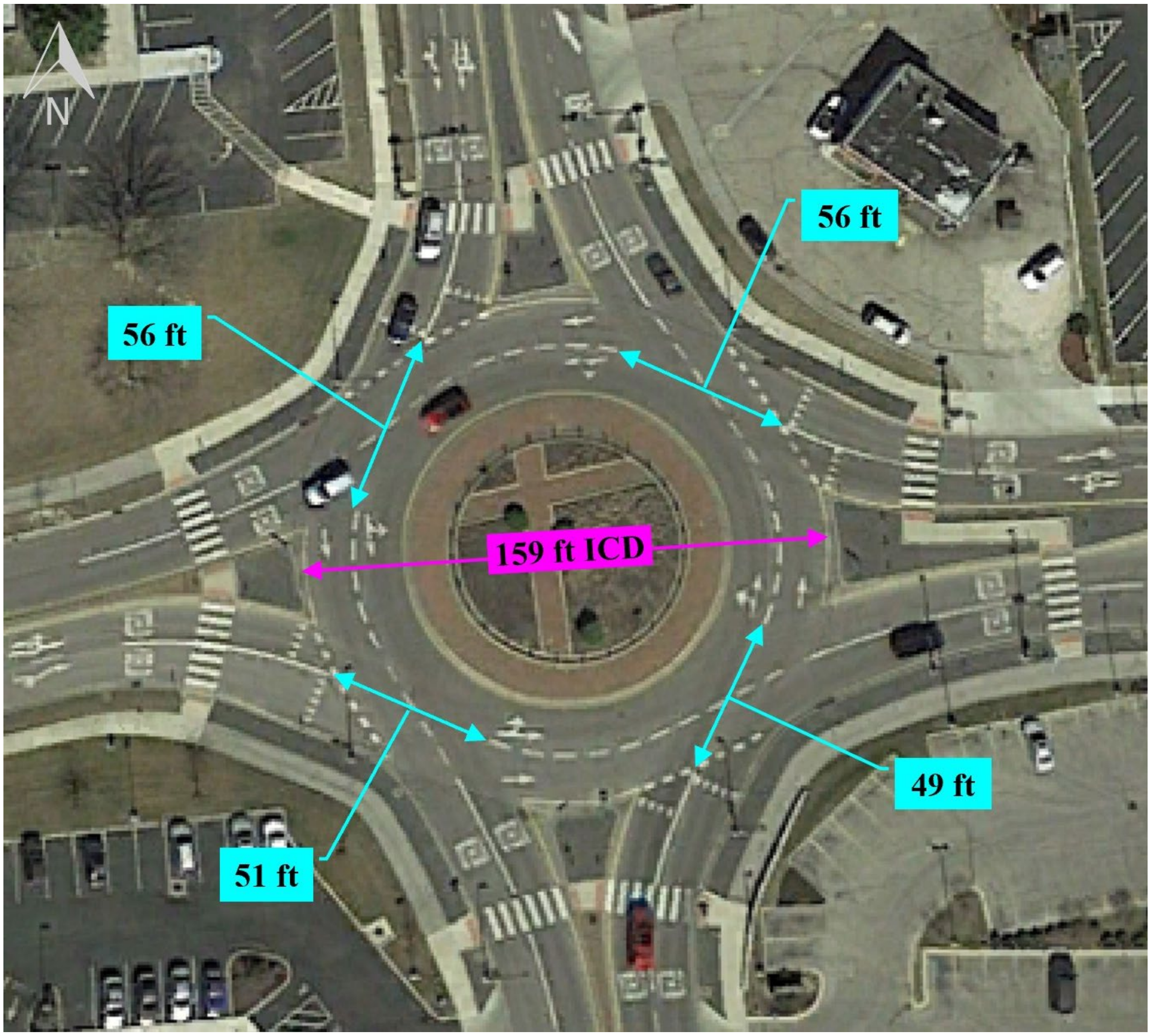
The control site in De Pere had the fewest crashes and the lowest volumes. This site has an ICD of 182 ft, with a slight skew angle between intersection legs that results in larger conflict areas in front of the southbound and northbound entries, as illustrated in figure 43. However, the size of the conflict areas did not correlate to the location of crashes at De Pere. Over the 3-yr period, 13 of the 23 total crashes occurred in the southwest corner adjacent to the eastbound entry, which has the smallest conflict area. At this site, other factors, such as turning movement patterns and network influences, appear to have a greater impact; these factors are discussed in more detail in chapter 6.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: May 17, 2018. 44° 25′ 57.57″ N and 88° 00′ 58.87″ W. Elevation 598 ft.
Eye altitude 1,485 ft.

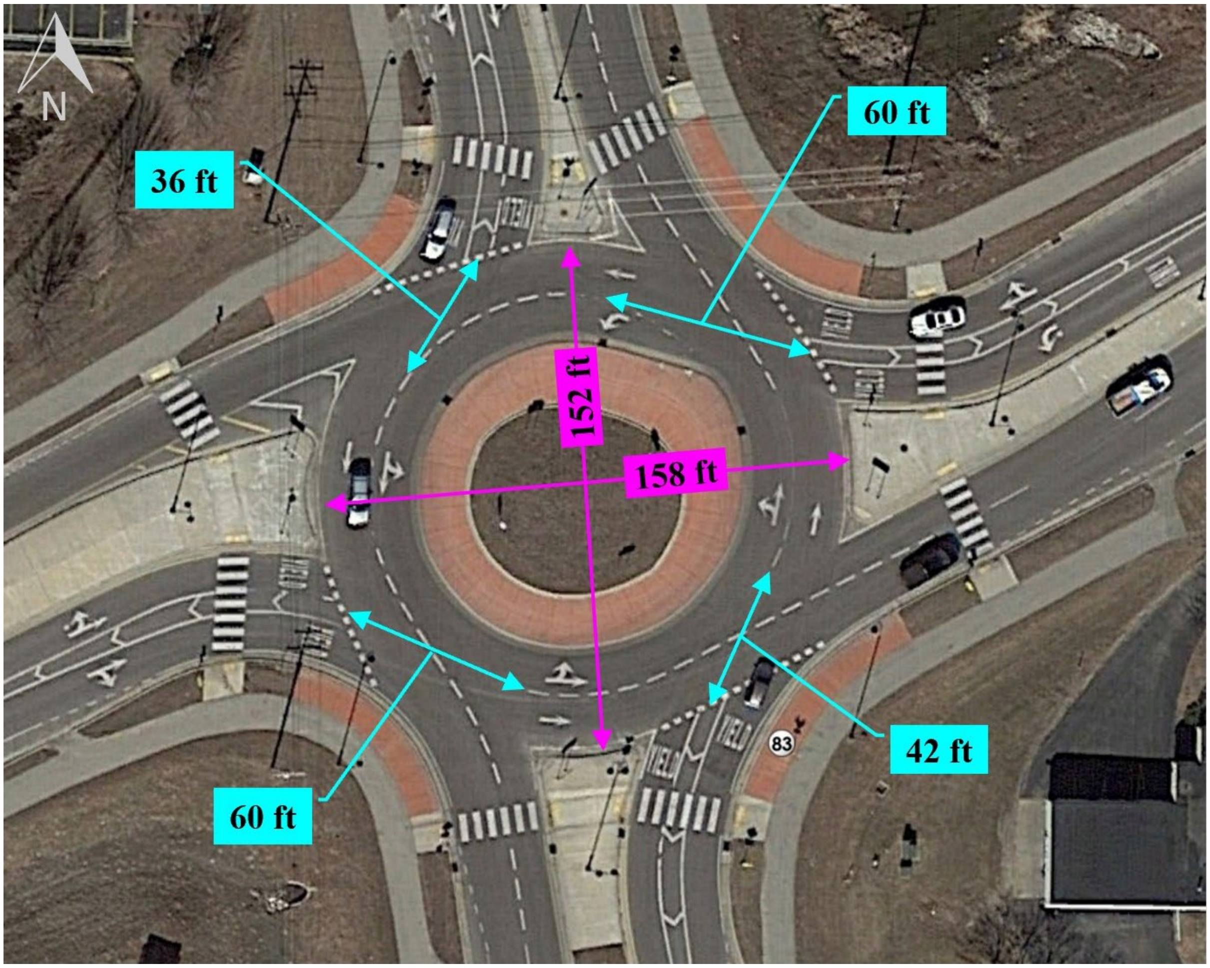
Figure 43. Photo. De Pere—conflict areas.

Each of the remaining three sites at Hilliard (figure 44), Wales (figure 45), and Oshkosh (figure 46) have more compact ICDs, ranging from 135 to 159 ft. These reduced ICDs generally result in smaller conflict areas than the other study sites. However, crashes involving failure to yield were the highest at the Hilliard site, which had 21–35 crashes of this type at each entry over 3 yr. At Wales, 11–15 crashes involving failure to yield were reported for each entry over 3 yr, which is comparable with the number of crashes recorded at the other problem sites where large conflict areas were present. In contrast, the Oshkosh site had 1–3 failure-to-yield crashes at each entry over 3 yr. Oshkosh had a smaller ICD than Hilliard and Wales but generally had comparably compact conflict areas. These findings suggest that other factors were likely to contribute to the observed failure-to-yield crashes at Hilliard and Wales.



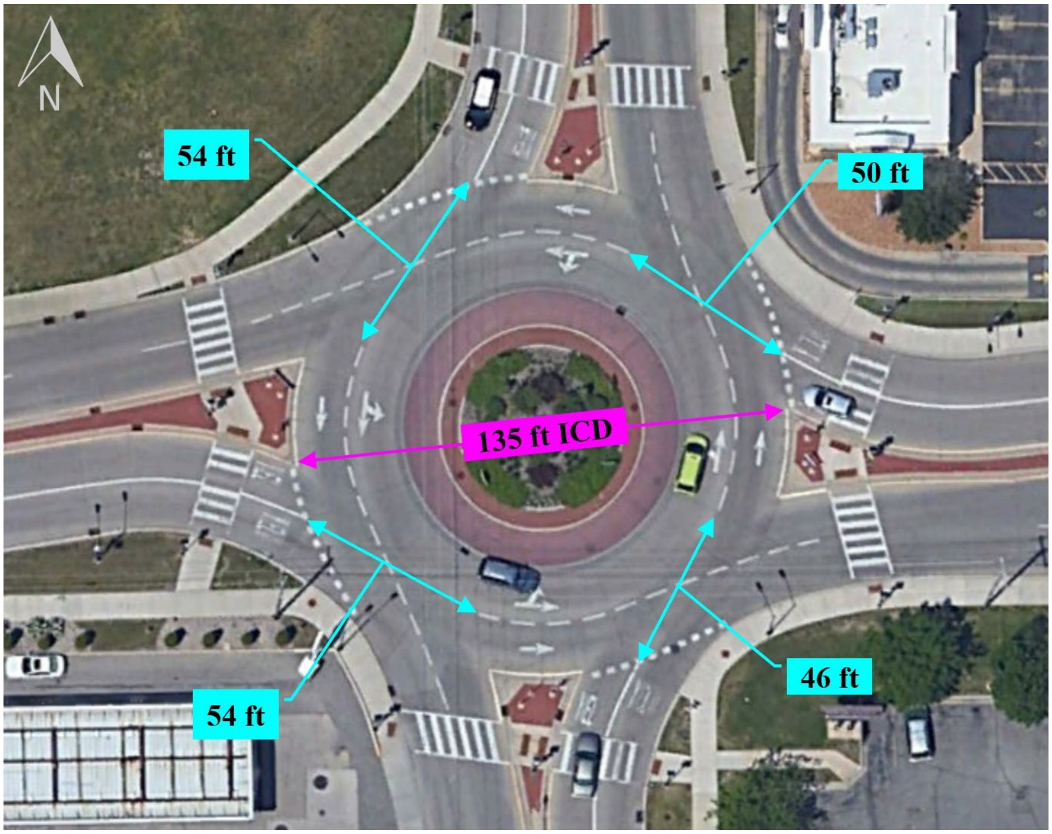
Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 17, 2018. 40° 01′ 48.28″ N and 83° 09′ 40.58″ W. Elevation 937 ft.
Eye altitude 1,935 ft.

Figure 44. Photo. Hilliard—conflict areas.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 16, 2018. 43° 00′ 43.21″ N and 88° 23′ 02.71″ W. Elevation 987 ft.
Eye altitude 2,450 ft.

Figure 45. Photo. Wales—conflict areas.



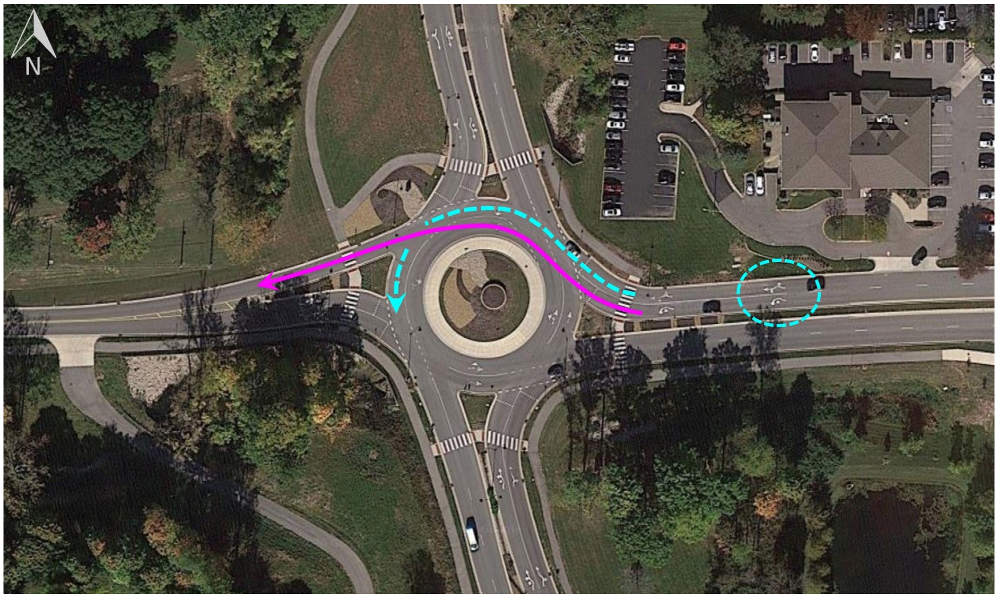
Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: April 13, 2015. 44° 02′ 21.52″ N and 88° 32′ 33.17″ W. Elevation 760 ft.
Eye altitude 1,539 ft.

Figure 46. Photo. Oshkosh—conflict areas.

APPROACH LANES ENDING IN MANDATORY TURN LANES

Where an approach lane ends at the roundabout as a mandatory turn lane, drivers may use the incorrect lane or make lane changes within the roundabout if additional emphasis is not provided upstream of entry.

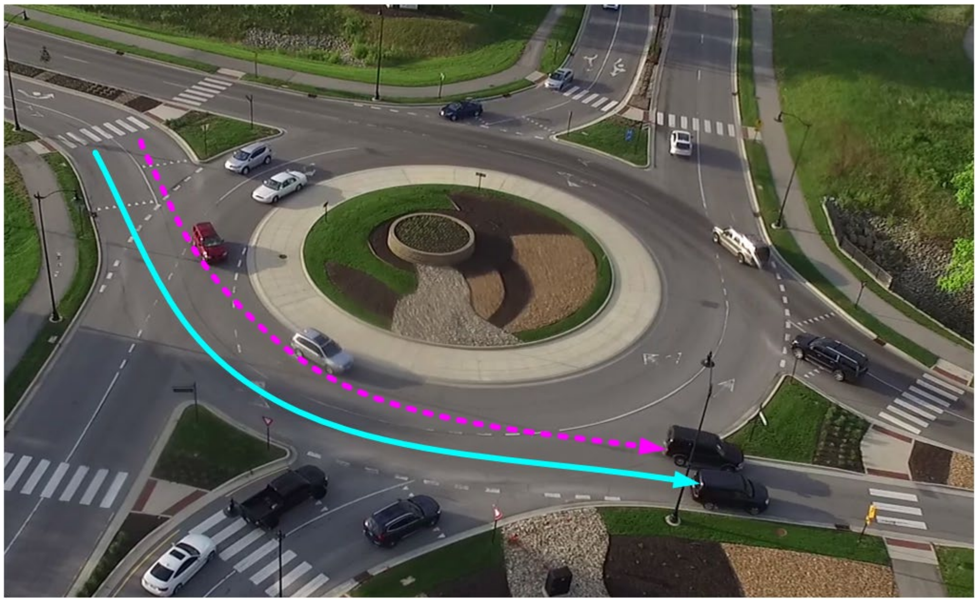
At the westbound approach to Carmel 106th, there are two approaching lanes; however, the inside lane is an exclusive left-turn lane. The outside lane allows a vehicle to make a left turn, continue straight westbound, or turn right. The combination of the lane drop with the relatively short spacing (685 ft) to the upstream roundabout at the adjacent interchange may be influencing driver lane selection or ability to change lanes during periods of heavier volume. Over 4 h, 194 through vehicles were noted to incorrectly use the inside lane to continue westbound (13-25 percent of westbound through vehicles). These data correspond to a key crash pattern, illustrated in figure 47, associated with vehicles using the incorrect lane to make a through movement and changing lanes at the westbound exit. This crash pattern generated 11 percent (or 5) of the intersection's total crashes.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: Imagery date: October 10, 2018. 39° 56′ 29.71″ N and 86° 09′ 40.36″ W. Elevation 821 ft. Eye altitude 1,752 ft.

Figure 47. Photo. Carmel 106th—Westbound through from incorrect exclusive left-turn lane.

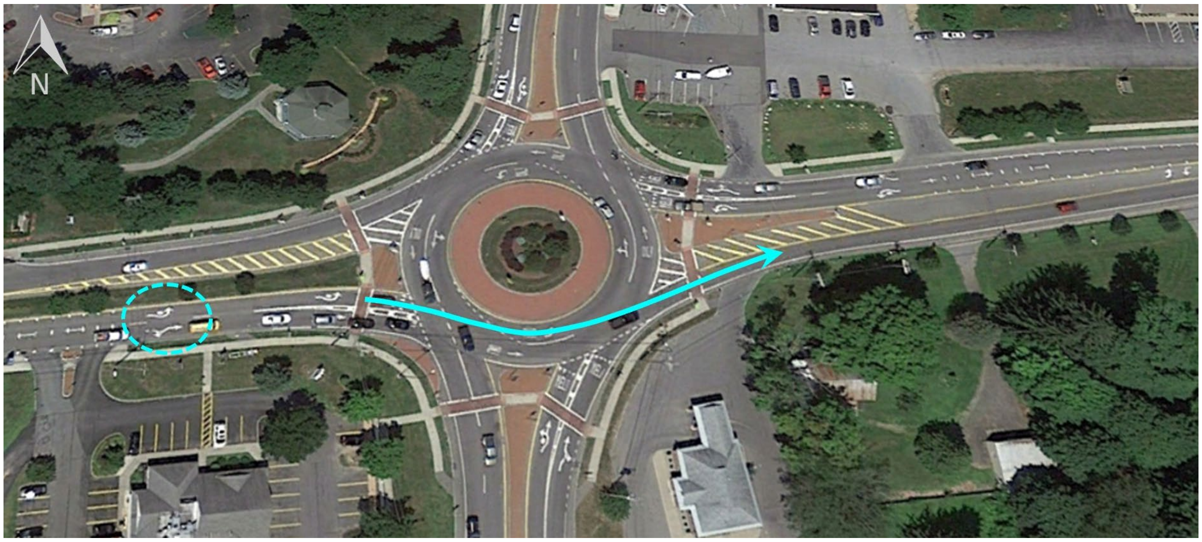
Figure 48 illustrates an observed near-crash on the westbound exit at Carmel 106th. A vehicle incorrectly making a through movement from the exclusive left-turn lane (inside lane) almost collided with an adjacent vehicle making the through movement from the correct outside lane.



Source: FHWA.

Figure 48. Carmel 106th—Observed near-crash from westbound through from incorrect exclusive left-turn lane (image facing south).

At Malta, as illustrated in figure 49, the eastbound approach has two continuous lanes, with the inner lane becoming a mandatory left turn only lane at the roundabout. The outer entry lane serves the eastbound through and right-turn movements. During the morning peak hour, high eastbound-to-southbound right turns were observed for vehicles traveling from I–87. Due to the high right-turn demand, there is a substantial lane imbalance, with 69 percent of vehicles in the outside lane. This imbalance resulted in 5 percent of the eastbound through vehicles (10 vehicles) during the morning peak using the incorrect inside lane, which is designated as left-turn only, to make an eastbound through movement. The westbound approach also has a mandatory left turn only lane; however, the second westbound entry lane is developed as a lane addition, as discussed in the next section.



Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 49. Photo. Malta—Exclusive eastbound left-turn lane.

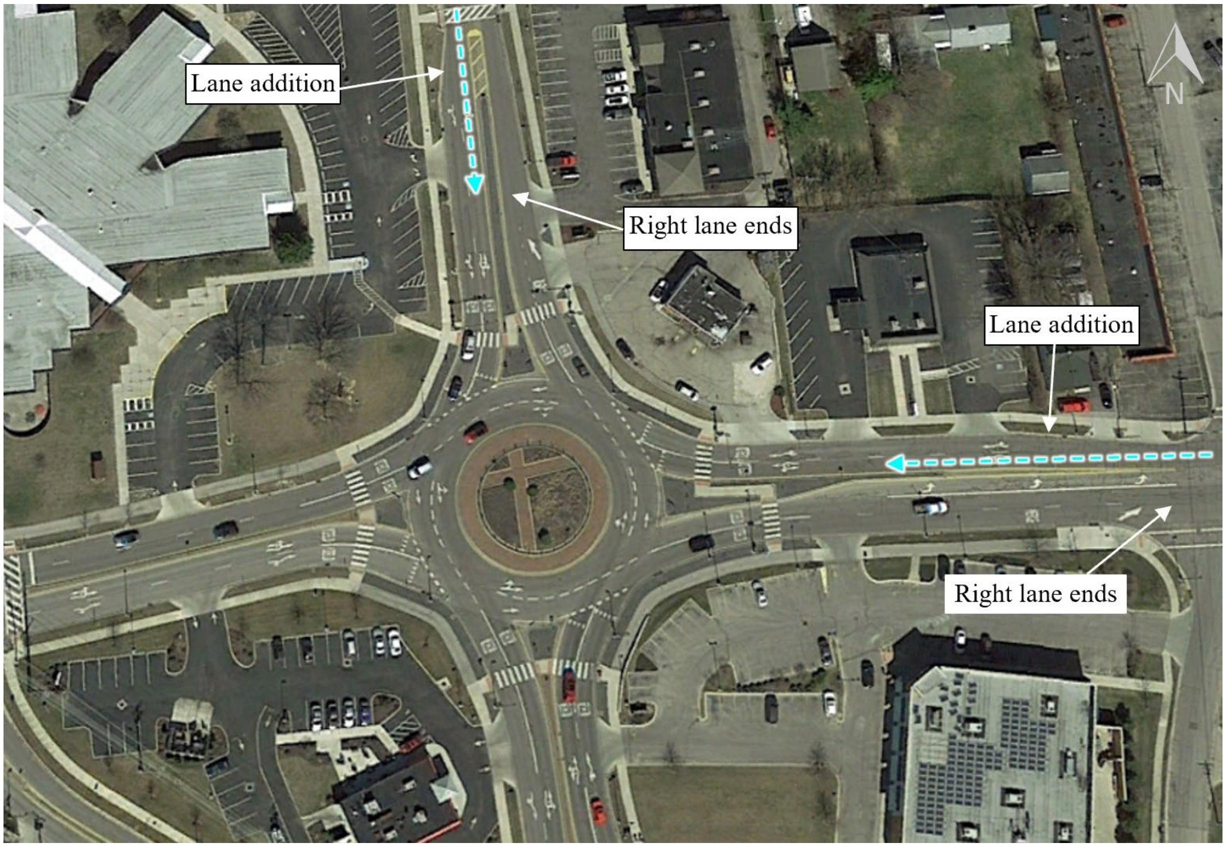
Exclusive left turns are also present at Wales (westbound entry) and Slingerlands (eastbound and westbound entries). However, in both cases, the exclusive lanes are developed through a lane addition. These cases are further discussed in the next section.

ALIGNMENT OF ENTRY LANE ADDITIONS AND EXIT MERGING

At roundabouts, the addition of lanes on the approach and then the merging of lanes on exit is a relatively common strategy. According to the 2000 version of *Roundabouts: An Informational Guide*, the wide-nodes/narrow-roads strategy focuses on putting the capacity at the intersection where it is needed and allowing for fewer lanes along the roadway segment between intersections.(4) A common application is the use of a two-lane, undivided roadway (one lane in each direction) that widens to two entering lanes at the roundabout. Depending on the lane configuration, the downstream exit lane can be a single-lane exit or a two-lane exit that merges to a single lane beyond the roundabout exit.

Seven of the intersections in this study had lane additions, and 2 of these 7 intersections had lane merging immediately beyond the exit. The design approach to adding entry lanes and merging exit lanes appeared to affect vehicle lane selection and lane utilization.

At Hilliard, the westbound and southbound approaches each have lane additions. Each uses a standard taper to add a shared through-right lane toward the outside. As illustrated in figure 50, the single approach lane is aligned with the inside entry lane that is designated as a shared through-left lane. Each of the northbound, westbound, and southbound entries had between 8 and 11 reported crashes related to right turns from incorrect lanes over 3 yr. These crashes may be attributable, in part, to drivers aligning into the inside left through lane on entry, as well as influences from downstream exit-lane merging in close proximity to the circulatory roadway.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 17, 2018. 40° 01′ 48.28″ N and 83° 09′ 40.58″ W. Elevation 937 ft.
Eye altitude 1,935 ft.

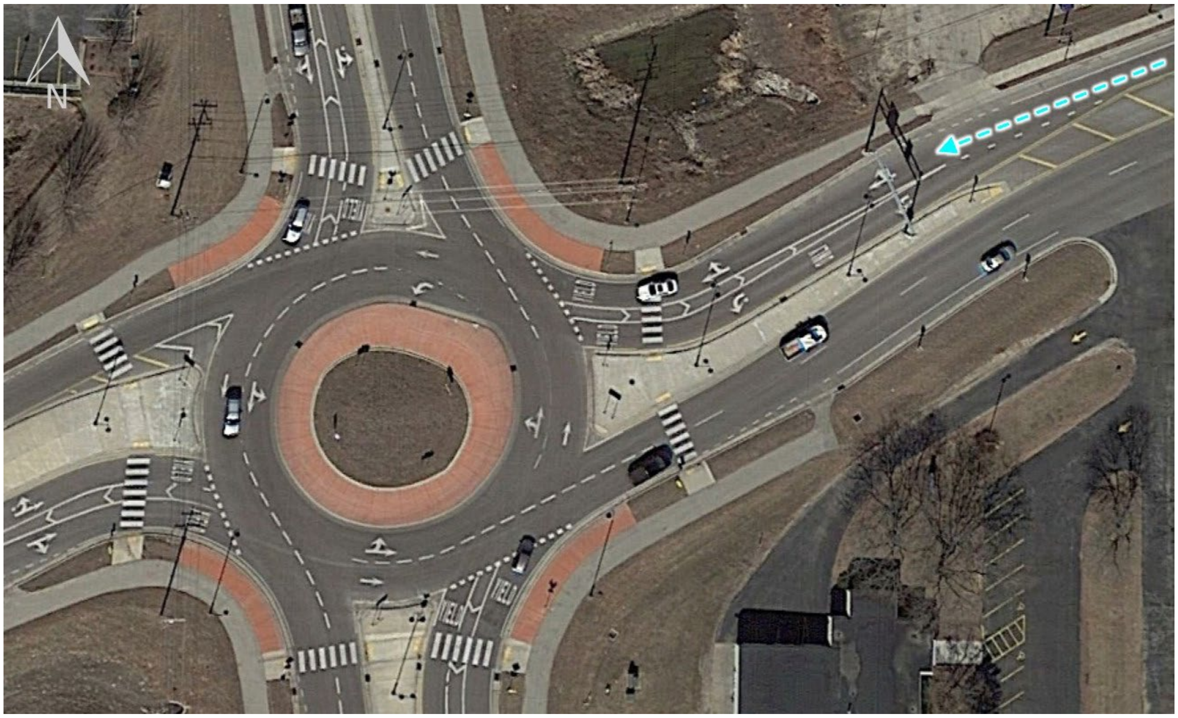
Figure 50. Photo. Hilliard—Lane additions and lane merging.

During each of the 4 h, the westbound approach at Hilliard was imbalanced, with 56–78 percent of the westbound drivers using the inside entry lane. This result was likely further influenced by two factors: relatively low right-turn demand, and network influences related to a downstream lane drop beyond the roundabout to the west and exit-lane merging to the north. However, the combination of crashes related to right turns from incorrect lanes and fewer drivers using the correct outside lane suggests that the alignment of vehicles to favor the inside lane may be contributing to drivers making incorrect lane selections for right turns.

On the southbound entry at Hilliard, which experienced the highest conflicting flows at the intersection, the alignment of the lane addition appeared to have less impact on lane utilization, which was more balanced, with a maximum of 54 percent in the dominant lane. In addition to right turns from incorrect lanes, a primary crash type for the southbound entry was crashes related to failure to yield to both circulating lanes. The imbalance in volume on the westbound entry results in higher volume in the inside circulating lane, leaving the outside lane more vacant. This imbalance may be creating conditions favorable to failure-to-yield crashes on the southbound entry, where a driver may attempt to enter beside another circulating vehicle.

As illustrated in figure 50, the northbound and eastbound exit lanes at Hilliard merge into a single lane immediately beyond the crosswalks. This factor may also be influencing crashes involving right turns from incorrect lanes on the northbound and westbound entries. Some drivers may be using the incorrect lane to avoid the downstream lane drop immediately after their turn. The lane merging northbound and eastbound may also be influencing lane changing through the exits, which was a top source for violations at the Hilliard site.

At Wales, the westbound approach widens from a single approach lane to two entry lanes with the addition of an exclusive left-turn lane. As illustrated in figure 51, the approaching vehicles are aligned into the outside lane, which is designated as a shared through-right lane.

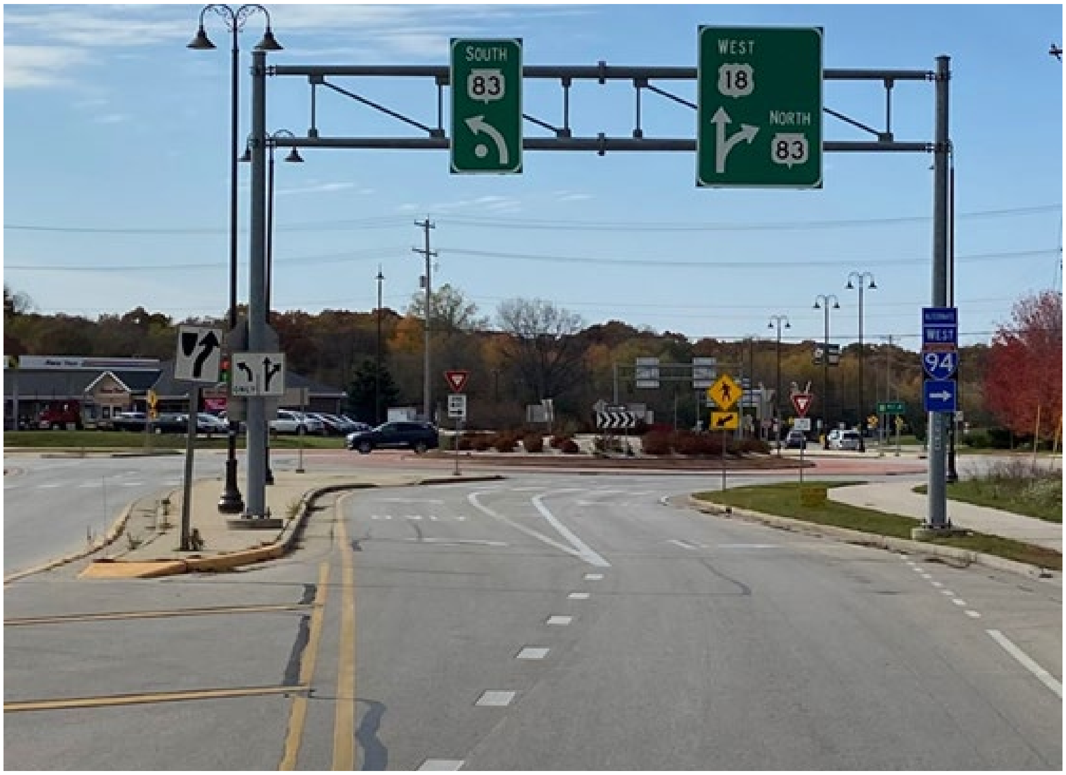


Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 16, 2018. 43° 00′ 43.20″ N and 88° 23′ 00.62″ W. Elevation 987 ft.
Eye altitude 1,628 ft.

Figure 51. Photo. Wales—Westbound lane addition (plan view).

As illustrated in figure 52, an abrupt alignment shift on the westbound approach upstream of the roundabout further directs vehicles into the outside lane and may be contributing to

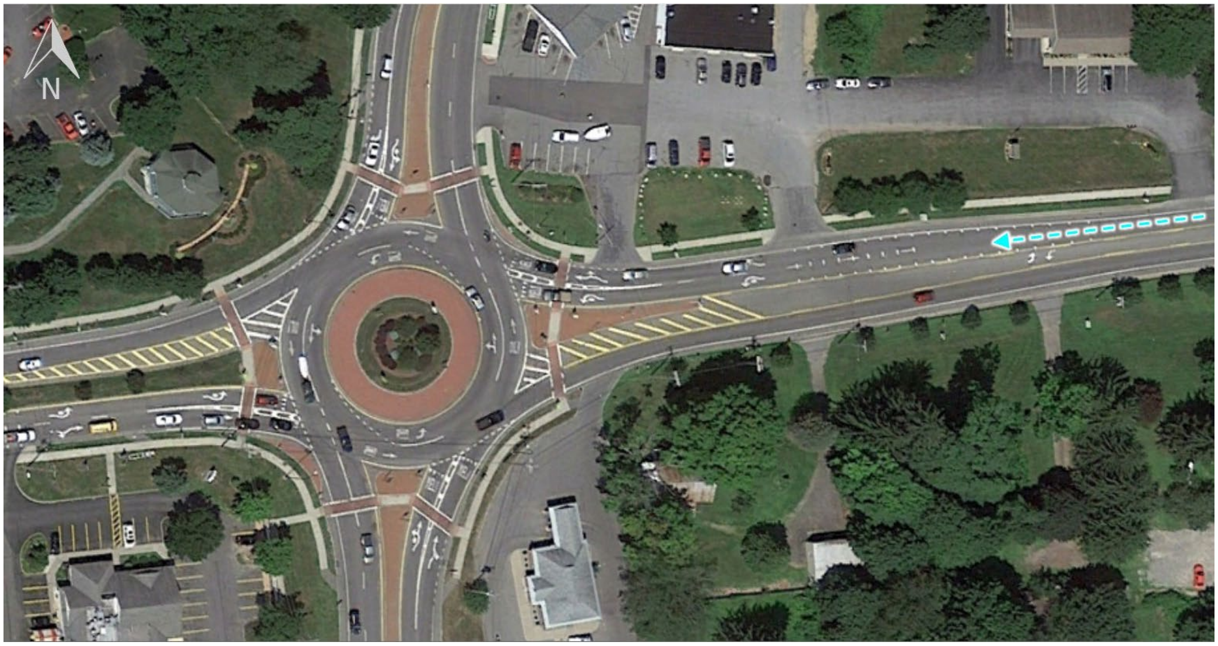
54 left-turning vehicles over 4 h observed to use the incorrect outside lane from the westbound entry. However, this alignment shift is not translating to a crash pattern related to the inside lane being designated left turn only. While the signing and markings do not allow a left turn from the outside lane, the overall intersection lane configurations would support left turns from both westbound entry lanes. Higher numbers of crashes may be expected with the same westbound entry geometry if the inside lane is designated as a shared through-left with two westbound exit lanes.



Source: FHWA.

Figure 52. Photo. Wales—Westbound lane addition (ground-level view).

Figure 53 shows Malta, where the westbound approach widens from a single lane to two entry lanes approximately 270-ft upstream of the yield line.

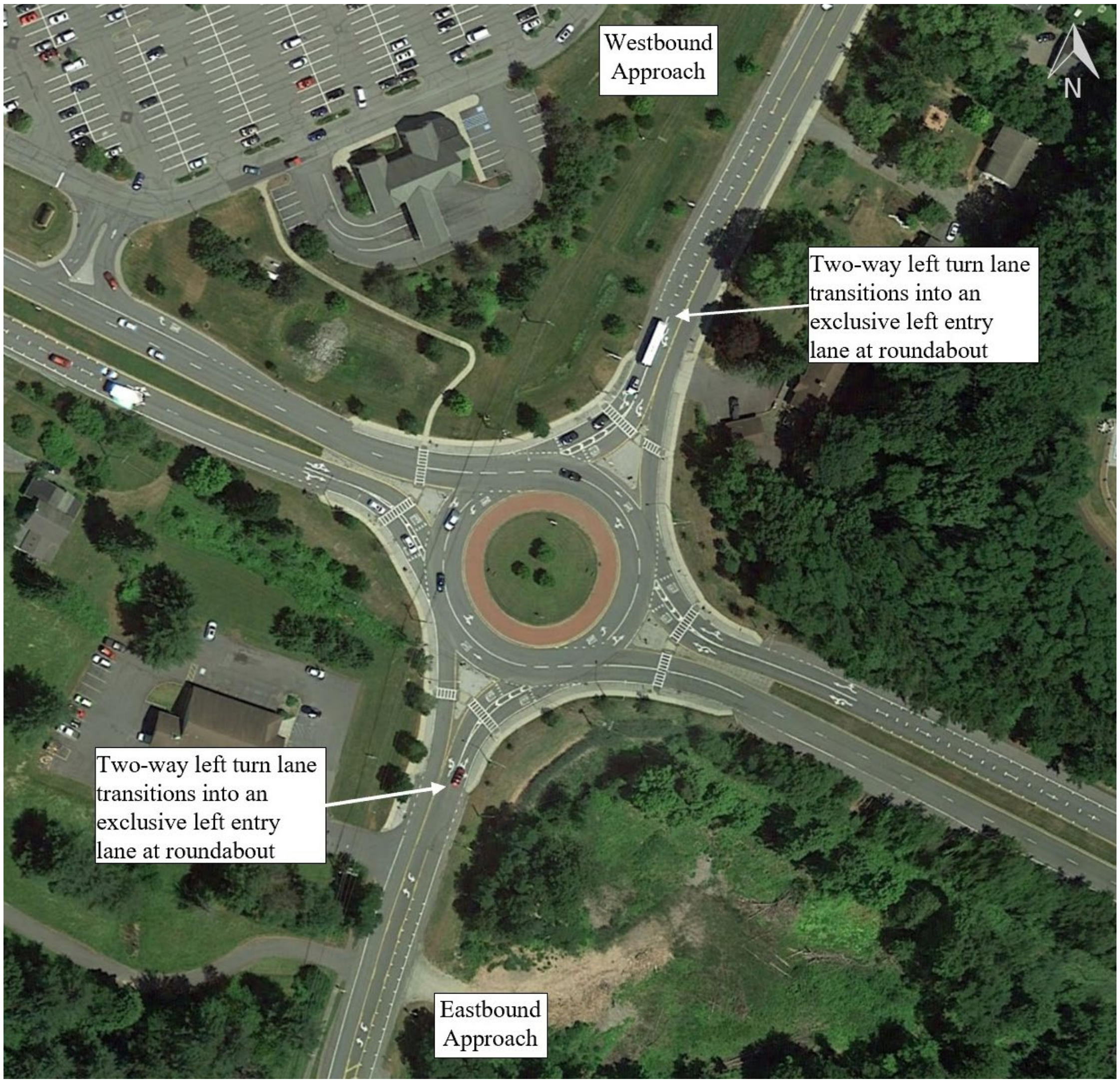


Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 53. Photo. Malta—Westbound lane addition.

At Malta, the second entry lane is developed by widening toward the outside with a 120-ft taper. Widening toward the outside aligns approaching drivers into the inside entry lane, which is designated as left turn only. Drivers must use the outside entry lane to continue straight toward a downstream interchange, the primary movement on the westbound entry. Compared to the shorter taper used at Hilliard, the longer taper at Malta appears to better support drivers selecting the correct lane for the through movement. During each of the 3 h evaluated at Malta, between 69 and 78 percent of drivers used the outside lane on the westbound entry. During each hour, between 7 and 14 drivers (or 2–6 percent of the westbound through volume) were observed to use the incorrect lane. These instances of incorrect lane use appeared to be influenced by volume imbalances and drivers aligning into the inside lane.

Figure 54 shows Slingerlands, where two legs have one travel lane in each direction with a two-way center turn lane. The two-way left-turn lanes transition into exclusive left-turn lanes at the roundabout entry.

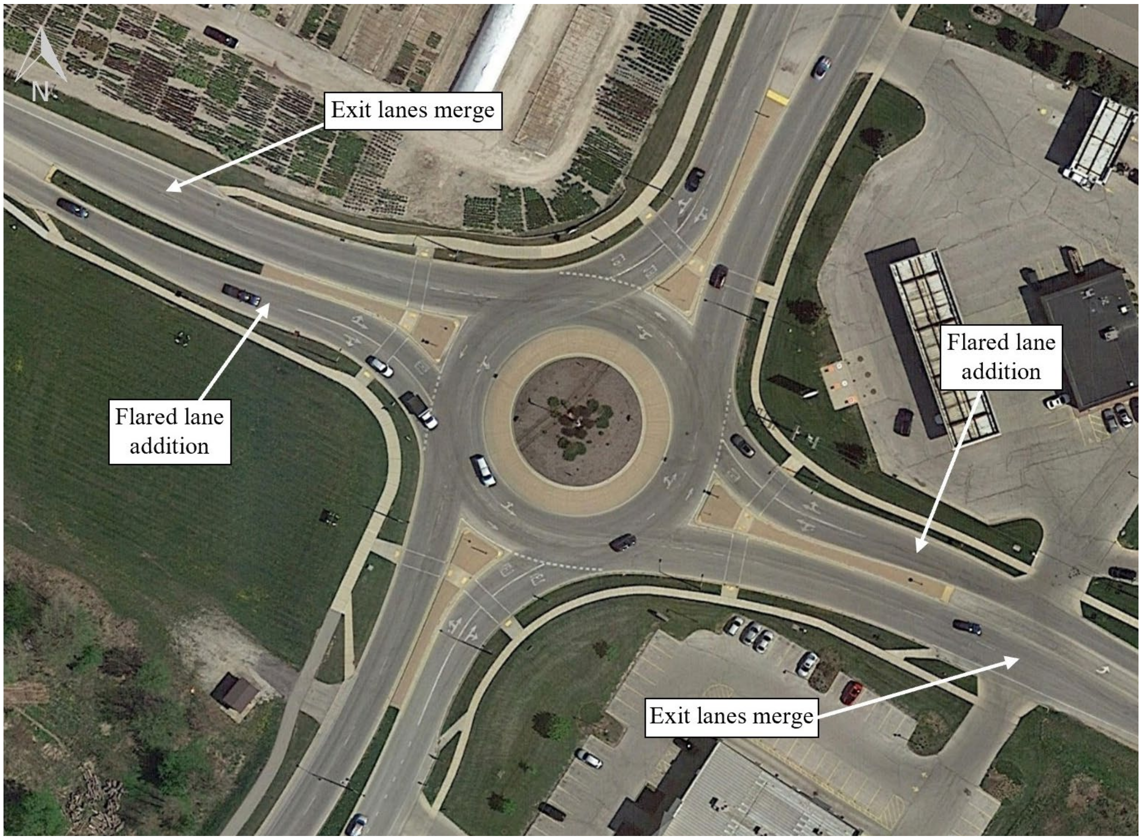


Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 38′ 13.51″ N and 73° 51′ 21.50″ W. Elevation 217 ft.
Eye altitude 1,205 ft.

Figure 54. Photo. Slingerlands—Entry lane additions.

Drivers approaching the entry are aligned into the outside entry lane, which has a shared left-through-right lane-use designation. Therefore, drivers intending to use the inside entry lane must make a lane change, similar to moving into a left-turn lane at an intersection with other control types. This required lane change results in heavy lane imbalances but lower instances of through vehicles using the incorrect lane. For the 1 h of data evaluated at Slingerlands, the westbound and eastbound approaches had 65 percent and 85 percent of vehicles in the outside lane, respectively. The team observed 3–4 through vehicles per approach using the incorrect lane, likely in an attempt to bypass vehicle queues due to the heavy lane imbalances. Over a 3-yr period, only two crashes were reported related to through vehicles using the incorrect lane.

Figure 55 shows De Pere, where the eastbound and westbound legs widen from a single approach lane to two entry lanes. This widening is accomplished through a uniform flare to the left and right to reduce priority being given to one entry lane. Drivers on the westbound approach favored the outside lane (56–65 percent of vehicles during each hour). Meanwhile, drivers on the eastbound approach favored the inside lane (72–75 percent of vehicles during each hour). On the westbound entry, six drivers were observed to use the incorrect lane for either a left-turn or right-turn movement over the 4 h analyzed. Nine drivers used the incorrect lane for the left turn or right turn on the eastbound approach, with most using the incorrect outside lane for the left turns to bypass queuing in the inside lane. At this site, the turning movement patterns appeared to have a greater influence on the lane selection due to the geometry of the entry lane additions.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: May 17, 2018. 44° 25′ 57.57″ N and 88° 00′ 58.87″ W. Elevation 598 ft.
Eye altitude 1,485 ft.

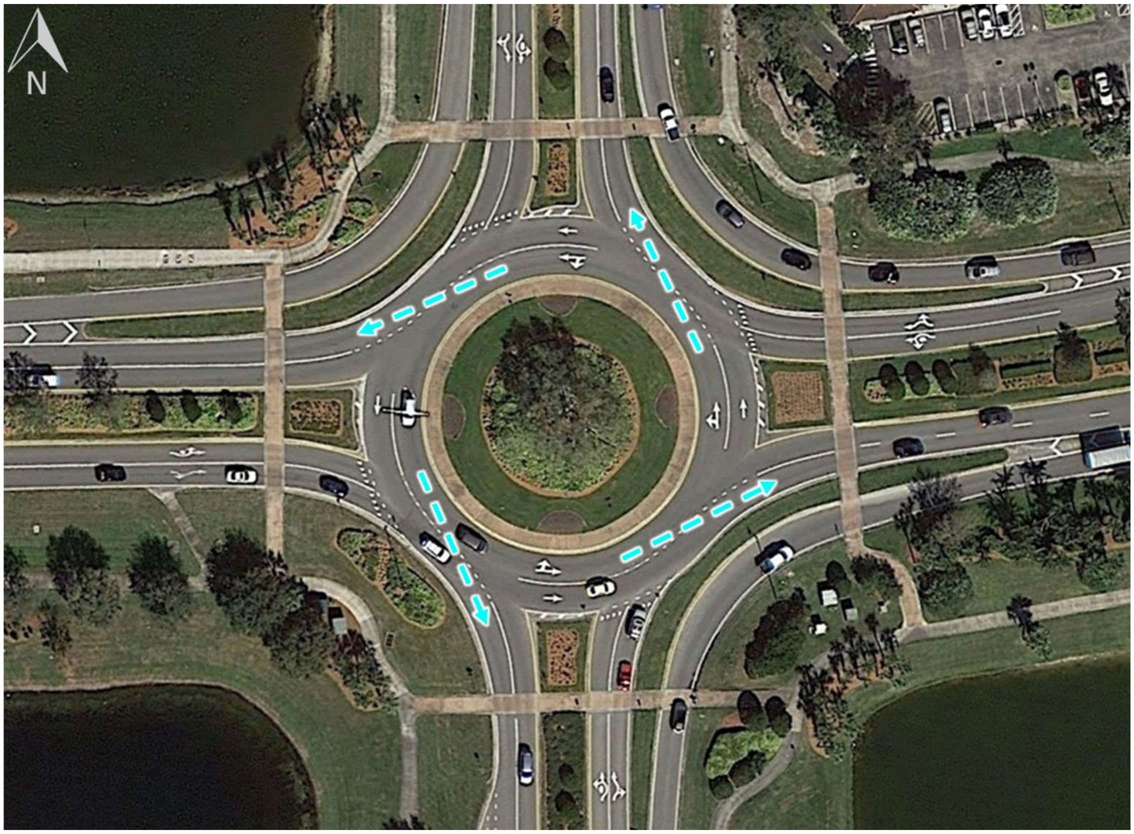
Figure 55. Photo. De Pere—Flared lane additions and lane merging.

At De Pere, the eastbound and westbound exit lanes also merge from two lanes to one lane within 140–180 ft beyond the roundabout exit. The exit lanes are posted with a sign indicating that the right lane ends to direct drivers in the outside exit lane to merge left. On the westbound entry, 64–80 percent of drivers making a through movement during each hour use the inside lane. However, this use is also influenced by the lane imbalance on the westbound entry favoring the outside lane due to high westbound right-turn volume. On the eastbound entry, 64–75 percent of drivers during each hour also use the inside lane to make a through movement, despite the heavy lane imbalance favoring the inside lane. This trend suggests that the downstream lane drop on the westbound exit may be influencing drivers' lane choices.

REVERSE CURVES THROUGH EXITS

Lane changing through the roundabout exits is a common violation identified in the conflict analysis across the study sites. The use of reverse curves through the exits with no tangent provided between the circulating lane line and exit curve appears to be increasing the potential for vehicles to change lanes through the exit.

Melbourne is one example site where this lane changing occurs, with each exit featuring relatively small exit radii and back-to-back reversing curves coming out of the circulatory roadway, as illustrated in figure 56. Over a 4-h period, 237 vehicles were observed to change lanes through the exits when making a left turn, and 59 vehicles were observed to cut across lanes when going straight. Traffic patterns influence the actual number of lane-change violations at each exit; however, the southbound exit was observed to have the highest number of vehicles changing from the inside to the outside lane through the exit.



Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

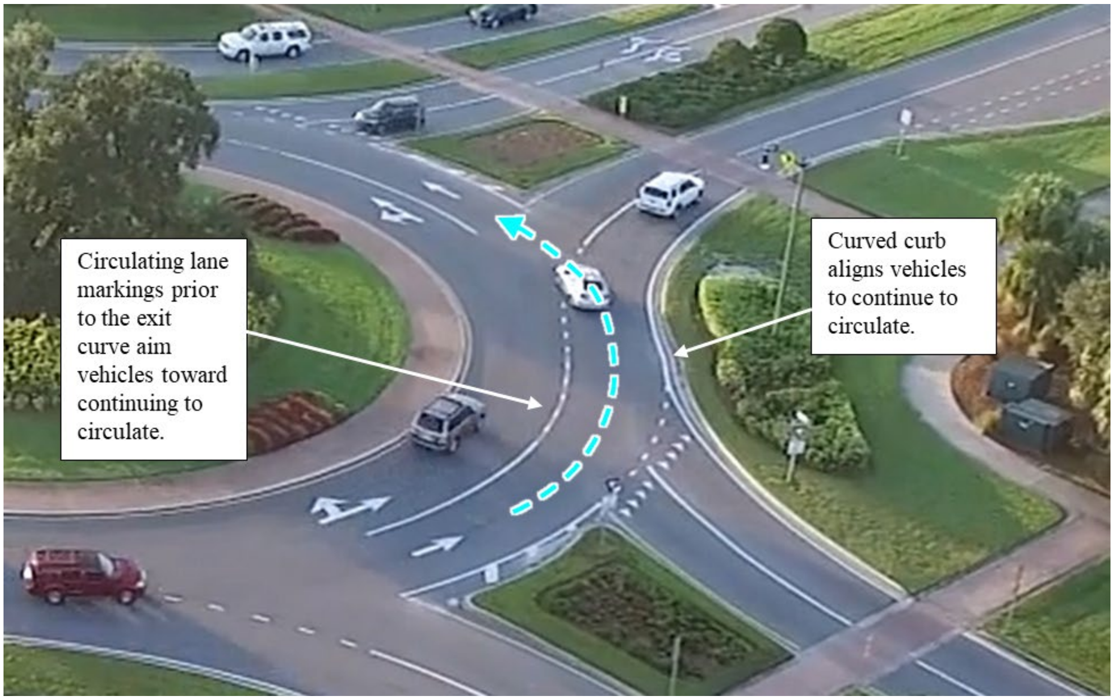
Figure 56. Photo. Melbourne—Lane changing through exit reverse curves (plan view).

Figure 57 provides a ground-level view of a vehicle approaching the exit and the path that the vehicle traveled as it crossed lanes through the exit.

Source: FHWA.

Figure 57. Photo. Melbourne—Lane changing through exit reverse curves (ground view).

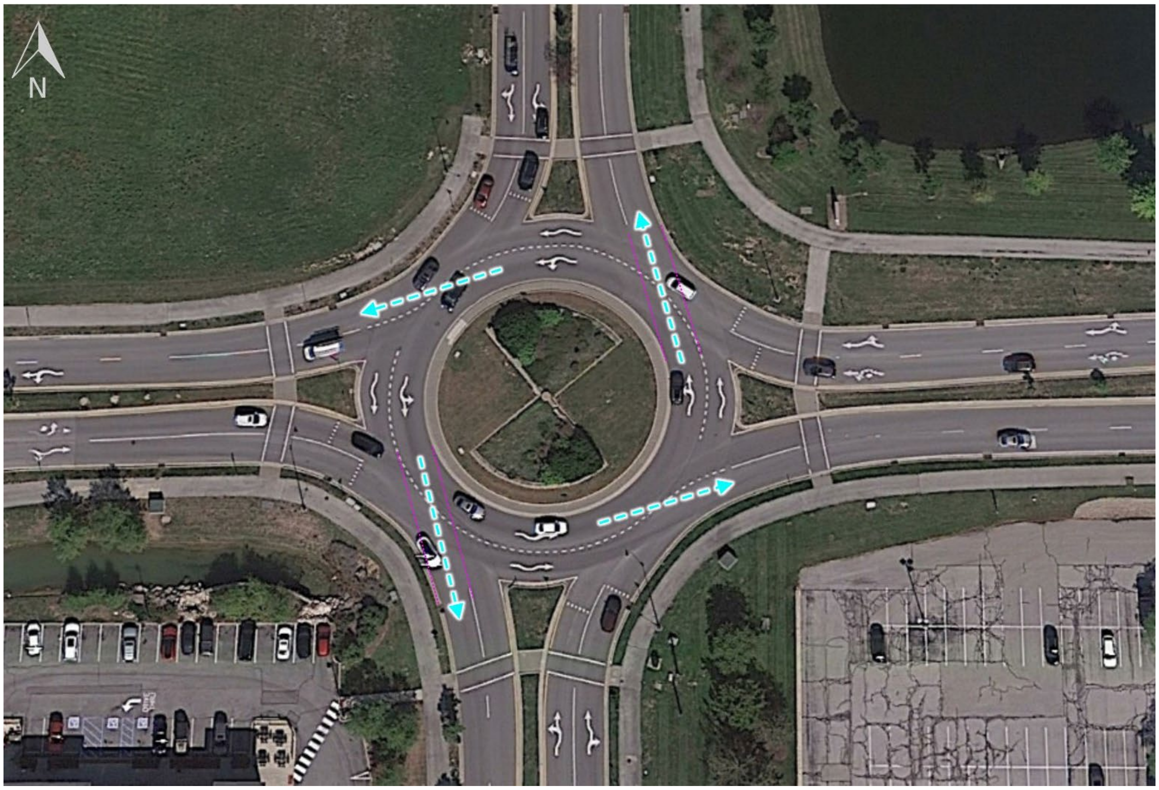
At Melbourne, drivers become accustomed to the curvature around the central island due to the large 200-ft ICD and often made smooth and natural—but incorrect—left-turn movements using the outside lane. An example is illustrated in figure 58 for southbound left-turning vehicles, where 685 vehicles over a 4-h period were observed to make a left turn from the incorrect lane. Network influences, discussed in chapter 6, contribute to incorrect lane use; however, the smooth left-turn path from the outside lane created by the reverse exit curvature also appeared to influence driver perception of allowable movements at Melbourne.



Source: FHWA.

Figure 58. Photo. Melbourne—Exit reverse curves influencing left turns from the incorrect lane.

At Carmel 116th, a larger exit radius is used compared to Melbourne. However, the short reverse curves along the lane line leading into the eastbound and westbound exits appear to be influencing higher observed lane-change violations through the exit. On the northbound and southbound exits, concentric lane markings do not provide guidance to drivers to lead them to the correct exit lane. Also, the physical alignment of the exit in relation to the circulatory roadway aligns drivers using the inside circulating lane into the outside exit lane on the northbound and southbound exits, as shown with the solid lines in figure 59. Lane changes through the exits accounted for approximately 55 percent of the total violations recorded at Carmel 116th, with 424 violations recorded over a 4-h period at all exits. The highest instances were on the southbound and eastbound exits, which are also influenced by network considerations that are discussed in more detail in chapter 6.

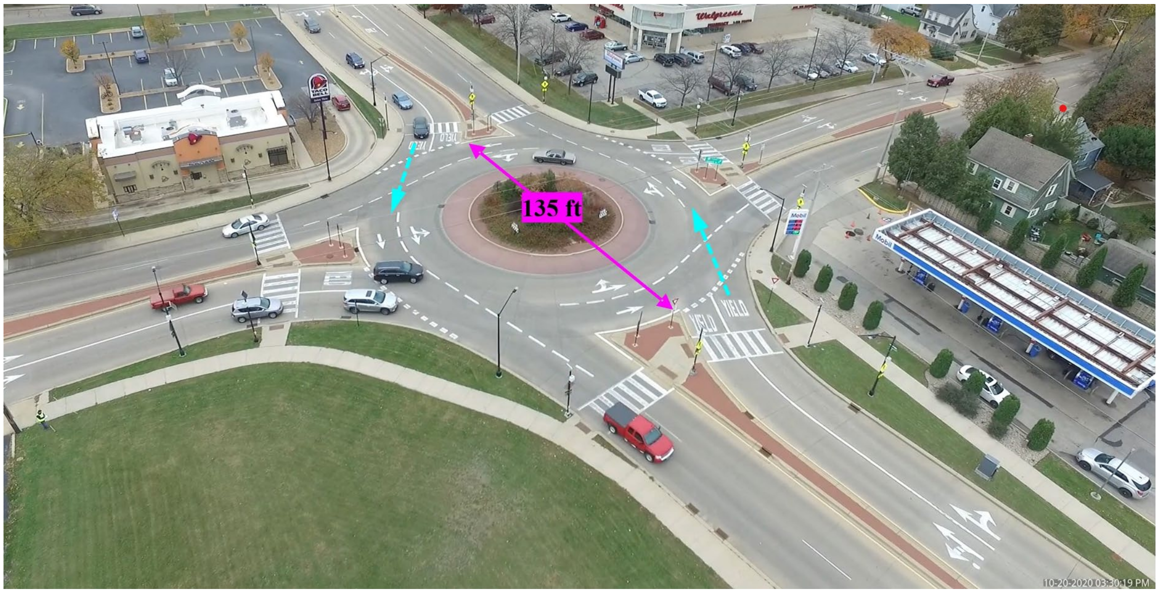


Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 59. Photo. Carmel 116th—Lane changing through exit reverse curves.

SMALL DIAMETERS

Figure 60 shows Oshkosh, which has the smallest ICD of any study site of 135 ft; all the other study sites have ICDs ranging from 150–200 ft. While Oshkosh was a control site that experienced among the lowest total annual crashes (13 per year), it generated unique patterns of crashes compared to the other sites. A higher proportion (15 percent) of the crashes at Oshkosh were related to sideswiping and lane changing within the circulatory roadway. An additional 10 percent of the crashes at Oshkosh were related to rear-end crashes at the north, west, and east exits.



Source: FHWA.

Figure 60. Photo. Oshkosh—Photo from drone facing southeast.

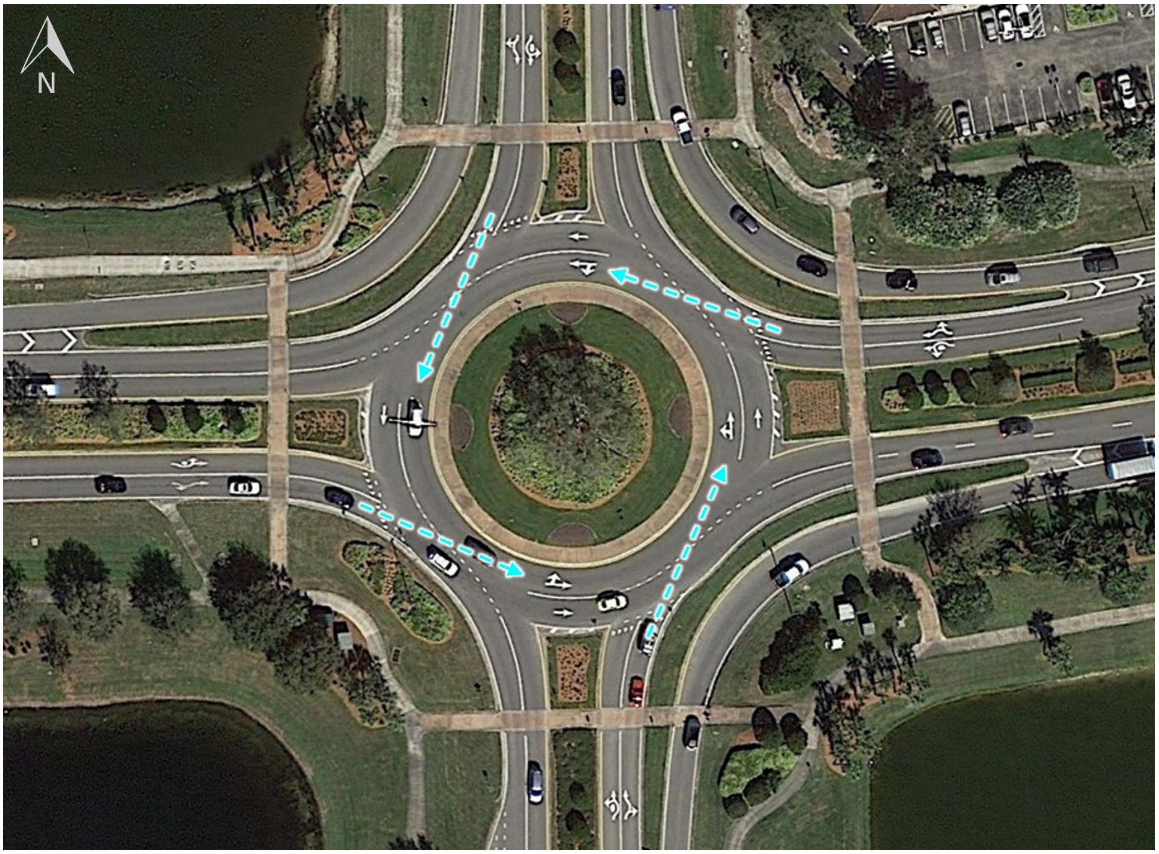
At Oshkosh, violations related to lane straddling or occupying both lanes accounted for 78 percent of all events. Over a 4-h period, 743 events were recorded related to drivers straddling the lane line in the circulatory roadway or cutting across lanes when going straight. This represents 9.2 percent of the total entering volume. Balancing competing objectives of vehicle alignment and speed control becomes more challenging with very small ICDs. At Oshkosh, the outside entry lane is aligned toward the circulating lane line. This overall design composition is a likely contributing factor to the observed lane straddling. However, despite the high violations, there were no incidents or near-crashes from lane straddling during the analysis period.

While independent of ICD, the location of the pedestrian crossings at Oshkosh may also be contributing to unexpected driver behavior. Pedestrian crossings at this site are less than 20 ft from the circulatory roadway. The proximity of these crossings may be influencing rear-end crashes at exits where drivers are not expecting the driver in front of them to stop for pedestrians while still partially in the circulatory roadway. The compact size of the roundabout and the close spacing of the pedestrian crossings result in a compressed space for driver reactions. This finding was consistent with field observations where drivers were noted to be somewhat more aggressive in accelerating from the yield line when entering the roundabout, possibly due to the shorter time and distance to make decisions.

ENTRY ALIGNMENT

The alignment of entering lanes into the correct receiving lanes affects observed violation types, including lane changes through the entry (sometimes referred to as vehicle path overlap) and lane straddling through the circulatory roadway. While these violation types and associated crashes were not found to be a primary crash type near roundabout exits, they contribute to drivers' perceptions of safety and the total PDO crashes at the intersections.

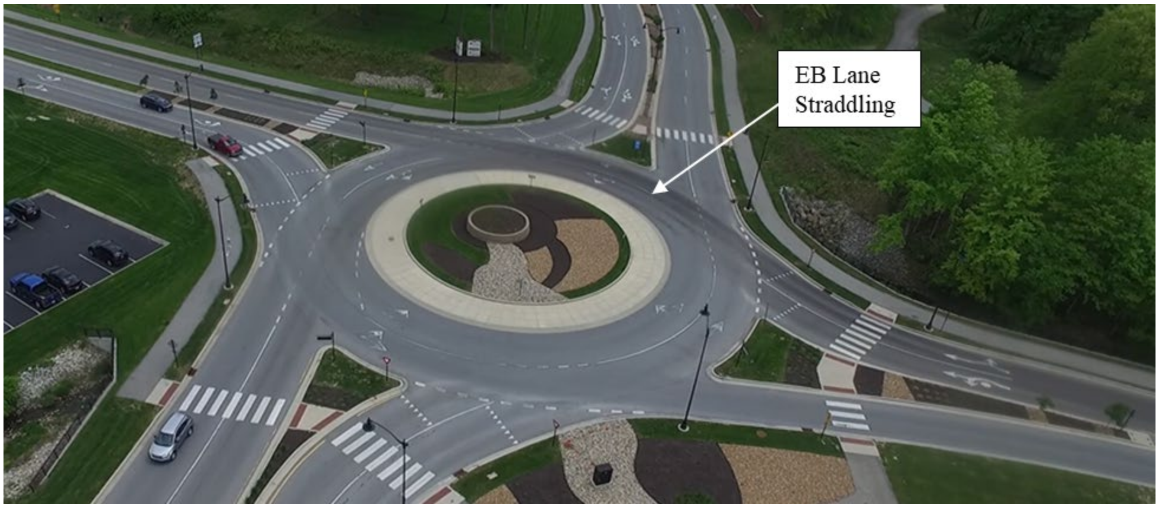
Among the study sites, Melbourne had the most severe misalignment. This misalignment resulted from the combination of several geometric elements: a large ICD; a small entry radius; a lack of large radius or tangent near the yield line; and the distance between the entry and downstream exit, which created a long distance between the yield line and the start of the circulating lane line. Figure 61 illustrates the misalignment of the outside entry lane on each approach with the inside circulating lane.



Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

Figure 61. Photo. Melbourne—Entry lane alignment.

On a similar note, at Carmel 106th the eastbound entering lanes are not well-aligned with the corresponding circulating lanes. As a result, vehicles were observed to straddle the circulating lane line when making an eastbound through movement. This trend is consistent with the tire marks visible in figure 62. The large shift to the left for the westbound entry creates a skewed angle of intersection to the adjacent northbound exit. This angle was observed to affect vehicle alignment, particularly when there were not two vehicles side-by-side at the yield line. Vehicles traveling westbound across the northern portion of the circulatory roadway were frequently observed to cross the lane line and encroach into the inside circulating lane.



Source: FHWA.

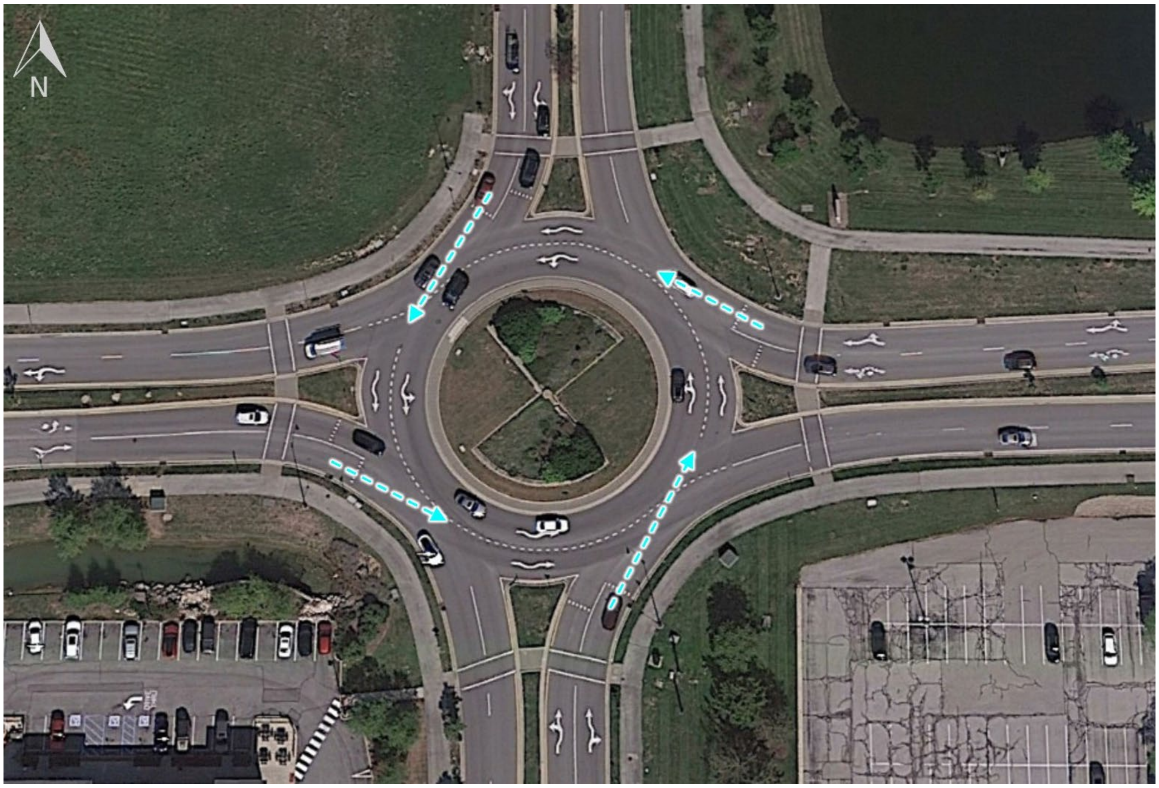
Figure 62. Photo. Carmel 106th—Eastbound lane straddling within circulatory roadway due to entry lane alignment.

Figure 63 shows how the entry lane alignment for the eastbound and westbound entries at Carmel 106th guides drivers entering from the outside entry lane into a position that straddles the circulating lane line.

Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: October 10, 2018. 39° 56′ 29.71″ N and 86° 09′ 40.36″ W. Elevation 821 ft.
Eye altitude 1,752 ft.

Figure 63. Photo. Carmel 106th—Entry lane alignment.

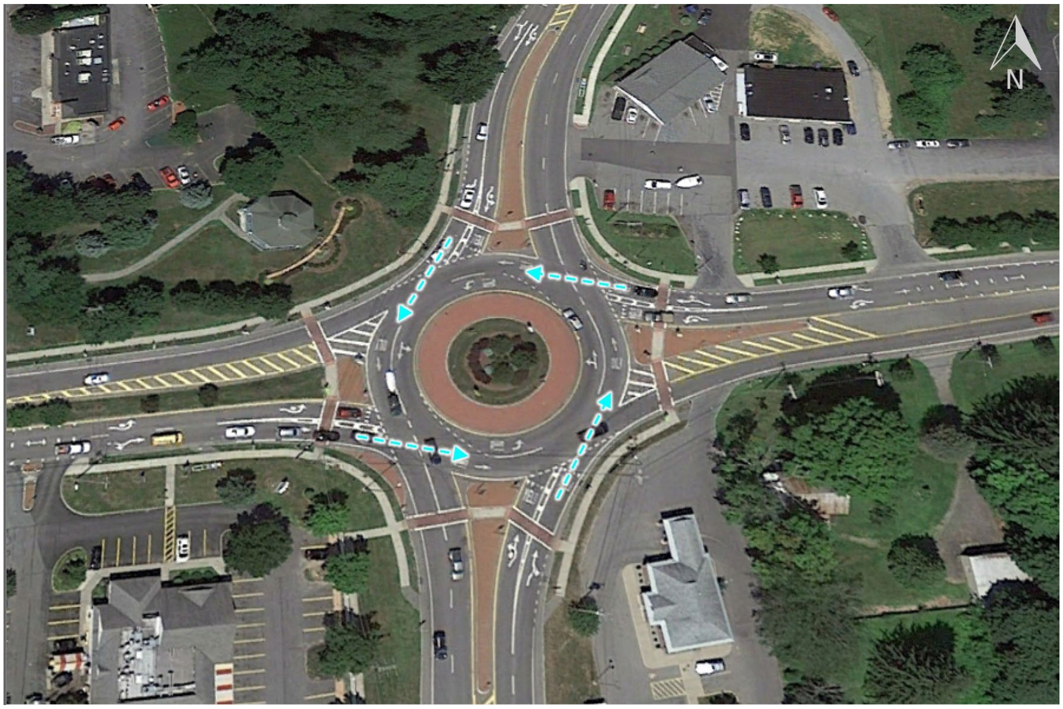
Like the Carmel 106th eastbound entry, all the approaches at Carmel 116th have entry lane misalignment. The northbound and southbound entries at Carmel 116th have a longer distance between the yield line and the start of the circulating lane line, as illustrated in figure 64, which may influence the potential for poor path alignment. Vehicles were observed to straddle both circulating lanes, particularly in the northbound and southbound directions. The use of a wider inside circulating lane (16 ft) relative to the outside lane may also have contributed to the potential for lane straddling and poor path alignment. Conversely, the eastbound and westbound entries had a shorter distance between the yield line and the start of the circulating lane lines due to the partially concentric striping pattern in the circulatory roadway. This shorter distance and striping pattern appeared to help eastbound and westbound drivers maintain the correct lanes as they entered.



Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 64. Photo. Carmel 116th—Entry lane alignment.

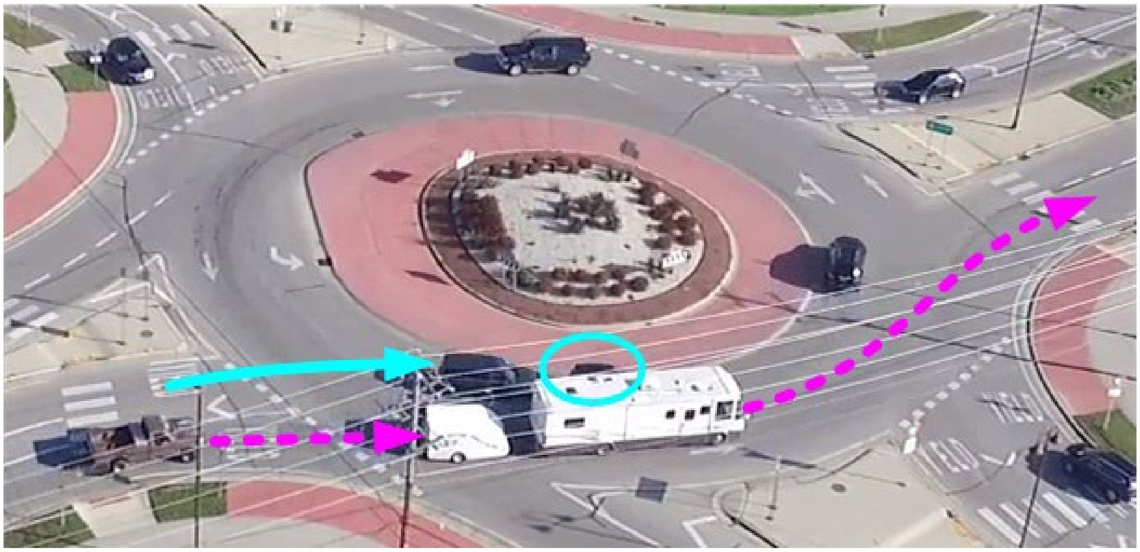
At Malta, the southbound, eastbound, and westbound entries each have varying degrees of misalignment with the corresponding circulating lanes. As illustrated in figure 65, the southbound entry has the strongest misalignment, with vehicles in the outside entry lane generally aligned with the circulating lane line. The team identified 63 southbound through vehicles to be straddling both lanes over the 3-h period analyzed. The eastbound and westbound approaches generally had reasonable alignment; however, the shape of the spiral markings within the circulatory roadway resulted in a larger conflict area, which was observed to affect how well drivers maintained their alignment. Over a 3-h period, 144 eastbound and 157 westbound through vehicles were observed to straddle lanes within the circulatory roadway.



Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 65. Photo. Malta—Entry lane alignment.

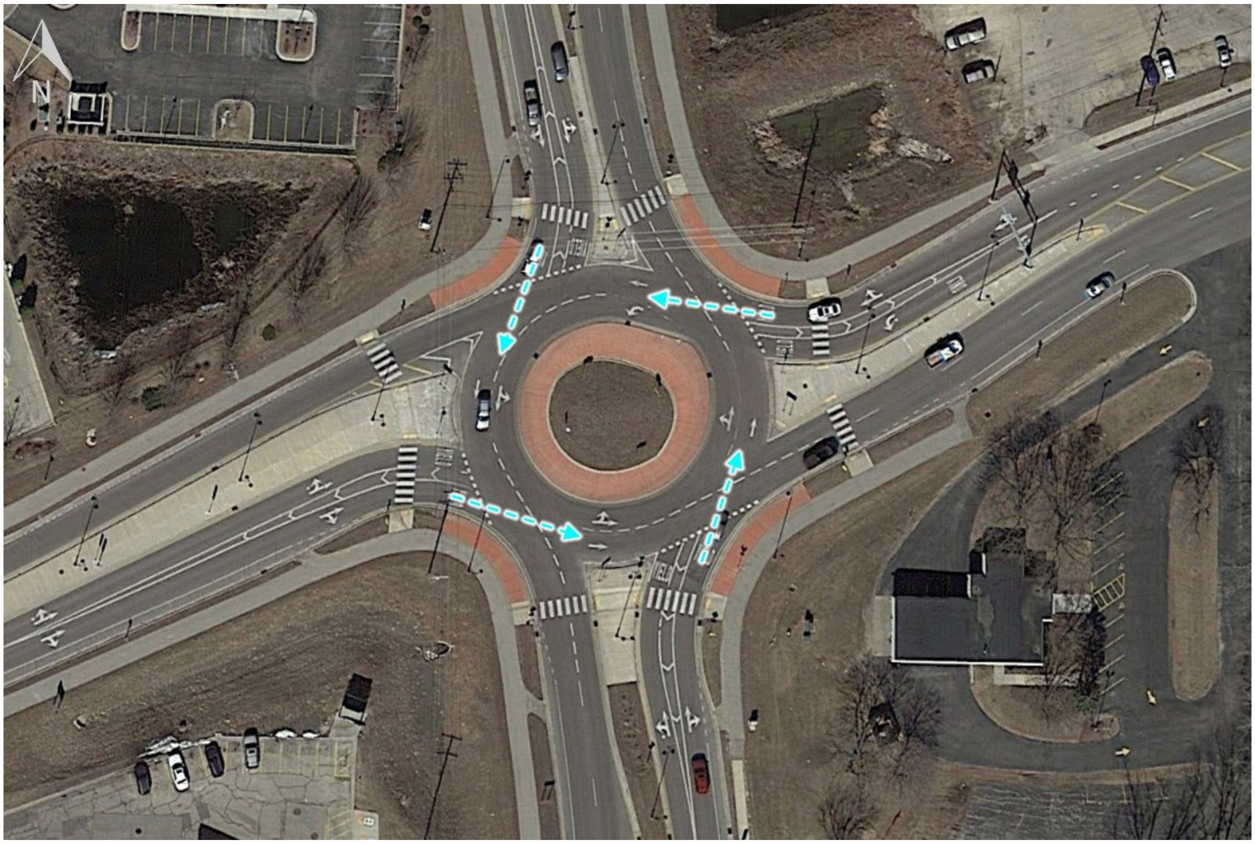
Each of the Wisconsin sites at Wales, Oshkosh, and De Pere has similar entry lane alignment. The entry geometry at these sites varies slightly, depending on accommodations for trucks, with Wales incorporating gore striping between entry lanes. However, at each site, drivers in the outside entry lane are generally aligned toward the lane line within the circulatory roadway instead of toward the center of the outside circulating lane. As a result, the team observed higher instances of lane straddling. Figure 66 illustrates an example of a near-crash associated with lane straddling for southbound entering vehicles at Wales.



Source: FHWA.

Figure 66. Photo. Wales—Observed lane-straddling conflict.

As illustrated in figure 67, the alignment of each entry at Wales generally guides drivers from the outside entry lane toward the correct outside receiving lane. However, at the entrance line, the vehicle path is aligned more toward the circulating lane line, resulting in increased lane straddling. The lane straddling also results in degradation of the lane markings within the circulatory roadway, as illustrated in figure 66, which the team observed from drone video footage. The degradation of the lane markings further complicates the ability of drivers to identify and maintain lanes. Sideswipes and lane changes account for 18 percent of the total intersection crashes (19 crashes over 3 yr), with most of these crashes associated with the northbound, southbound, and eastbound movements. Occupying or straddling both lanes was the leading cause for violations, conflicts, and near-crashes based on conflict analysis. Over a 4-h period, the team noted 309 lane-straddling violations, 10 lane-straddling conflicts or near-crashes, and 62 lane-change violations through the circulatory roadway. Entry alignments may have factored into these events.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 16, 2018. 43° 00′ 42.79″ N and 88° 23′ 02.10″ W. Elevation 988 ft. Eye altitude 1,656 ft.

Figure 67. Photo. Wales—Entry lane alignment.

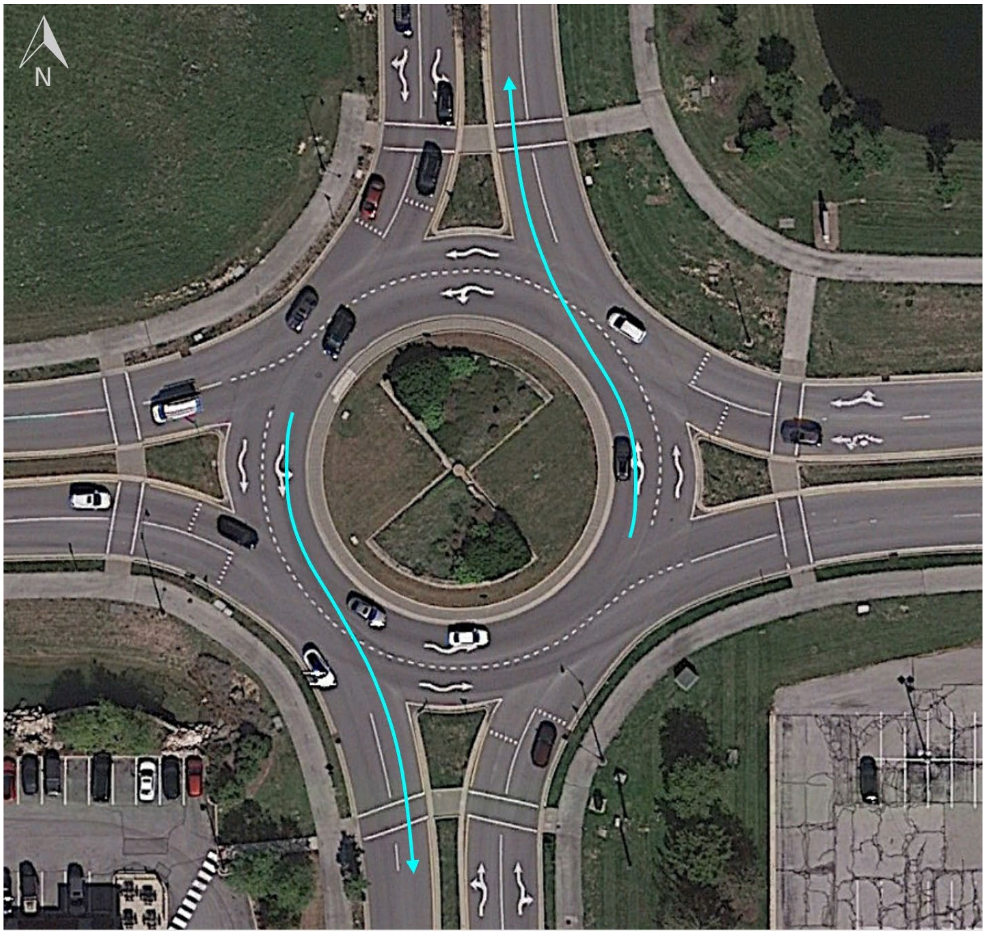
The two Wisconsin sites show similar effects of entry alignment on lane straddling. At the De Pere site, lane straddling was the top violation type, with 258 violations and 13 potential conflicts over a 4-h period. Lane straddling was the top violation type at the Oshkosh site, as discussed previously in the section titled "Small Diameters."

CIRCULATORY ROADWAY STRIPING

Circulatory roadway striping was found to contribute to crashes and conflicts in two ways, as follows:

- Concentric striping that is inconsistent with approach lane-use assignments.
- Painted spiral striping to shift circulating vehicles to the outside lane.

Striping in the northeast and southwest corners of Carmel 116th may contribute to left turns from incorrect lanes. Figure 68 shows the Carmel 116th roundabout and the variation in striping between the northeast and southwest corners and the southeast and northwest corners.



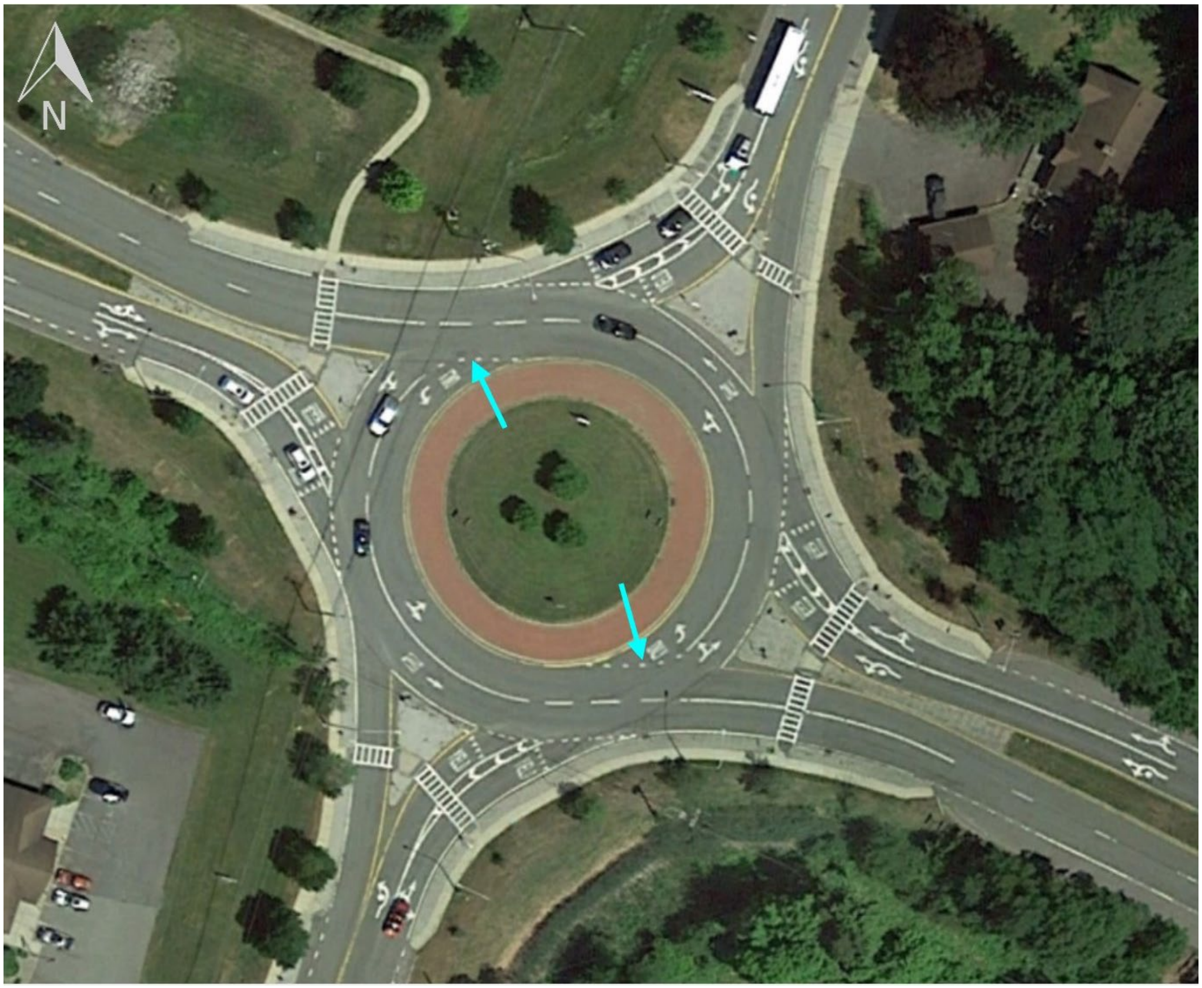
Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 68. Photo. Carmel 116th—Concentric lane-line markings.

In the southeast and northwest corner, the circulatory roadway striping leads drivers in the outside circulatory lane toward the east and west exits and provides drivers in the inside lane the option of continuing to circulate or exiting the roundabout. In the northeast and southwest corners, concentric lane-line markings require drivers who want to exit the roundabout from the inside lane to cross the dotted circulatory lane lines. These concentric lane-line markings are inconsistent with the entry lane-use assignments on the northbound and southbound entries, which allow through movements from either entry lane. However, these two different lane-line marking treatments yielded similar numbers of crashes in the northwest and southwest corners. The northwest corner had 48 crashes over 3 yr involving left turns from incorrect lanes, compared to 47 crashes over 3 yr of the same type in the southwest corner. These data reinforce that getting drivers into the correct lane before entry is critical in reducing the potential for these crash types.

At Carmel 116th, the southbound, eastbound, and northbound entries each had high numbers of crashes related to failure to yield to vehicles in the inside lane. In each case, the outside circulating lane was less likely to be occupied due to the patterns of left turns from the southbound and westbound entries.

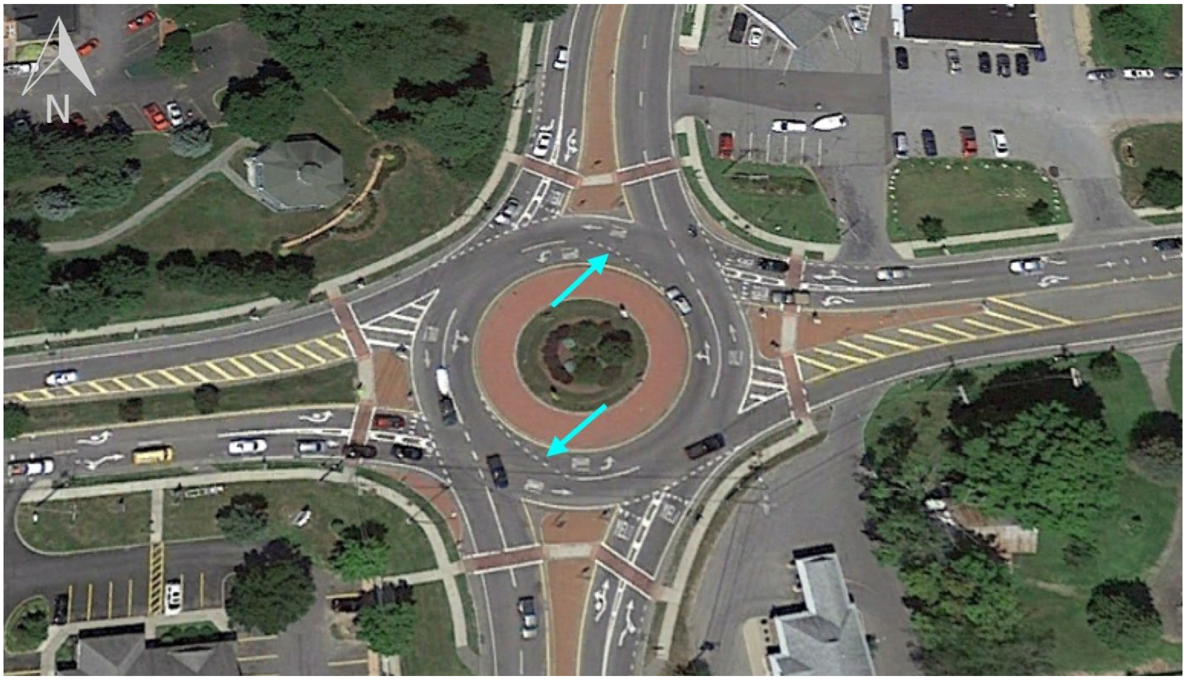
At Slingerlands, the spiral striping in the northeast and southwest quadrants is developed with only pavement markings and is very abrupt, as shown in figure 69. As a result, many left-turning drivers followed the circular central island curb instead of following the spiral markings, which led them into the inside circulating lane. Once in the inside circulating lane, drivers were required to make a lane change to exit eastbound or westbound. The curvature of the circulatory roadway before the exit may give some drivers the false impression that they may continue to circulate (and make improper left turns) from the outside lane.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 38′ 13.51″ N and 73° 51′ 21.50″ W. Elevation 217 ft.
Eye altitude 1,205 ft.

Figure 69. Photo. Slingerlands—Spiral pavement markings.

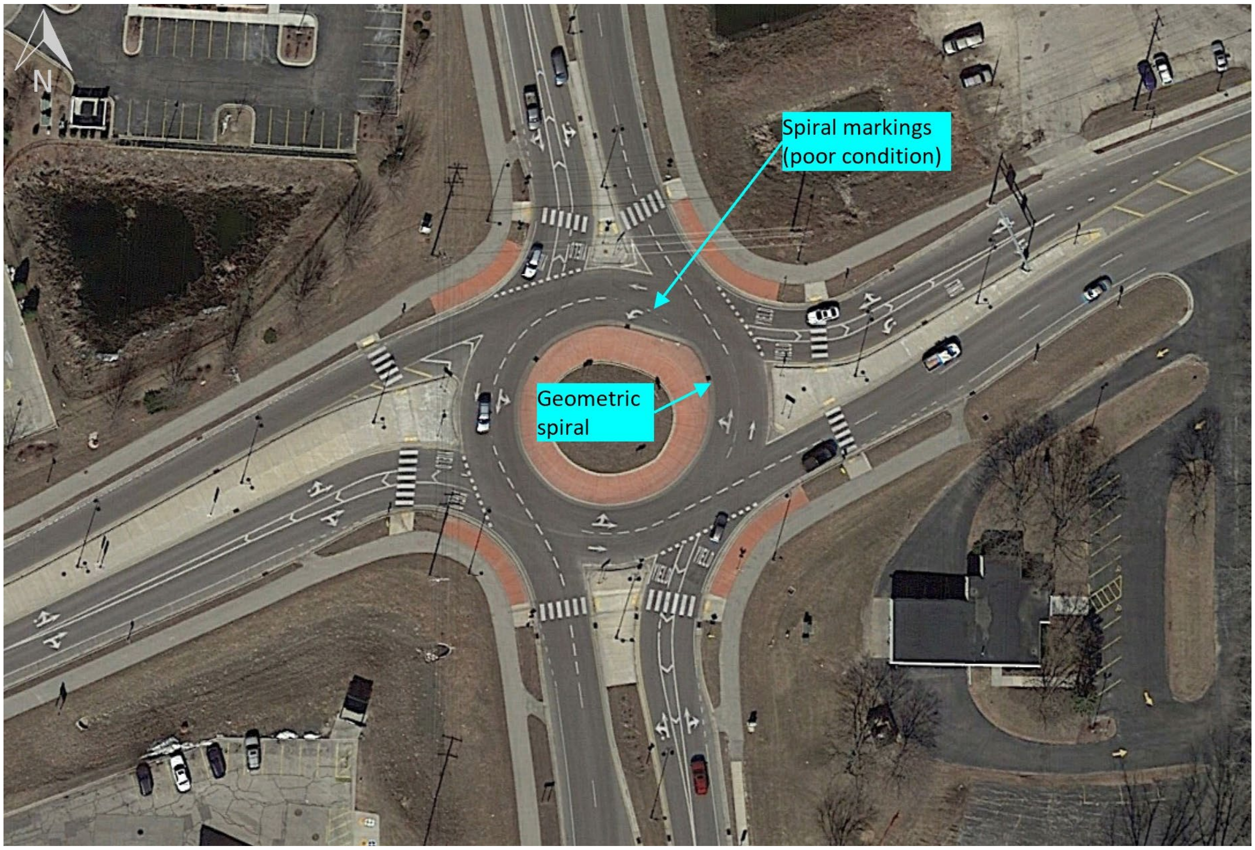
Similar to Slingerlands, the Malta site has abrupt painted spirals, as shown in figure 70. Many northbound left-turning drivers were observed to continue to follow the circular central island curb into the inside circulating lane instead of following the spiral markings to the intended outside circulating lane. Furthermore, high volumes of traffic make the northbound-to-westbound left-turn movement toward the I–87 interchange throughout the day. The team observed drivers making this movement from the incorrect outside lane during each peak hour.



Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: July 15, 2015. 42° 58′ 16.76″ N and 73° 47′ 33.94″ W. Elevation 338 ft.
Eye altitude 1,415 ft.

Figure 70. Photo. Malta—Spiral pavement markings.

Figure 71 shows Wales, where the design explicitly incorporates a geometric spiral into the shape of the central island, giving the central island a noncircular shape. The spiral begins along the east side of the central island to start drivers along the spiral path while they are adjacent to the central island curb. Dotted lane markings continue the spiraled path to guide drivers from the inside lane on the east side of the circulatory roadway to the outside lane on the north side of the circulatory roadway. This design was observed to result in fewer left-turning vehicles failing to follow the intended spiral path. However, over a 4-h period, the team observed 56 northbound left-turning vehicles staying in the inside lane along the north side of the circulatory roadway instead of spiraling to the outside lane. This trend resulted in late lane changes near the westbound exit.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 16, 2018. 43° 00′ 42.79″ N and 88° 23′ 02.10″ W. Elevation 988 ft. Eye altitude 1,656 ft.

Figure 71. Photo. Wales—Geometric spiral and spiral markings.

As illustrated in figure 72, the condition of the circulating lane markings was poor, which is likely contributing to these observations. Figure 72 shows a sequence of photographs where a northbound left-turning white van follows the geometric portion of the spiral toward the correct outside circulating lane, cuts back toward the inside lane, and eventually changes lanes to exit westbound. It is unclear whether more visible markings would have altered this observed behavior.

Source: FHWA.

Figure 72. Photo. Wales—Vehicles navigating the northbound left-turn spiral.

YIELD SIGNS AND PAVEMENT MARKINGS

The team observed various treatments across the study sites with respect to yield signs and pavement markings. For signing, the following combinations were seen in the field across the study sites:

- Yield signs only on each side of the entrance, used in Carmel 106th and Carmel 116th. Figure 73 shows an example from Carmel 116th.
- Yield signs on each side of the entrance with a one-way sign over the left yield sign, as shown in figure 74 in Slingerlands.
- Yield signs on each side of the entrance with a one-way sign over the left yield sign and a "TO ALL LANES IN CIRCLE" supplemental plaque underneath each yield sign, used in Slingerlands and Malta. Figure 75 shows an example from Slingerlands.
- Yield signs on each side of the entrance with a one-way sign under the left yield sign and a "TO TRAFFIC FROM LEFT" supplemental plaque under the right yield sign, used in De Pere, Wales, and Oshkosh. Figure 76 shows an example from De Pere.
- Yield signs on each side of the entrance with a "TO BOTH LANES IN ROUNDABOUT" supplemental plaque under each yield sign, as shown in figure 77 in Hilliard.

Source: FHWA.

Figure 73. Photo. Carmel 116th yield signs only on each side of entrance.

Source: FHWA.

Figure 74. Photo. Slingerlands —Yield signs with a one-way sign.

Source: FHWA.

Figure 75. Photo. Slingerlands—Yield signs with a one-way sign and 'TO ALL LANES IN CIRCLE' supplemental plaques.

Source: FHWA.

Figure 76. Photo. De Pere—Yield signs with a one-way sign and a 'TO TRAFFIC FROM LEFT' supplemental plaque.

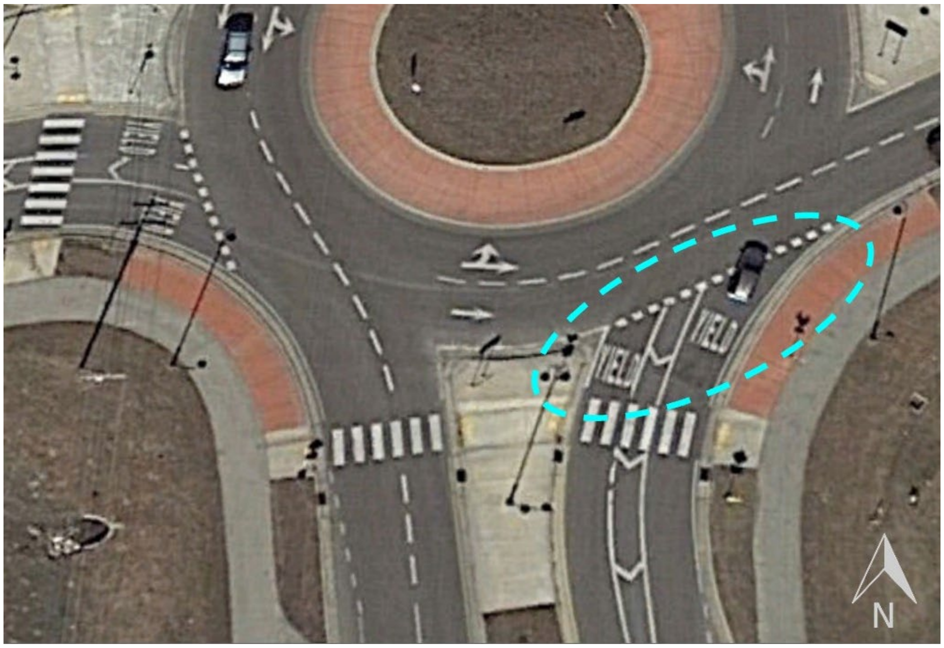
Source: FHWA.

Figure 77. Photo. Hilliard yield signs with 'TO BOTH LANES IN ROUNDABOUT' supplemental plaques.

Despite the variety of yield signing configurations, no clear pattern emerged to distinguish crash patterns as a function of these configurations.

For markings, the following combinations were seen in the field across the eight study sites:

- Entrance line only (circulatory roadway edge-line extension).
- Entrance line with "YIELD" word legend marking used in De Pere and Wales. Figure 78 shows an example from De Pere.
- Entrance line with staggered yield lines, used in Carmel 106th, Carmel 116th, Hilliard, Malta, and Slingerlands. Figure 79 shows an example from Carmel 106th.
- Entrance line with yield line running approximately parallel to the entrance line, as shown for Melbourne in figure 80. This use of the yield line is inconsistent with *MUTCD*, which requires the yield line to be perpendicular to the direction of traffic.(6)



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 16, 2018. 43° 00′ 42.79″ N and 88° 23′ 02.10″ W. Elevation 988 ft.
Eye altitude 1,656 ft.

Figure 78. Photo. Wales entrance line and 'YIELD' word markings.

Source: FHWA.

Figure 79. Photo. Carmel 106th entrance line and yield lines.

Source: FHWA.

Figure 80. Photo. Melbourne entrance line and parallel yield line.

Similar to signing, no clear pattern emerged to distinguish crash patterns as a function of marking configurations.

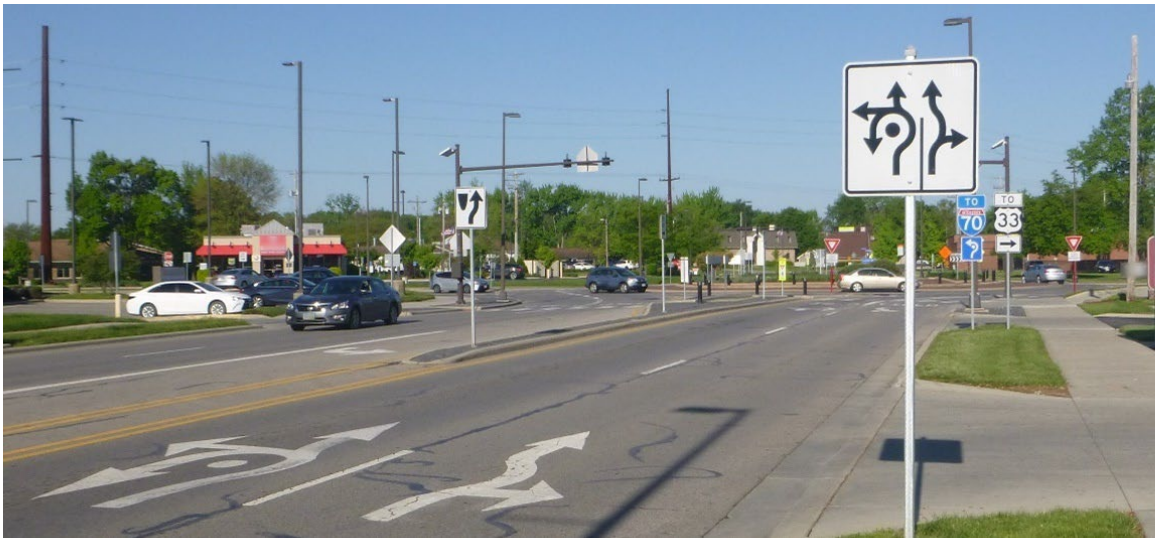
ADVANCE LANE-CONTROL SIGNS AND PAVEMENT MARKING ARROWS

Lane-control signs and pavement marking arrows support drivers' lane selections prior to reaching the roundabout entry. Various treatments were observed across the study sites for advance lane-control signs and pavement marking arrows. A wide range of combinations was seen in the field across the eight study sites, including the following:

- A single, side-mounted lane-control sign and one set of fishhook pavement marking arrows were used in Melbourne, as shown in figure 81.
- A single, side-mounted lane-control sign and two sets of fishhook pavement marking arrows were used in Hilliard, Carmel 106th, and Carmel 116th. Figure 82 shows an example from Hilliard.
- Overhead lane-control signs with two sets of standard pavement marking arrows were used in Oshkosh and Wales. Figure 83 shows an example from Oshkosh.

Source: FHWA.

Figure 81. Photo. Melbourne side-mounted lane-use sign and single set of fishhook markings.



Source: FHWA.

Figure 82. Photo. Hilliard side-mounted lane-use sign and two sets of fishhook markings.

Source: FHWA.

Figure 83. Photo. Oshkosh overhead lane-use signs and two sets of standard arrow markings.

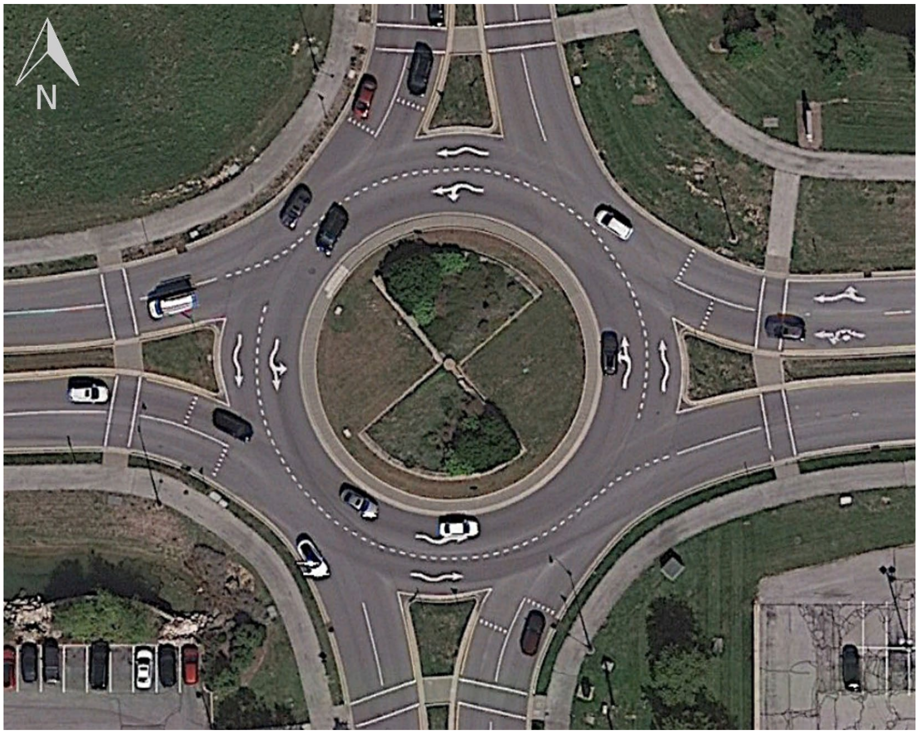
The team anecdotally found the overhead lane-control signs with standard arrows to be more visible and simpler to read at a glance than lane-control signs with fishhook arrows. However, the effect of signing and marking differences on drivers' lane selections could not be isolated in the analysis.

CIRCULATORY LANE-USE PAVEMENT MARKING ARROWS

Circulatory lane-use pavement marking arrows reinforce the allowable movements from each circulating lane based on the posted lane configurations at each entry. The study sites varied in terms of arrow style and placement. No clear pattern emerged to distinguish crash patterns as a function of pavement arrow style or placement configurations.

While specific patterns of crashes could not be tied to arrow placement as part of this study, arrow placement may serve two purposes for influencing how drivers use the arrows for navigation: first, reinforcing entry alignment and second, reinforcing the presence of two circulating lanes. For the first purpose, arrows such as those seen at Hilliard that are placed near the start of the circulating lane line (i.e., near the exit side of the splitter island) may be primarily visible to entering drivers traveling in the same direction as the arrow, thus reinforcing the entry lane configuration and supporting vehicle alignment. For the second, circulatory lane-use pavement marking arrows placed closer to the entry side of the raised splitter island are more likely to reinforce the presence of two conflicting circulating lanes and the associated conflicting lane configurations to entering drivers. None of the study sites had arrows placed near the entry sides of the splitter islands during the observations. However, arrows have since been relocated to this position at Hilliard as part of recent modifications. Arrows placed adjacently to the center of the splitter island may serve both purposes for smaller diameter roundabouts such as Oshkosh.

As described in *NCHRP Report 672* and MUTCD, standard arrows are typically used in the circulatory roadway for legibility.(7,8) However, as illustrated in figure 84, fishhook arrows were used within the circulatory roadway at Carmel 116th. While the use of fishhook arrows may affect legibility, the team could not isolate their impact on actual crash patterns from other possible factors.



Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.24″ N and 86° 09′ 44.43″ W. Elevation 854 ft. Eye altitude 1,723 ft.

Figure 84. Photo. Carmel 116th—Fishhook arrows within the circulatory roadway.

The remaining sites all used standard pavement arrows; however, the placement of the pavement arrows varied. Two examples of sites using standard pavement arrows included Melbourne (figure 85) and Oshkosh (figure 86). The Melbourne site has the pavement arrows placed toward the start of the circulating lane line (i.e., the exit side of the splitter island); the Oshkosh site has the pavement arrows placed near the middle of the circulating lane line (i.e., centered in front of the splitter island).

Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 47.22″ N and 80° 43′ 32.82″ W. Elevation 32 ft.
Eye altitude 1,013 ft.

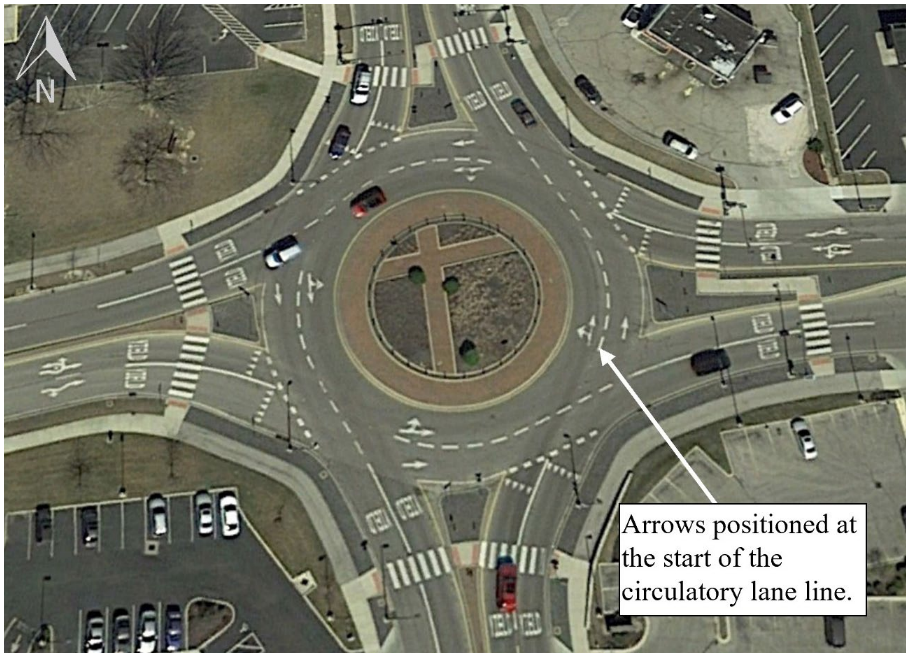
Figure 85. Photo. Melbourne—Circulatory lane-use pavement arrows.

Original map: © 2015 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: April 13, 2015. 44° 02′ 21.52″ N and 88° 32′ 33.17″ W. Elevation 760 ft.
Eye altitude 1,539 ft.

Figure 86. Photo. Oshkosh—Circulatory lane-use pavement arrows.

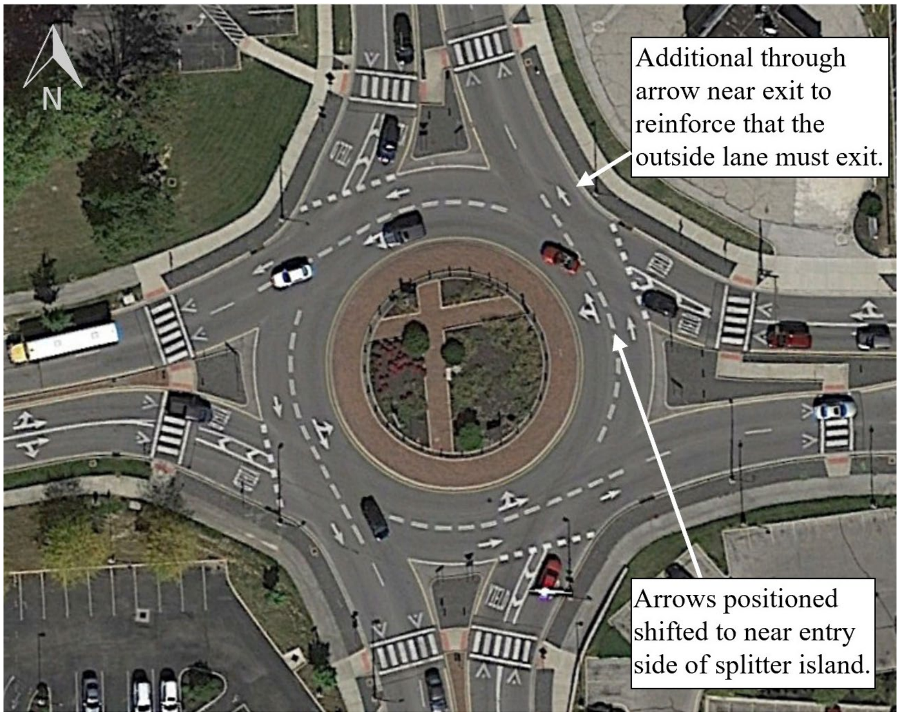
As illustrated in figure 87, Hilliard also used standard arrows; however, the arrow position was initially located at the start of the circulating lane line.

As part of modifications implemented after field evaluations were conducted for this TPF study, circulatory lane-use pavement marking arrow positions were shifted closer to the entry side of the splitter island at Hilliard. The purpose of this adjustment was to make the arrows more visible to entering drivers to reinforce the presence of two conflicting circulating lanes. A second through arrow was also added immediately prior to the exit in the outside lane to reinforce the requirement to exit. Figure 88 illustrates the recently implemented modified arrow position at Hilliard.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: Imagery date: March 17, 2018. 40° 01′ 48.28″ N and 83° 09′ 40.58″ W. Elevation 937 ft. Eye altitude 1,935 ft.

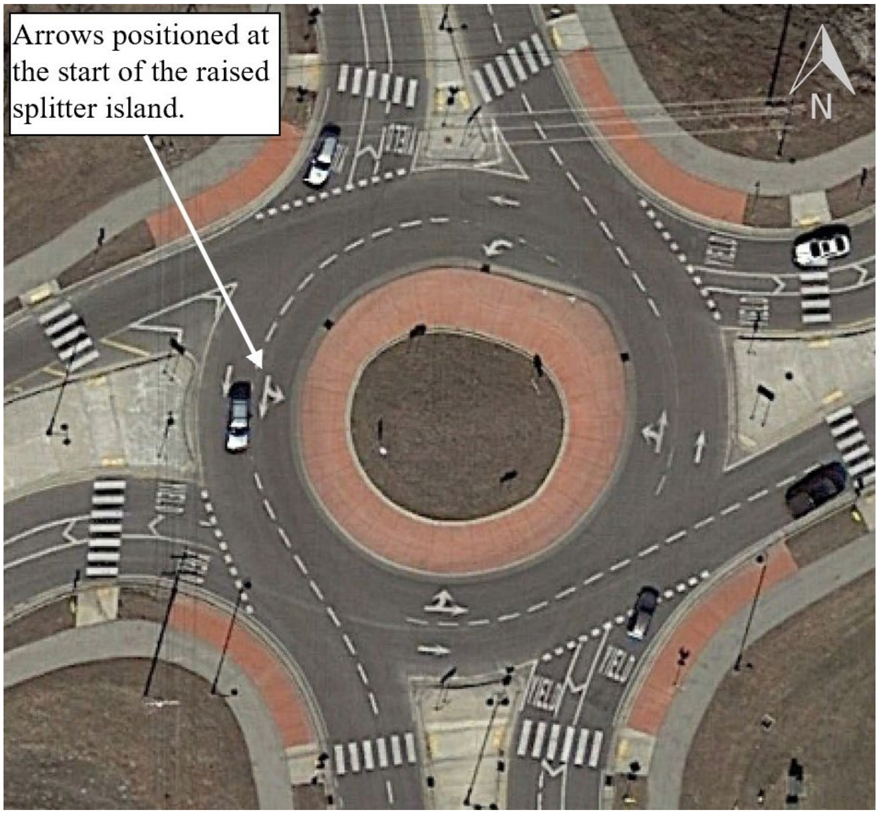
Figure 87. Photo. Hilliard—Observed circulatory lane-use pavement arrows.



Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: 40° 01′ 47.68″ N and 83° 09′ 40.14″ W. Elevation 937 ft. Eye altitude 1,410 ft.

Figure 88. Photo. Hilliard—Current circulatory lane-use pavement arrows.

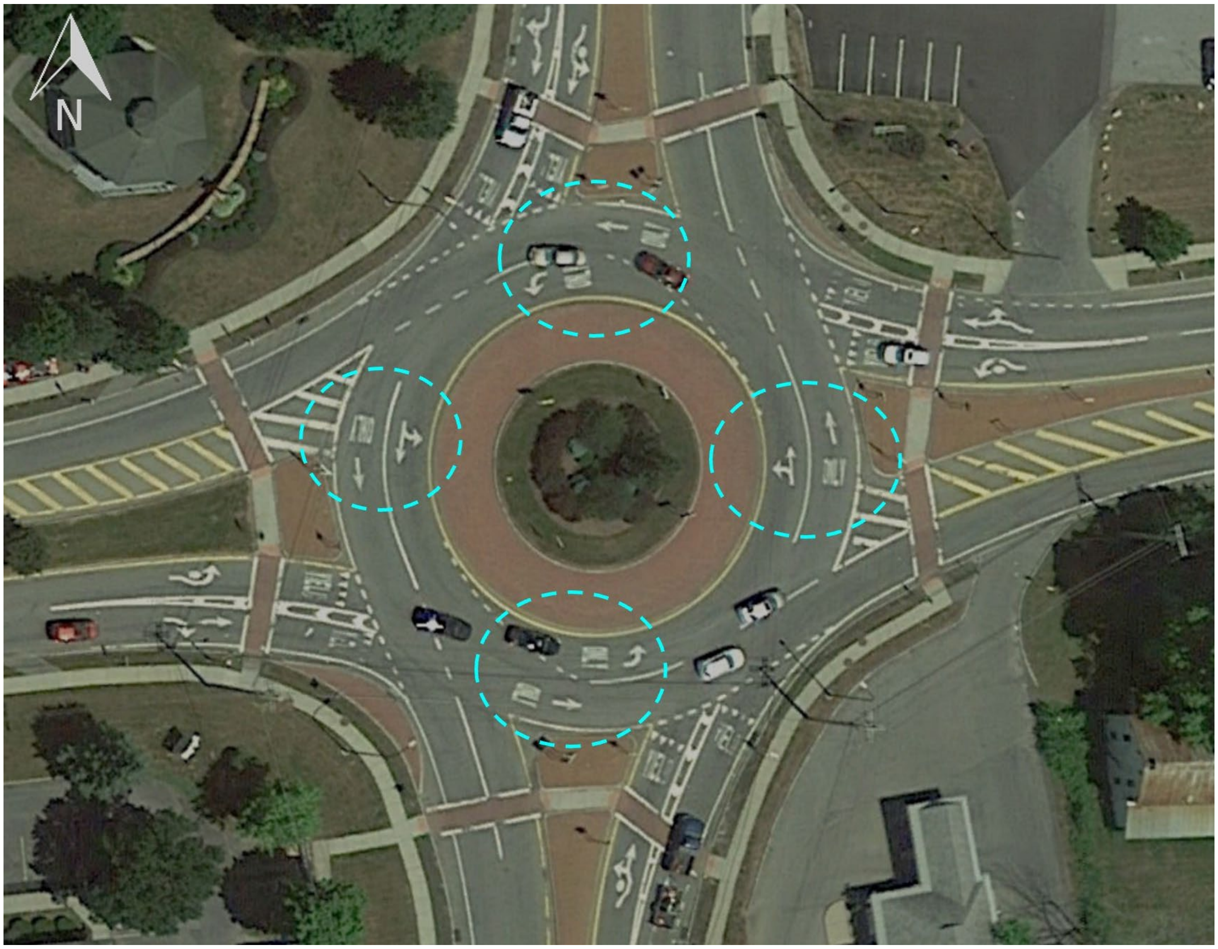
The Wales site applies standard arrows with the positioning near the start of the raised splitter island, as illustrated in figure 89.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section). Data: Imagery date: March 16, 2018. 43° 00′ 42.79″ N and 88° 23′ 02.10″ W. Elevation 988 ft. Eye altitude 1,656 ft.

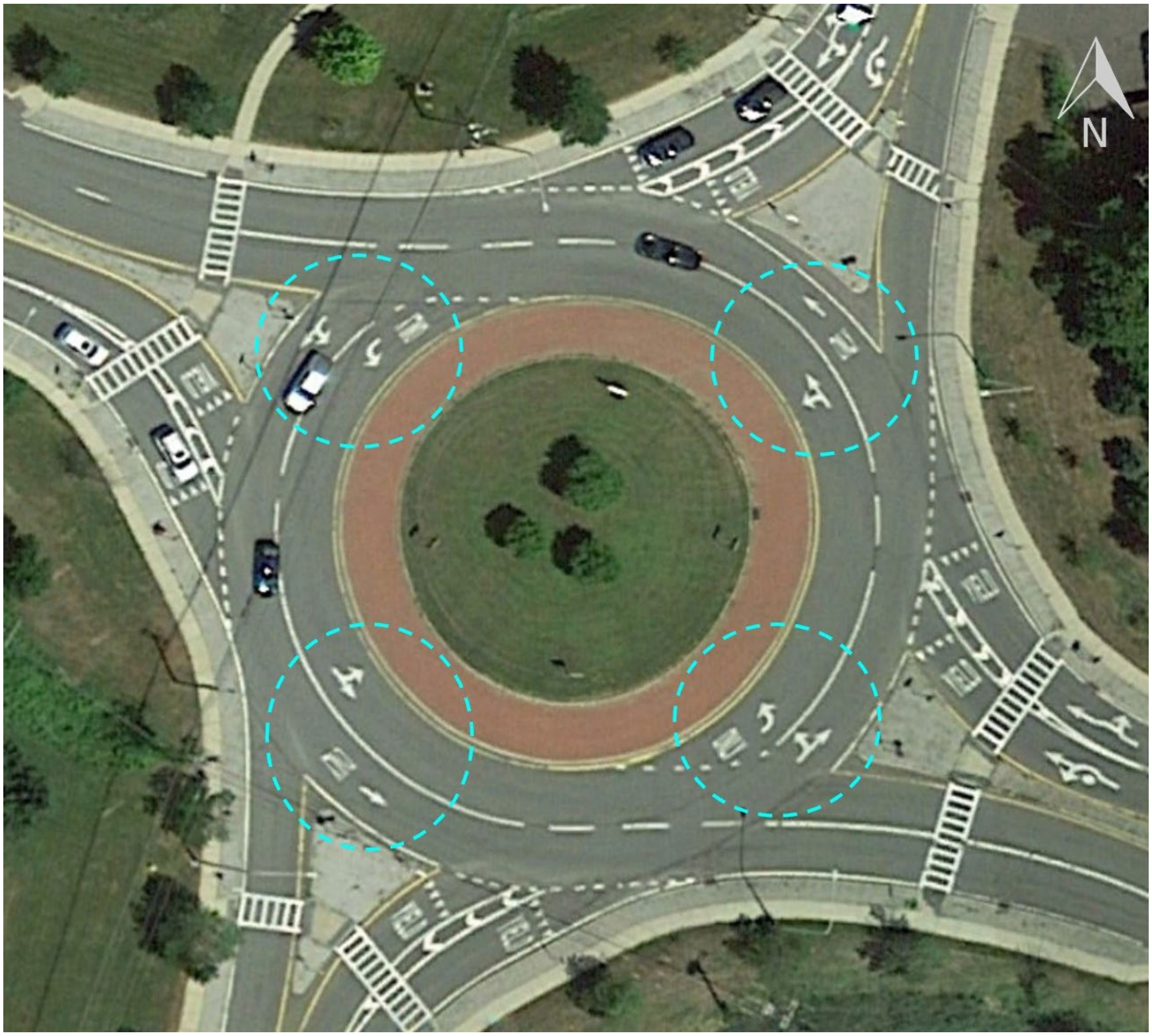
Figure 89. Photo. Wales—Circulatory lane-use pavement arrows.

Some sites also applied supplemental “ONLY” markings for exclusive left-turn lanes or to supplement the outside through lane. As illustrated in figure 90 and figure 91, at Malta and Slingerlands standard through arrows are supplemented with “ONLY” messages for outside circulating lanes to emphasize the requirement that vehicles in the outside lane must exit. “ONLY” word markings are also used in conjunction with a standard left-turn arrow for receiving exclusive left-turn lanes. Arrow placement varies at Malta due to a previous intersection retrofit. Arrows are placed near the start of the raised splitter islands on each leg.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 58′ 16.43″ N and 73° 47′ 34.33″ W. Elevation 339 ft.
Eye altitude 1,045 ft.

Figure 90. Photo. Malta—Circulatory lane-use pavement arrows and 'ONLY' markings.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 38′ 13.51″ N and 73° 51′ 21.50″ W. Elevation 217 ft.
Eye altitude 1,205 ft.

Figure 91. Photo. Slingerlands—Circulatory lane-use pavement arrows and 'ONLY' markings.

CHAPTER 6. NETWORK INFLUENCES

In addition to details of the design at each roundabout, as covered throughout chapter 5, the research team captured field observations and other information regarding the site context and surrounding roadway network. This chapter summarizes observations related to potential network influences on observed crash and conflict patterns. For each of the study sites, the team noted some level of network influence that directly related to observed patterns of conflicts and historical crashes.

The observations at these sample sites reinforce that considering the broader site context and roadway network in the planning and design of multi-lane roundabouts is crucial to achieving safety and operational performance. The team noted network influences that affected selection of incorrect lanes for navigating the roundabout, lane imbalances at entry, circulating lane imbalances, and approach platooning.

The research team identified five general categories of network influences, as follows:

1. Interchange or other major network connection proximity: This category includes having a downstream interchange or other major network connection that may influence driver lane selection or create heavy turning movement patterns.

2. Adjacent land uses and access: This category includes the context of the area and types of uses, which may impact driver familiarity, as well as the intensity of uses and locations of access points. Trip origins may influence a driver's starting lane position, and lane selection for roundabout navigation may be further influenced by the downstream destination. Both conditions could result in incorrect lane selection or lane changing within the roundabout.

3. Close intersection spacing near the roundabout: For very close intersection spacing, roundabouts can provide desirable operational benefits over other intersection control forms. However, they may also create challenges for drivers to change lanes between intersections if vehicles are traveling in platoons or if queues are present that further limit the space available for lane changing.

4. Adjacent traffic signal influences: Upstream signalized intersections have the potential to create platooned arrivals that limit drivers' abilities to interpret lane-use information and change to the correct lane on approach. Upstream signals can also result in fluctuating volume levels at the roundabout, with alternating periods of relatively intense volume and lower volume. During the more intense volume periods within the signal cycle, drivers have an increased potential for vehicle conflicts and a greater navigation task load than during lower volume periods within the signal cycle.

5. Downstream lane drop: This category could include the merging of two lanes on an exit or one of the exit lanes dropping as right turn only or left turn only at a downstream intersection or driveway. These conditions can impact upstream lane utilization for movements with more than one lane.

Table 29 summarizes information related to the five generalized categories of network influences for each of the control sites. Network influences were identified at each of the study sites. The relative magnitude of impact on vehicle conflicts and historical crashes varies by site, with other contributing factors including overall volume conditions and peak-hour turning movement patterns.

Table 29. Summary of network influences for control sites.

Intersection	Proximity to Interchange or Major Network Connection	Adjacent Land Use Influences and Access	Close Intersection Spacing (<600 ft)	Adjacent Signal Platooning Influences	Downstream Lane Drop
Carmel 106th	Interchange ramp gore 580 ft from exit; start of entrance ramp 360 ft from roundabout exit	Hospital	685 ft to upstream roundabout	No	No
Oshkosh	Interchanges 2.5 and 4 mi away influence traffic patterns.	Business access points near entry and exits	240 ft to upstream signal; 550 ft to another upstream signal	Yes	170 ft from WB exit
De Pere	Interchange 2 mi away influences traffic patterns.	Limited influences	2,700 ft to nearest upstream controlled intersection	Yes	No

Table 30 summarizes information related to the five generalized categories of network influences for each of the problem sites.

Table 30. Summary of the network influences for problem sites.

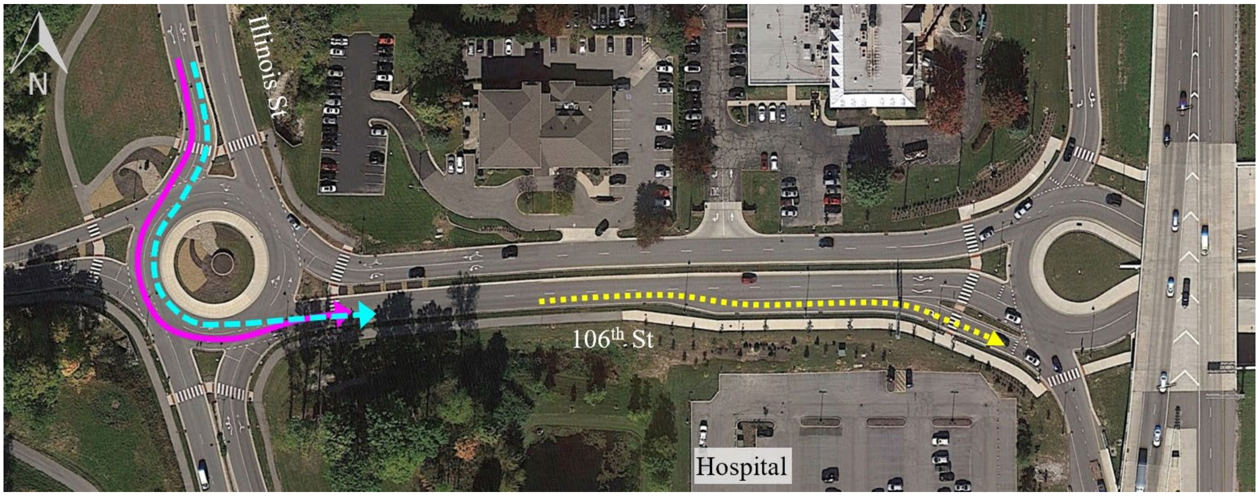
Intersection	Proximity to Interchange or Major Network Connection	Adjacent Land Use Influences and Access	Close Intersection Spacing (<600 ft)	Adjacent Signal Platooning Influences	Downstream Lane Drop
Carmel 116th	Interchange ramp gore 700 ft from exit; start of entrance ramp 500 ft from roundabout exit	Hospital shopping center	450 ft to upstream roundabout	No	No
Hilliard	Interchanges 2–4 mi away	Elementary school; nearby business access points	225 ft to upstream roundabout; 225 ft to signal on separate leg	Yes	650 ft from WB exit
Melbourne	Interchange 0.35 mi away	Hospital; places of worship	1,000 ft or greater to upstream signals on all legs	Yes	No
Slingerlands	Network connections induce heavy left-turn and right-turn movements	Limited influences	1,370 ft or greater to upstream signals on all legs	Possible. Signals 0.5 to 1 mi from entry on 3 legs	No
Malta	Interchange 0.35 mi away	High U-turns due to corridor access management	700 ft to upstream signal	Yes	No
Wales	Interchange 2.8 mi away	High school	480 ft to upstream roundabout	Yes	0.2 mi from EB exit

INTERCHANGE OR OTHER MAJOR NETWORK CONNECTION PROXIMITY

Four of the study sites (one control site and three problem sites) are located in close proximity to an interchange. Each of the remaining study sites has interchanges 2–4 mi away or other major network connections in the broader site vicinity that directly influence vehicle turning movement patterns and directional traffic flows throughout the day.

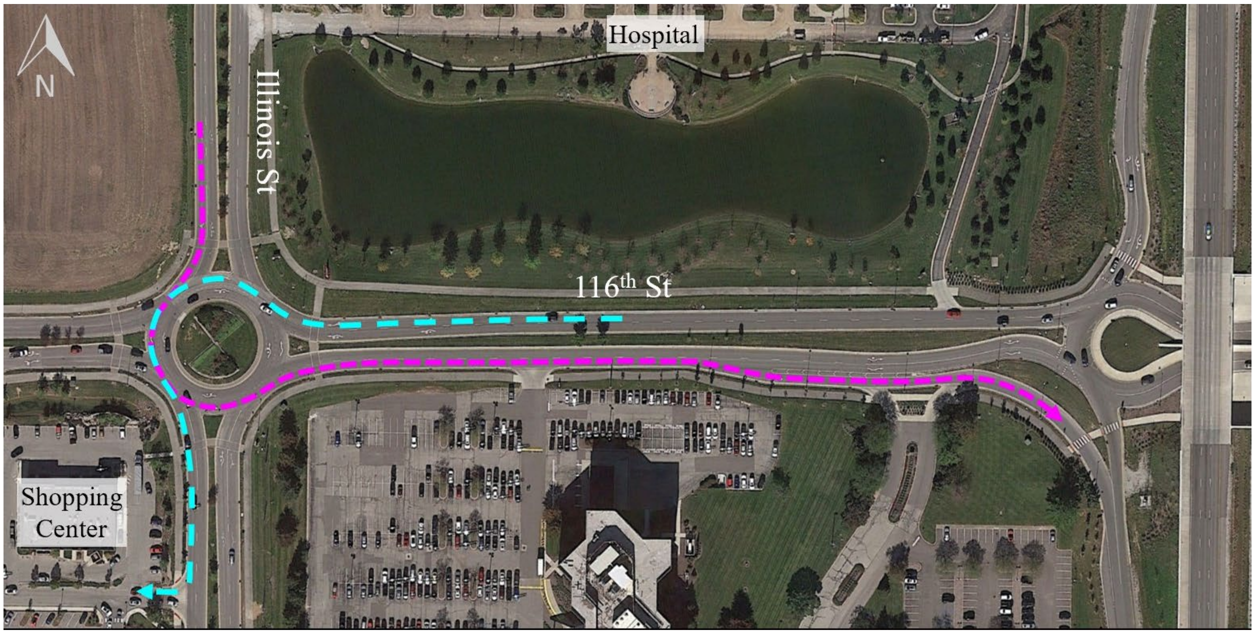
For each of the four sites in close proximity to interchanges, the study team noted increased instances of left turns and right turns from incorrect lanes for movements traveling to the interchange area. Some drivers appear to be pre-positioning for their desired downstream movement onto the entrance ramp by using the incorrect outside entry lane rather than using the designated inside entering and circulating lanes for their intended left-turn maneuver and then changing lanes between the roundabout and the interchange. Exits with nearby downstream ramps or network connections also tended to have higher instances of lane-change violations and conflicts as vehicles exited the circulatory roadway.

Carmel 106th (control site) and Carmel 116th (problem site) are approximately 1 mi apart, with each located 580–700 ft west of an interchange ramp, as illustrated in figure 92 and figure 93, respectively.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: October 10, 2018. 39° 56′ 30.38″ N and 86° 09′ 33.81″ W. Elevation 836 ft.
Eye altitude 2,523 ft.
Note: SB vehicles destined for the downstream freeway entrance ramp (line with short dashes) were frequently observed to either make a left turn using the incorrect lane (solid line) or change lanes through the roundabout exit (line with long dashes).

Figure 92. Photo. Carmel 106th—Influences of adjacent interchange ramp.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: October 22, 2018. 39° 57′ 22.30″ N and 86° 09′ 37.02″ W. Elevation 856 ft.
Eye altitude 2,523 ft.
Note: SB vehicles destined for the downstream freeway entrance ramp were frequently observed to make a left turn using the incorrect lane (line with short dashes) or change lanes through the eastbound exit. Vehicles destined for the adjacent shopping center were frequently observed to make a WB left turn using the incorrect lane (line with long dashes) or change lanes through the southbound exit.

Figure 93. Photo. Carmel 116th—Examples of possible system influences

For both sites, key crash and violation patterns included use of the incorrect lane for southbound left turns and northbound right turns as vehicles traveled toward the interchange:

- For Carmel 106th, 11 percent of southbound left-turning vehicles during the afternoon and evening peak hours entered the roundabout in the incorrect outside lane. This pattern appears to be influenced by the driver's desire to access the freeway entrance ramp, which begins 360 ft from the roundabout exit. Crashes associated with southbound left turns from incorrect lanes comprised 14 percent (6 crashes over 3 yr) of the intersection total. Drivers using the correct inside lane on the southbound entry were also frequently observed changing lanes through the eastbound exit to position for the freeway entrance ramp. This use of the incorrect lane may also be influenced by lane imbalances on the southbound approach, where 61–67 percent of the entering vehicles use the inside lane.

- For Carmel 116th, southbound left turns from incorrect lanes accounted for 24 percent (or 47 crashes over 3 yr) of the intersection total. During the noon and afternoon peak hours, 26–40 vehicles per hour (12–14 percent of left-turning vehicles) entered the roundabout using the incorrect outside lane on the southbound approach. Similar to Carmel 106th, these data may be influenced by drivers positioning to be in the outside lane on the downstream eastbound exit to access the southbound freeway entrance ramp. Drivers using the correct inside lane on the southbound entry were also frequently observed making lane changes as they exited eastbound. Increases in volume on the southbound approach, and corresponding increases in left-turn violations, may also be influenced by a shift change at the adjacent hospital during the 3:45–4:45 p.m. period.

For both Carmel 106th and Carmel 116th, one of the key crash types involved northbound right turns from incorrect lanes. During peak hours, approximately 1–2.5 percent of northbound right turns used an incorrect inside lane. However, over a 3-yr period, these data translated to 5 crashes (11 percent of the intersection total) at Carmel 106th and 11 crashes (6 percent of the intersection total) at Carmel 116th. Pre-positioning for the downstream interchange may be a factor. Entry lane imbalances may also contribute to drivers selecting the incorrect lane to bypass vehicle queues. At Carmel 106th, approximately 74–83 percent of the northbound entry volume used the outside lane during each hour analyzed. At Carmel 116th, approximately 60–70 percent of the northbound entering volume used the outside lane during each hour analyzed.

At Carmel 106th and Carmel 116th, lane imbalances associated with turning movements to and from the interchange also resulted in volume imbalances where drivers favored the inside circulating lane. This imbalance may be contributing to crash types involving drivers in the outside entry lane failing to yield to drivers in the inside circulating lane, resulting in a crash near the adjacent exit. For the eastbound entry at Carmel 106th, 78–80 percent of the conflicting circulating vehicles during each hour are positioned in the inside circulating lane, likely due to origin-destination influences from the adjacent interchange and the hospital in the southeast corner of the intersection. Crashes associated with the outside lane on the eastbound entry failing to yield to the inside circulating lane comprised 14 percent (6 crashes over 3 yr) of the intersection total. At Carmel 116th, the patterns of left turns on the southbound and westbound entries also result in more frequent instances where a conflicting circulating vehicle is only present in the inside lane on the southbound, eastbound, and northbound entries. These patterns correspond to the locations for all 30 crashes involving failure to yield as reported over the 3-yr period.

The Melbourne roundabout and surrounding roadway network are illustrated in figure 94. At the Melbourne site, 685 vehicles (representing 33.5–39.5 percent of the southbound left-turn volume during each hour analyzed) were observed over a 4-h period to use the incorrect outside lane to make the southbound left turn when traveling toward the interchange. These left turns using incorrect lanes likely resulted in 16 crashes over 3 yr near the southbound exit. Due to a heavy southbound left-turn pattern traveling toward the freeway during the noon, afternoon, and evening peak hours, the inside lane on the southbound entry operates as a de facto left turn only lane. Fewer than six through vehicles per hour were observed to use the inside lane for the southbound through movement. This lane use pattern likely helped to limit higher instances of conflicts and crashes near the southbound exit than might be expected with a higher through volume.

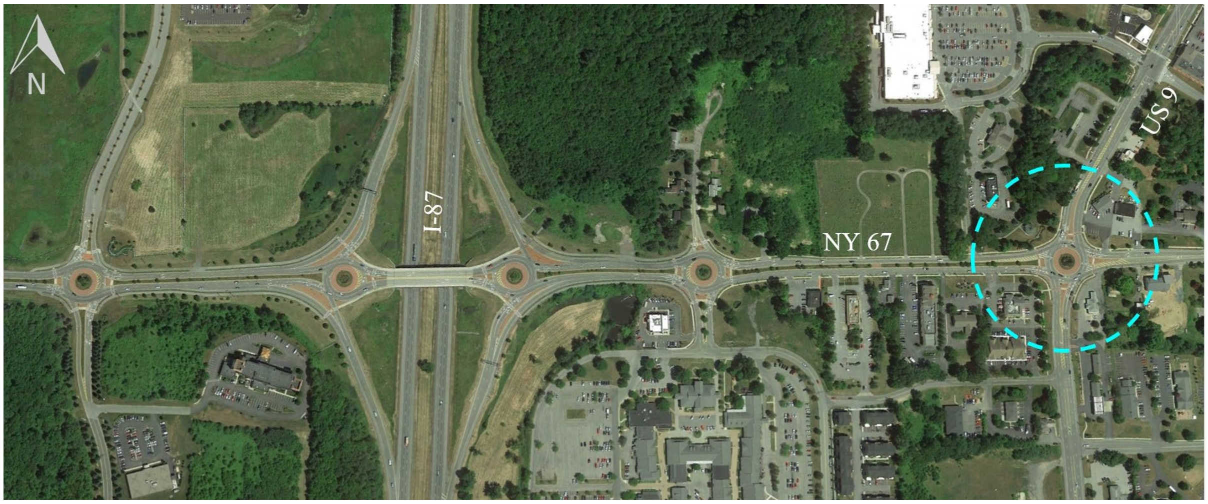
Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 51.56″ N and 80° 43′ 23.71″ W. Elevation 30 ft. Eye altitude 3,396 ft.
Note: Adjacent traffic signal locations are identified with a dashed circle.

Figure 94. Photo. Melbourne—Roadway network and adjacent signalized intersections.

The team observed several compounding network influences at Melbourne that may be contributing to the high instances of southbound left turns from incorrect lanes. The predominant southbound left-turn volume creates lane imbalances favoring the inside lane at the southbound entry, which may result in some drivers selecting the incorrect outside lane for the southbound left turn to avoid queues and reduce delay. An upstream signal also creates platoons of arriving vehicles that may make it more difficult for drivers to identify the correct lane for the left-turn maneuver and then change lanes if needed. Drivers destined for I–95 southbound may also be choosing to use the incorrect outside lane to minimize the number of lane changes required to access the freeway entrance ramp. The combination of queuing from the signalized intersection between the roundabout and interchange and weaving from the northbound roundabout free-flow bypass lane makes it more difficult to change lanes during peak periods of the afternoon.

At Melbourne, the westbound approach has three primary lanes, with the outside lane being dropped at the roundabout as a right turn only, free-flow bypass lane. An upstream signal is located approximately 1,050 ft from the roundabout entry. An interchange exit ramp is located 650 ft further upstream of the signal. Westbound vehicles arriving from the interchange in the outside lane must change lanes within platoons created by the signal to continue straight or turn left at the roundabout. Vehicles desiring to make a left turn would need to make two lane changes to get to the inside entry lane. The density of vehicle platoons from the signal makes lane changing more difficult and may affect lane selection.

Figure 95 illustrates the roadway network and land uses within the vicinity of the Malta site, which is located 0.35 mi from an interchange with I–87. The Malta site is also a major network connection with US 9, which parallels I–87. This network configuration results in regional travel patterns to and from I–87 that influence volume levels for various intersection turning movements throughout the day and may influence potential violations and conflicts. Entry lane imbalances due to increases in turning volumes traveling to and from the interchange may contribute to increased instances of left, right, and through movements from incorrect lanes during individual hours on each leg.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 58′ 15.68″ N and 73° 47′ 58.80″ W. Elevation 338 ft. Eye altitude 4,333 ft.
Note: Study intersection is identified with a dashed circle.

Figure 95. Photo. Malta—Roadway network and adjacent land uses.

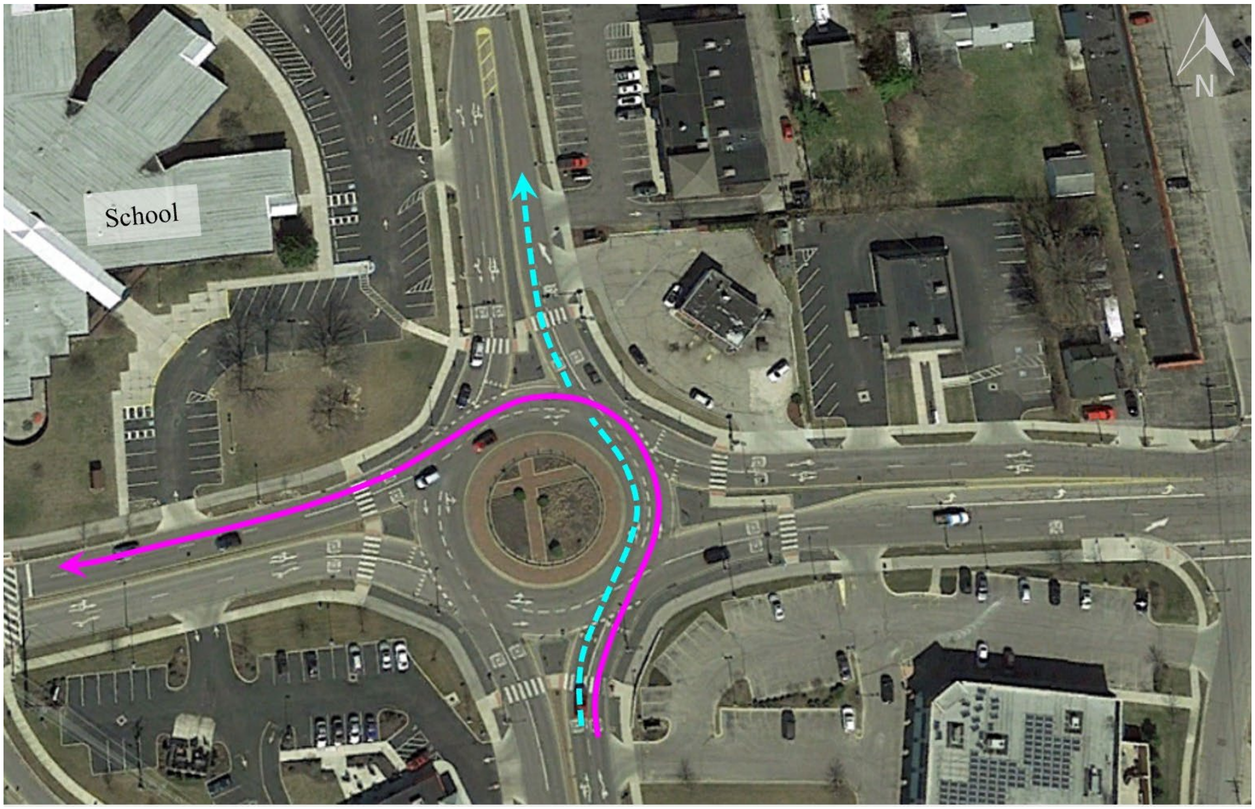
ADJACENT LAND USES AND ACCESS

Surrounding land uses and area contexts may impact driver familiarity. As previously noted, four of the study sites are located immediately adjacent to freeway interchanges. Each of these sites also has hospitals, retail shopping center uses, or recreational areas nearby that create the potential for increased numbers of unfamiliar drivers. However, driver familiarity alone is not sufficient for predicting the potential for vehicle crashes. For the study site in Hilliard, which is located in an urbanized city-center context, the city previously reviewed at-fault driver addresses and determined that crashes were predominantly caused by drivers that are local to the city of Hilliard and surrounding counties and would thus be expected to be familiar with roundabout navigation.(11)

Based on site observations, the intensity of uses and locations of property access points appear to influence driver navigation and possible frequency of various violations or conflicts. Trip origins and destinations also appear to influence incorrect lane selection, with some drivers pre-positioning for the downstream driveway destination instead of using the designated lanes for their maneuver. Some drivers were also observed to change lanes within the roundabout or through the exit to access driveways located immediately beyond the exit.

At the Carmel 116th site, the team observed a strong pattern of drivers making the westbound left turn through the roundabout destined to the shopping center in the southwest quadrant of the study intersection. As previously illustrated by the blue line in figure 42, the team observed drivers incorrectly using the outside circulating lane when making the left turn to position for the right turn into the shopping center immediately after exiting the roundabout to the south. Vehicles using the correct inside circulating lane to make the westbound-to-southbound left turn frequently crossed over to the outside lane through the exit to position for turning into the shopping center driveway. Westbound vehicles turning left from the incorrect lane represented 25 percent (48 crashes over 3 yr) of the intersection total.

At the Hilliard site, an elementary school is adjacent to the northwest quadrant of the roundabout. The school influences traffic patterns, particularly during the morning peak hour (heavier northbound left-turn and westbound through volumes) and during the early afternoon period during school dismissal. During the morning peak, heavy northbound-to-westbound left-turn flows create queuing in the inside lane on the northbound approach. To bypass the queue, multiple northbound left-turning drivers were observed to intentionally use the incorrect outside lane to make a right turn into the school after exiting the roundabout to the west. Crashes associated with northbound left turns from incorrect lanes reflected approximately 4 percent (10 crashes over 3 yr) of the intersection total. This crash pattern is illustrated in figure 96.

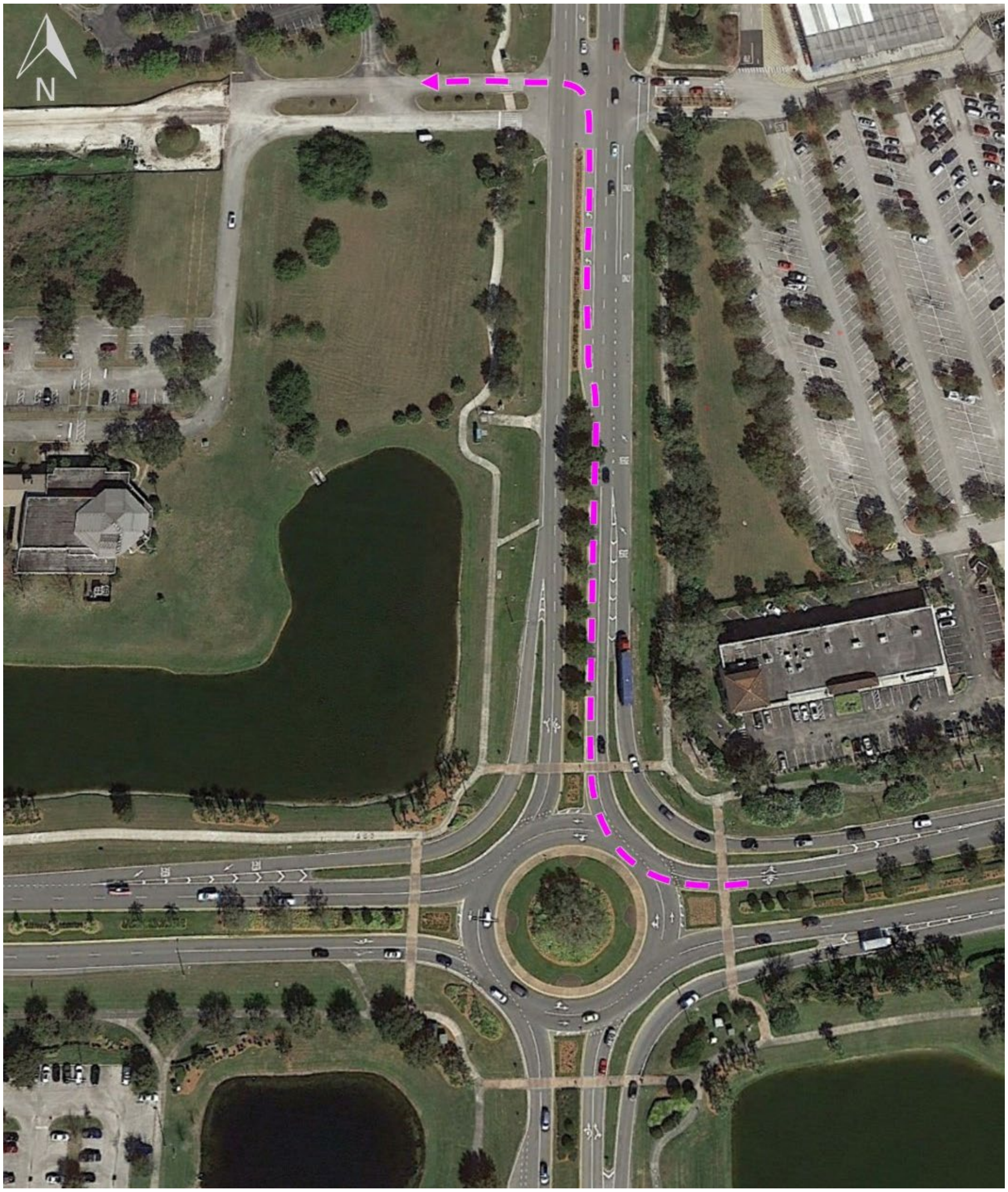


Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 17, 2018. 40° 01′ 48.28″ N and 83° 09′ 40.58″ W. Elevation 937 ft. Eye altitude 1,935 ft.

Figure 96. Photo. Hilliard—Left turn from the incorrect lane for trips to school.

At the Melbourne site, the hospital adjacent to the southwest corner, annotated in figure 94, has access points 1,000 ft to the west of the roundabout and approximately 400 ft to the south. Some drivers traveling to the hospital were noted to make an improper westbound-to-southbound left turn from the outside lane to be able to make a right turn into the hospital immediately after exiting the roundabout southbound. Crashes associated with westbound left turns from incorrect lanes accounted for 23 percent (42 crashes over 3 yr) of the intersection total. Approximately 10–18 percent of the hourly westbound vehicles turning left were observed to use the incorrect lane. Drivers using the correct inside circulating lane for the westbound left turn were observed to change lanes through the exit to cross to the outside exit lane. For vehicles accessing the hospital using Wickham Road to the west, some westbound through drivers were observed to enter the roundabout in the outside lane and then change to the inside lane through the roundabout exit to position themselves for the downstream left turn into the hospital.

Also at the Melbourne site, two places of worship are adjacent to the northwest corner of the roundabout. Vehicles making a right turn using the westbound-to-northbound right-turn bypass lane are required to make a rapid lane change across three lanes to make a northbound left turn into these properties. Instead, drivers appear to be using the incorrect inside lane on the westbound entry to make a right turn based on their downstream destination, as illustrated in figure 97. This trend may have contributed to up to 15 westbound right-turn crashes that were reported from the incorrect inside lane. Note that activity for these places of worship is likely to be more heavily weighted toward weekends and was not captured as part of the drone data collection.

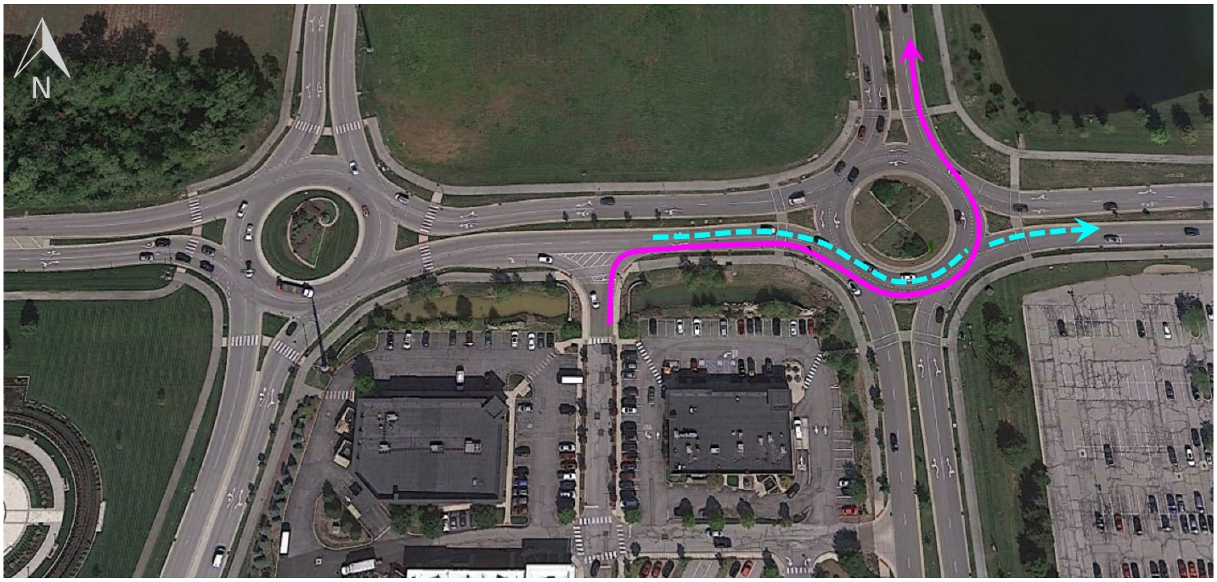


Original map: © 2020 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: February 2, 2020. 28° 13′ 50.05″ N and 80° 43′ 31.21″ W. Elevation 30 ft.
Eye altitude 1,789 ft.

Figure 97. Photo. Melbourne—Improper right turns to access places of worship.

Driveways in close proximity to an entry were also observed to create the potential for drivers to use the incorrect lane for making a left-turn maneuver. One example is at the Carmel 116th site, where a right-in/right-out driveway for the adjacent shopping center is located approximately

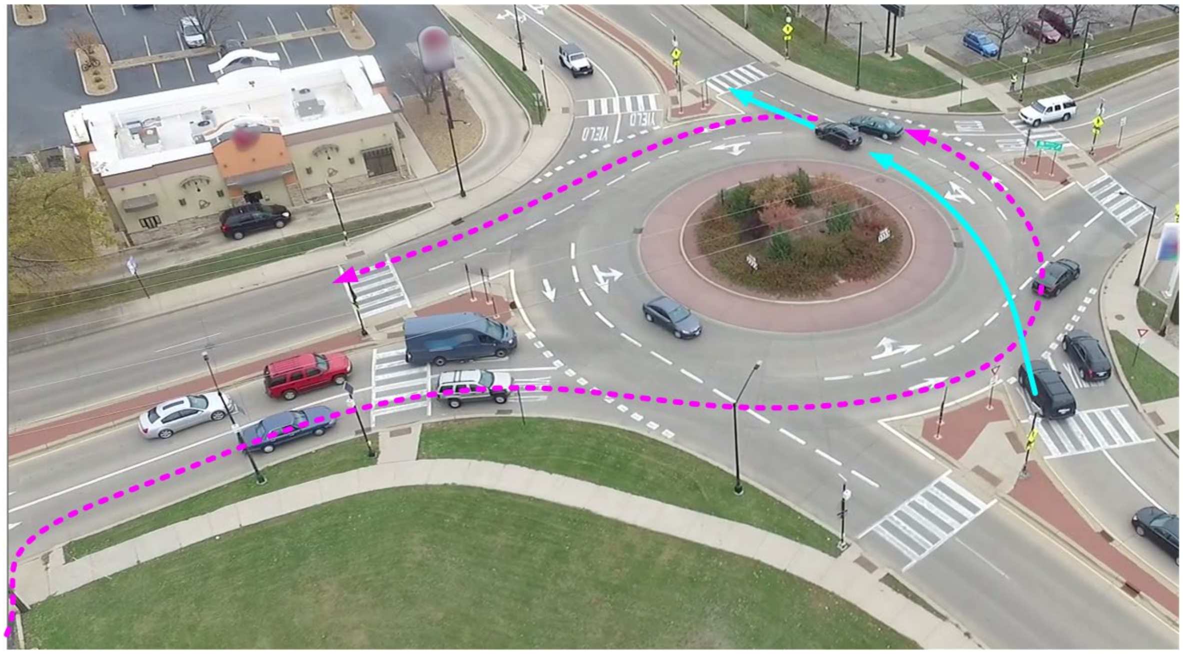
200 ft west of the roundabout entry. As illustrated in figure 98, some drivers leaving the shopping center were observed to have difficulty during peak periods in getting into the left lane on 116th Street eastbound prior to the roundabout entry, which could be contributing to vehicles making left turns from the incorrect lanes. A total of 19 crashes over 3 yr (10 percent of the intersection total) were related to improper eastbound left turns from incorrect lanes. Between 2.2 percent and 5.8 percent of all eastbound left-turning vehicles were observed to use the incorrect lane.



Original map: © 2022 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: 39° 57′ 22.14″ N and 86° 09′ 47.30″ W. Elevation 854 ft. Eye altitude 2,049 ft.

Figure 98. Photo. Carmel 116th—Left turn from incorrect lane after departing adjacent driveway.

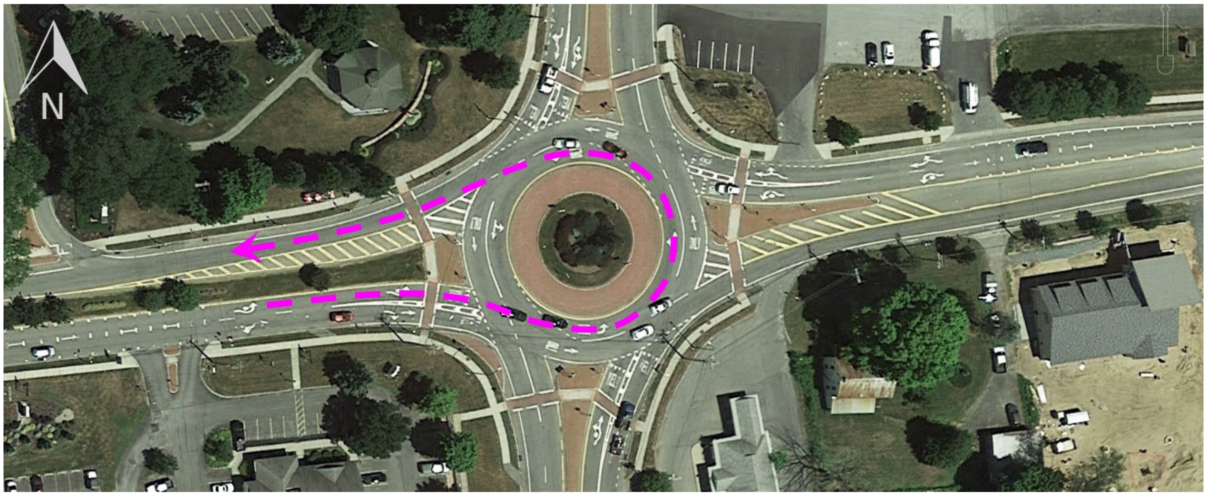
At the Oshkosh site, a retail store is located north of the roundabout with a right-in/right-out driveway approximately 95 ft upstream of the roundabout entry. Drivers have a short distance to move into the inside lane if they desire to make a left-turn or U-turn at the roundabout. During congested periods with queues present, drivers may be more likely to have difficulty getting to the correct inside lane prior to entry. One near-crash was observed due to a driver making a U-turn from the incorrect lane after turning right from this driveway, as illustrated in figure 99.



Source: FHWA.

Figure 99. Photo. Oshkosh—U-turn from incorrect lane after departing an adjacent driveway.

At the Malta site, access management between the roundabouts along the SR 67 corridor resulted in a relatively high number of eastbound-to-westbound U-turn movements. Some drivers were observed to follow the central island curb instead of the spiral markings, resulting in the U-turning vehicles changing lanes to continue westbound using the single-lane westbound exit, as illustrated in figure 100. For driveways near the entries, such as on the eastbound and westbound approaches, the short distance also created challenges for some vehicles to get into the correct inside lane for a left-turn movement during congested periods.



Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: June 25, 2018. 42° 58′ 16.43″ N and 73° 47′ 34.33″ W. Elevation 339 ft. Eye altitude 1,045 ft.

Figure 100. Photo. Malta—Observed U-turn-related lane changing.

CLOSE INTERSECTION SPACING

For very close intersection spacing, roundabouts can provide desirable operational benefits due to shorter queues and more efficient use of lanes than comparable signalized intersections. However, they may also create challenges for drivers who need to change lanes between intersections, especially if vehicles are traveling in platoons or if queues between roundabouts are present that further limit the space available for lane changing. In these cases, drivers would benefit from having appropriate information (such as destinations assigned to each lane) to minimize the need for lane changing between closely spaced intersections.

In Hilliard, the study site is located approximately 225 ft from an adjacent multi-lane roundabout to the south, as illustrated in figure 101. During brief periods during peak hours of the day, queuing on the northbound approach would make it more difficult for drivers to change lanes between roundabouts, which may contribute to use of the incorrect lane for left-turn or right-turn movements. Approximately 3 percent of vehicles used the incorrect lane to make a northbound left turn during the congested morning and evening peak hours, compared to approximately 1 percent of vehicles during the uncongested midday hours. Figure 102 illustrates queuing on the northbound approach during the morning peak hour, with heavy northbound left-turn movements associated with school arrivals. A traffic signal is also located nearby, approximately 225 ft to the west along Cemetery Road, which similarly reduces the space for lane changing between intersections.

Original map: © 2018 Google® Earth™. Annotations by FHWA (see Acknowledgements section).
Data: Imagery date: March 17, 2018. 40° 01′ 47.07″ N and 83° 09′ 40.75″ W. Elevation 940 ft. Eye altitude 2,649 ft.

Figure 101. Photo. Hilliard roadway network and surrounding development patterns.

Source: FHWA.

Figure 102. Photo. Hilliard—Northbound vehicle queues during peak a.m. hours.

Similar spacing considerations to adjacent roundabouts are present at the Carmel 106th site, illustrated in figure 92, as well as at the Carmel 116th site, illustrated in figure 98. For both sites, the upstream roundabout influenced lane choice, and periodic peak-hour queues between intersections may have made it more difficult for drivers to identify and get into the correct lane for their intended turning movement. The Wales site also has a roundabout located approximately 480 ft to the west; however, the spacing did not appear to substantially affect drivers' lane selections, based on the observed volume levels and queuing.

Several sites also have traffic signals nearby; both Oshkosh and Hilliard have traffic signals within 240 ft. Other sites had signals farther away: Malta has a signal 700 ft from the roundabout, and Melbourne has a signal 1,000 ft away. Signal operational impacts are discussed in the next section. However, close spacing between intersections may further compound the ability of drivers to get into the correct lane. Queue spillback from the adjacent signal into the study roundabout was only observed at the Melbourne site.

ADJACENT TRAFFIC SIGNAL INFLUENCES

Upstream signalized intersections have the potential to create platooned arrivals that can affect drivers' abilities to interpret lane-use information and, if needed, change to the correct lane prior to entry. Due to their cyclical operation, upstream signals can create periods of relatively intense flow followed by lower flow periods. During the more intense flow periods within signal cycles, drivers at the roundabout may experience an increased potential for vehicle conflicts and a greater navigational task load than what might be expected during lower flow periods within the cycle. These cyclic variations may not be detected by considering only average flow conditions over the peak hour or day. As summarized in table 29 and table 30, multiple roundabout sites had upstream signals at varying distances from the roundabout.

For the Melbourne site, the adjacent signals illustrated in figure 94 to the east and north had the most significant observed impact on operations among the study sites. As illustrated in figure 103, the signal to the east would consolidate vehicles arriving from the I–95 interchange and then release heavy platoons toward the roundabout. The short intersection spacing and platoon density may be affecting drivers in their ability (or willingness) to identify the correct lane and make the corresponding lane change before reaching the roundabout. The arriving westbound platoons also temporarily cause delay and queuing on the adjacent southbound entry. Given the volume imbalances on the southbound entry favoring left turns, queuing tended to be higher in the inside lane, which could be causing drivers to use the incorrect outside lane for southbound left turns to bypass the standing entry queues. Platooned arrivals on the southbound approach from the upstream signal may also be impacting drivers' abilities to change lanes prior to entry.

Source: FHWA.

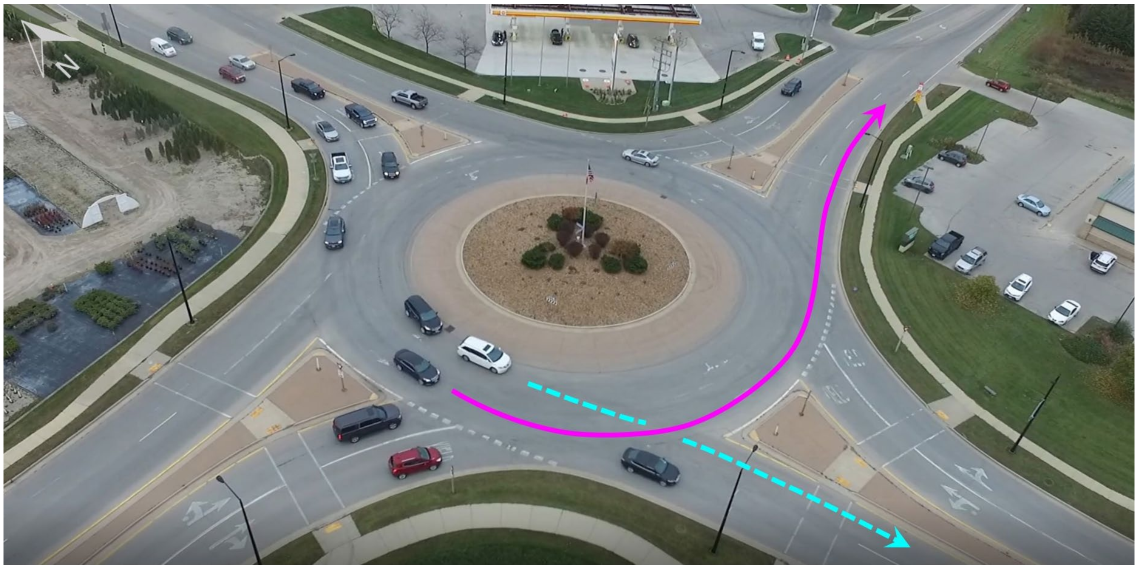
Figure 103. Photo. Melbourne—Platooned westbound arrivals (top) resulting in southbound queueing (left).

During the evening peak hours, queues from the adjacent signal to the east were observed to temporarily extend into the roundabout on multiple occasions, as illustrated in figure 104. Also, note in figure 104 the lack of vehicles on the westbound entry (top) and southbound entry (left) due to the previous platoons already being processed through the roundabout and the next platoons not yet arriving from the adjacent signals.

Source: FHWA.

Figure 104. Photo. Melbourne—Queues from the adjacent signal extending into the roundabout.

For the site in De Pere, a traffic signal 2 mi to the north was observed to influence the roundabout operations with vehicles arriving in platoons, as illustrated in figure 105. The crash pattern illustrated in figure 105 reflects 48 percent (or 11 crashes) out of the intersection's 3-yr total. This trend appears to be influenced by the platooned arrival patterns where there was more likely to be another vehicle in the adjacent lane if a driver did not use the correct lane to make their left-turn movement. The platooned arrivals may also have affected drivers' ability to identify the correct lane for their movement and their ability to change lanes prior to entry, despite the De Pere site having the lowest volumes of the study intersections.



Source: FHWA.

Figure 105. Photo. De Pere—Platooned vehicle arrivals at southbound entry and crash patterns caused by left turn from incorrect lane.

Similar platooned arrival patterns from adjacent upstream signals were observed at Oshkosh, Hilliard, Malta, Slingerlands, and Wales. Potential impacts on crash patterns and observed violations and conflicts vary by intersection, depending on the turning-movement patterns associated with each entry.

DOWNSTREAM LANE DROPS

Downstream lane drops reflect one of the exit lanes dropping as right turn only or left turn only at a downstream intersection or driveway. These lane drops can impact lane utilization at the upstream roundabout entries. (Merging of the two exit lanes is covered separately in Chapter 5.)

On the two-lane westbound exit at the Oshkosh site, the inside exit lane becomes a left turn only lane approximately 170 ft from the roundabout exit. This transition may be influencing driver lane selection and lane imbalances noted on the upstream westbound entry. Between 63.8 and 68.9 percent of drivers during each hour analyzed used the outside lane on the westbound approach, possibly to avoid the lane drop on the westbound exit.

As illustrated in figure 101, at the Hilliard site the outside lane on the westbound exit is dropped as right turn only into the school downstream of the roundabout. This dropped lane may be affecting the lane distribution on the westbound entry, where 56–78 percent of vehicles were observed in the inside entry lane during each period.

CHAPTER 7. SUMMARY OF FINDINGS

Based on field evaluations and subsequent analyses documented in this report, the research team identified several key findings and areas for further investigation. This chapter summarizes those key findings and offers menus of potential countermeasures for consideration based on the specific issues and conditions at individual sites.

SUMMARY OF KEY FINDINGS

The research team identified the following eight key findings related to crash and conflict patterns occurring near multi-lane roundabout exits:

1. The following key patterns of interest comprised most crashes and conflicts at the study intersections:

    - Drivers in the outside entering lane failing to yield to drivers in the inside circulating lane.
    - Drivers making left-turn movements from the incorrect outside lane.
    - Drivers making right-turn movements from the incorrect inside lane.
    - Drivers straddling lanes or changing lanes when entering, circulating, or exiting.

2. Key crash and conflict patterns varied across both the control and problem sites based on volume conditions (e.g., turning-movement patterns), roundabout geometry, and network considerations. The magnitudes and types of crashes and conflicts also varied based on the approaches at each individual site.

3. Control sites and problem sites generated comparable average hourly violations; however, problem sites generated nearly twice the number of conflicts and potential conflicts as control sites. Specifically, the following was observed regarding these data:

    - The magnitude and types of observed violations and conflicts varied across sites based on volume conditions, geometric factors, and network factors. In particular, the presence or absence of exclusive left-turn lanes was a key factor influencing the number of violations.

    - The primary observed violation types across all study sites included lane straddling, lane changing through exits, and left turns from incorrect lanes; however, these violation types did not necessarily result in observed conflicts. By comparison, the primary violation types resulting in observed conflicts included failure to yield at entry, exit lane changes, and left turns from incorrect lanes. These violation types accounted for 91 percent of observed conflicts at problem sites and 87 percent at control sites. Failure to yield at entry resulted in the highest average observed conflicts, with approximately 3 times as many conflicts per hour at problem sites as at control sites.

4. Volume magnitude, uniformity, and imbalances across lanes were potential contributors to number of failure-to-yield crashes observed. Specifically, the following was observed regarding these data:

   - The average sums of entering and conflicting volumes at each of the entries for the control sites, which ranged from 900 to 1,200 vehicles per hour, were more uniform and consistent across entries than at problem sites, which ranged from 900 to 2,100 vehicles per hour.

   - The 8 approaches with the most failure-to-yield crashes (more than 15 crashes over 3 yr per approach) each had 2 conflicting circulating lanes that were both allowed to exit. They also generally had a large imbalance in lane use, with either a high percentage of entering vehicles using the right/outside lane or a high percentage of circulating vehicles using the left/inside lane. Network influences and turning-movement patterns played a key role in lane imbalances; however, geometric factors also influenced some locations, as follows:

     - Heavy right-turn volumes made the outside circulating lane at the downstream entry more frequently unoccupied.

     - Heavy left-turn volumes caused lane imbalances that resulted in the outside circulating lane being frequently unoccupied at a downstream entry.

     - Approach lane addition and lane drop design also potentially influenced volume imbalances across lanes.

     - Sites with large conflict areas due to large ICDs, skewed angles between legs, or other factors experienced more failure-to-yield crashes. However, crashes of this type were also identified at sites with more compact geometry, such as Hilliard.

   - Experiences at problem sites varied widely. For individual approaches, failure-to-yield crashes ranged from 1 crash over 3 yr to 35 crashes over 3 yr. Volume alone does not explain the variation in observed crashes at the problem sites. No apparent strong relationship was identified between crash experiences and entering volume, circulating volume, or sum of entering and circulating volumes within individual conflict areas.

   - The team identified no apparent relationships between entry signing and markings and failure-to-yield crashes. Varied signing and marking treatments were present at both the control and problem sites, including variations on the use of yield word markings or yield lines and a range of plaques to supplement the yield signing. Similar plaques were present at approaches with lower and higher numbers of crashes.

5. It is imperative to get drivers into the correct lane prior to the yield line to address crashes associated with left turns from incorrect lanes. However, the ability to for drivers to

achieve this is largely dependent on the location of the roundabout relative to nearby origins and destinations. Specifically, the following was observed regarding these data:

- The volume of left-turning vehicles was not strongly correlated to the potential for crashes associated with left turns from incorrect lanes.

- Network influences for multiple sites, such as adjacent interchange ramps or business access points, appeared to directly influence drivers' desire to select the incorrect outside lane to position themselves correctly for their intended downstream turning movement.

- Modifications to circulatory roadway lane lines or arrow pavement markings alone are not anticipated to fully address crashes associated with left turns from incorrect lanes. Implementation of raised lane dividers (consistent with turbo roundabout design practices) or spirals within the circulatory roadway to guide drivers to the outside lane on exit may help to reduce incorrect lane use. However, in retrofit situations, existing geometry may still allow drivers to navigate through gaps in raised lane dividers to continue to make left turns from the outside lane. Similarly, the presence of lane dividers may shift the lane changing into a more compressed area in advance of or beyond the roundabout. The most substantial benefits appear to be gained from an emphasis on the following:

    - Providing appropriate approach lane configurations to promote balanced lane use.

    - Providing signing and markings to get drivers into the correct lane prior to entry.

    - Designing geometric elements to allow drivers to change lanes on approach and support balanced lane use.

6. Design of spirals within the circulatory roadway directly influences driver navigation and lane changing within the roundabout. Painted spirals are strongly associated with drivers straddling lanes.

7. Exclusive left-turn lanes are strongly associated with incorrect lane selection and lane changing within the roundabout.

8. Multiple geometric factors influence lane straddling and lane changing. This finding includes entry geometry/alignment, exit geometry/alignment, size of conflict areas, lane widths, and diameters at the edges of the typical ranges (very small or very large). However, network considerations also play a role in lane changing through exits.

ANALYSIS OF KEY FINDINGS

From the key findings identified in the previous section, the research team has identified a few key themes that appear to hold true across the studied sites, as follows:

- The study findings reinforce longstanding guidance to keep the roundabout configuration to the fewest lanes practical. Where 2x2 configurations are expected to be needed to serve forecasted future growth, phased project implementation that minimizes the number of initial lanes, such as use of a single-lane or 2x1 configuration, should be considered.

- Turning movement patterns and roundabout locations, relative to nearby origins and destinations, substantially affect PDO crashes. Drivers who have limited ability to change lanes prior to entering the roundabout or after exiting the roundabout due to their origin or destination may choose to navigate it using incorrect lanes because they perceive no other safe option. The research team believes that geometric changes or changes in traffic control device layout within the roundabout alone would be insufficient to correct these network-related challenges. Lane reductions (e.g., changing to single-lane movements) or changes to access placement away from the roundabout will be needed to reduce or eliminate these patterns.

- Heavy right-turn movements in shared through-right lanes appear particularly linked to safety-related challenges at downstream 2x2 conflict areas. If the outer lane at the entry upstream of the subject 2x2 conflict area is designated as shared through-right but has a heavy right-turning flow, the outside circulating lane can be starved relative to the inside circulating lane. In these cases, drivers in the right entry lane at the subject 2x2 conflict area may not perceive a conflict and thus may enter without yielding. It may be better to use right turn only lanes or channelized right-turn bypass lanes and tolerate increased congestion during times when two through lanes may be desired. If right turn only lanes are used, the design needs to be carefully arranged to discourage illegal use of the right turn only lane as a through lane.

- Painted spirals within the circulatory roadway are especially prone to lane straddling and lane changes in the exit-circulating areas. Drivers routinely drive over painted spirals, following instead the edge of the truck apron. Physical extension of the truck apron to cover the intended area of the spiral is likely to mitigate this problem. Existing sites may benefit from retrofitted truck apron extensions if the cross slopes of the circulatory roadway and truck apron are compatible. It may not be feasible to retrofit existing sites with crowned circulatory roadways due to conflicts with drainage along the inside edge of the circulatory roadway and grade breaks within the truck apron.

- The overall composition of the roundabout plays a greater role in safety performance than individual geometric, signing, or marking elements. Adjustments to individual design elements may support incremental reductions in specific types of violations and conflicts. However, the team anticipates a combination of improvements will be needed at most sites to address the ranges of crash types present.

MENUS OF COUNTERMEASURES

The research team observed a wide range of geometric, volume, and network conditions across the study sites. Each unique set of circumstances is expected to require a customized set of countermeasures to address the observed crash patterns. While education, enforcement, and potential benefits associated with connected and automated vehicles may also be beneficial, these areas are outside the scope of this study.

Potential countermeasures are organized into six categories. For each potential countermeasure, the potential benefits and effectiveness are assessed based on the findings of this project and the research team's judgment. The categories are as follows:

1. Lane configuration.
2. Network modifications.
3. Approach signing and markings.
4. Entry signing and markings.
5. Circulatory roadway and exit countermeasures.
6. Geometric modifications.

Lane Configurations

The goals of improvements to lane configurations include the following:

- Reduced vehicle-vehicle conflicts of all types.
- Reduced vehicular speeds.
- Improved safety and accessibility environments for pedestrians and bicyclists.

Possible treatments are listed in table 31, along with their potential benefits.

Table 31. Menu of potential lane configuration changes.

Treatment	Potential Benefits	Potential for Effectiveness
Reduce entering and circulating lanes where feasible.	The overall simplification of the roundabout by reducing through lanes, ideally to a 2x1 configuration (or a single-lane roundabout for sites that have been over-designed), has the potential to address many crash patterns identified in this study and provide other safety improvements as well. Lane reduction may result in peak-period congestion for motor vehicles but may have better safety performance for all modes over the course of the day and year. A lifecycle cost analysis may help to understand the tradeoff between safety and capacity.	High.
Convert shared through-right entry functioning as a de facto right turn only lane to a permanent right turn only lane.	This strategy provides some additional capacity for right-turn movements while allowing for removal of one lane within a portion of the circulatory roadway. Reduction in the number of circulating lanes addresses many of the observed crash patterns. However, dropping one of the primary lanes on a four-lane roadway could result in increased lane changing for through vehicles upstream of the roundabout.	Medium.
Add a yield-controlled right-turn bypass lane for approaches with heavy right-turn movements that are creating lane imbalances for through movements.	This strategy is targeted at providing more balanced distribution of circulating vehicles to reduce the potential for failure-to-yield crashes at the downstream entry. Adding a bypass lane may affect pedestrian navigation, add vehicle conflict points, and increase intersection footprints. These and other potential tradeoffs need to be considered based on specific site conditions.	Medium. Effectiveness may be offset by the addition of new conflicts associated with a bypass lane.
Convert shared left through entry lane functioning as a de facto left turn only lane to a permanent left turn only lane.	This strategy provides some additional capacity for left-turn movements (with potential reduction to through-movement capacity) while allowing for the downstream exit to be reduced from two lanes to one lane. The expected benefit is a potential reduction in crashes associated with left turns from improper lanes and failure-to-yield crashes for vehicles entering in the outside lane adjacent to the exit being modified. This treatment requires additional modifications to the circulatory roadway to guide left-turning vehicles from the inside lane to the outside lane for the new single-lane exit. Spiral pavement markings alone were found to be ineffective. Modification to the central island and truck apron may be needed to achieve the desired spiral vehicle paths.	Medium. Effectiveness may be offset by the addition of new conflicts associated with spiral transitions within the circulatory roadway.

Network Modifications

Improvements that address network influences aim to improve driver ability to change lanes between intersections. These improvements are anticipated to reduce the likelihood of turns from incorrect lanes.

Possible treatments are listed in table 32, along with their potential benefits. Additional signing and marking treatments that address network considerations are provided in the following section.

Table 32. Menu of potential network modifications.

Treatment	Potential Benefits	Potential for Effectiveness
Shift access point further away from roundabout.	This treatment may provide more distance for lane changing, which may reduce the likelihood of turns from incorrect lanes or lane changing through the roundabout entry and exit.	Medium.
Increase spacing between upstream or downstream signalized intersection and roundabout.	This treatment may provide more distance for lane changing, which may reduce the likelihood of turns from incorrect lanes at the roundabout.	Medium.
Replace upstream signalized intersection with roundabout.	This treatment may reduce the intensity of platoons of vehicles passing from the upstream signalized intersection to the roundabout, making lane changes in advance of the roundabout more feasible and reduce the likelihood of turns from incorrect lanes..	Medium.
For closely spaced intersections, modify the lane configuration of the intersection upstream of the roundabout.	This treatment reduces lane changing and increases the likelihood for a vehicle to use the correct lane based on predominant origin and destination patterns.	Medium.
Modify timing of upstream signals, such as by reducing cycle lengths or by providing coordination.	This treatment has the potential to influence arrival patterns of vehicles by reducing the intensity of vehicles arriving at the same time at the roundabout.	Medium.

Approach Signing and Markings

Goals of making improvements to approach signing and markings include the following:

- Appropriate lane selection prior to entry.
- Lane selection guidance for major destinations.

Possible treatments are listed in table 33, along with their potential benefits.

Table 33. Menu of potential signing and marking treatments.

Treatment	Potential Benefits	Potential for Effectiveness
Overhead lane-control signs	This treatment is likely to significantly improve visibility of lane-control signs and separate them from roadside visual clutter. Overhead signs may not be as effective on east-west alignments during times of the day when the sun is within the driver's cone of vision. In addition, overhead signs must comply with illumination guidelines for effectiveness at night.	High.
Larger side-mounted lane-control signs	This treatment may improve the visibility of lane-control signs, especially in roadway environments with visual clutter along the roadway.	Medium.
Lane-control signs on both sides of approach	This treatment may improve the visibility of lane-control signs in the left approaching lane.	Medium.
Multiple sets of lane-control signs and arrow markings	This treatment may improve the visibility of lane-control signs and markings by providing multiple opportunities for drivers to see them as they approach the roundabout.	Medium.
Overhead destination guidance	This treatment may improve driver selection of the correct lane prior to entry by linking lane-use selection to intended destination.	Medium.
Standard arrow signs and markings (with optional dot in inside lane)	Standard arrows for both signs and markings may improve driver comprehension more than fishhook-style arrows. An optional dot in the inside lane may reduce the already-low likelihood of a driver turning left in front of the central island.	Medium.
Add route shield markings	This treatment may improve driver selection of the correct lane prior to entry by linking lane-use selection to intended destination.	Medium.

Entry Improvement Countermeasures

Improvements to roundabout entries aim to do the following:

- Enhance driver yielding to both circulating lanes at entry.
- Enhance vehicle alignment between entering and circulating lanes.

Possible treatments are listed in table 34, along with their potential benefits.

Table 34. Menu of potential entry treatments.

Treatment	Potential Benefits	Potential for Effectiveness
Raise crosswalks to enhance yielding at entry and provide additional speed control.	Lower speeds may increase the likelihood of drivers yielding at the entry. The raised crosswalk may also have a significant benefit to pedestrians in terms of improving the likelihood of drivers yielding on both the entry and exit sides. The raised crosswalk can be part of a package of improvements to make the crossings accessible to people who are blind or have low vision.	High.
Replace yield line with yield word markings.	The use of words instead of symbols may have better driver recognition.	Medium.
Implement yield signs on both sides of entry.	This treatment is already recommended in *MUTCD*.(6)	Medium.
Adjust angle or position of entrance line.	Due to the staggered nature of two-lane entries, driver view angles in the outside lane are generally smaller than those in the inside lane. Where driver view angles at the entrance line are too severe, adjusting the angle or position of the entrance line may support improved view angles and corresponding improvements in driver yielding.	Medium to low.
Add supplemental signing under yield sign (e.g., "TO BOTH LANES").	These signs may have a small but unquantifiable benefit in improving driver yielding for unfamiliar drivers. The signs may lose effectiveness over time with familiar drivers.	Low.
Add supplemental signing in central island (e.g., custom, subject to approval for experimentation).	These signs may have a small but unquantifiable benefit in improving driver yielding for unfamiliar drivers. The signs may lose effectiveness over time with familiar drivers.	Low.

Circulatory Roadway and Exit Countermeasures

Improvements within circulatory roadways and exits aim to do the following:

- Encourage lane discipline for posted lane configurations.
- Reduce lane encroachment and lane changes.

Possible treatments that seem to have medium potential for effectiveness are listed in table 35, along with their potential benefits.

Table 35. Menu of circulatory roadway and exit treatments with medium effectiveness potential.

Treatment	Potential Benefits	Potential for Effectiveness
Add supplemental treatments such as lane line rumble strips, raised pavement markers, or raised lane dividers to promote lane discipline (e.g., turbo-style treatments).	Rumble strips and raised pavement markers provide a deterrent for drivers who may cross lane lines within a circulatory roadway. Mountable raised lane dividers provide increased physical channelization. Because a gap in these treatments is required adjacent to each entry to allow entering drivers to cross the lane line, the size of a conflict area and overall geometry of a roundabout continue to play critical roles in potential for effectiveness. For retrofit situations, these treatments may provide limited benefit at some sites in discouraging left turns from incorrect lanes or lane changing through the entry or exit due to the size of the conflict areas.	Medium. Effectiveness expected to be higher for new construction where the supplemental treatments are integral to the overall design. Maintenance is a factor.
Adjust circulating lane line position (narrower inside lane) to enhance entry alignment and allow tangent to be added between circulating and exit curves.	Adjustment to the position of the lane line is intended to reduce potential for lane changing through entry and exit. A wider outside circulating lane may help to encourage drivers in the outside lane to stay in the outside circulating lane where the roundabout geometry results in slight misalignment of entering and circulating lanes. Narrowing the inside circulating lane also allows for a tangent to be added along the lane line between the circulatory roadway and exit curves. State-level guidance encourages the use of a tangent at least 40-ft long along the exit lane line.(10)	Medium.

Possible treatments that seem to have low potential for effectiveness are listed in table 36, along with their potential benefits.

Table 36. Menu of circulatory roadway and exit treatments with low effectiveness potential.

Treatment	Potential Benefits	Potential for Effectiveness
Adjust shape of spiral markings.	The shape of spiral pavement markings has the potential to influence the size of conflict areas and the corresponding alignment for entering vehicles. However, painted spirals are prone to lane straddling or lane changing where drivers were frequently observed to follow the central island curb instead of the spiral lane markings. Adjustment to the shape of the spiral may provide a marginal benefit for guiding left-turning drivers.	Low.
Adjust lane line type (combination of solid and dotted lines versus consistent "strong dash," double lines).	These markings may have a small but unquantifiable benefit in minimizing late lane changes. These markings may lose effectiveness over time with familiar drivers. No relationship was identified between the lane line type and observed crash patterns across the study sites.	Low.
Adjust lane arrow positioning or additional set of lane arrows for larger ICDs.	Arrows positioned closer to the exit may provide benefits by reinforcing the number of conflicting lanes and the movements associated with those lanes (i.e., that both circulating lanes might exit straight). Additionally, they may encourage entering drivers to yield to both lanes and reinforce guidance to drivers that the outside lane must exit. For larger ICDs, multiple sets of lane arrows may be considered to support driver navigation.	Low.
Add through arrow to outside exit lane.	The intent of this treatment is to reinforce the requirement for drivers in the outside circulating lane to exit. This arrow supplements other arrow pavement markings in the circulating roadway. This treatment presents tradeoffs at locations where pedestrian crossings are present due to the potential for drivers to interpret the arrow as an indication of priority.	Low.

Geometric Countermeasures

Geometric countermeasures involve more substantive changes that may include adjustments to the curbs of a design. Depending on the magnitude of the changes, geometric countermeasures could lead to cascading design considerations, such as the relocation of drainage inlets. The goal of geometric countermeasures is to improve driver lane selection, driver yielding, and lane discipline through physical changes to the roadway curbs.

Possible geometric treatments that seem to have high potential for effectiveness are listed in table 37, along with their potential benefits.

Table 37. Menu of geometric treatments with high effectiveness potential.

Treatment	Potential Benefits	Potential for Effectiveness
Adjust alignment of a leg to correct a skew.	Depending on the site context, skewed entries may impact the size of conflict areas, vehicle speed control, entering vehicle lane alignment, and driver view angles. Adjusting the alignment of an entry or an adjacent exit to reduce the skew has the potential to improve driver yielding at entry and reduce lane changing and lane straddling.	High.
Modify the ICD of the roundabout.	For excessively large roundabouts, reducing the size of the roundabout may be necessary to remove exit-circulating conflicts inherent to separation between entries and the immediate downstream exit. This strategy requires substantial intersection reconstruction; thus, extensive cost-benefit analyses and exploration of alternative strategies to determine the viability of lane reductions are recommended.	High.
Replace painted spiral markings with truck apron extension.	Physical extension of the truck apron enhances guidance to drivers for navigating the intended path to single-lane exits where exclusive lanes are used. This enhancement will reduce lane straddling and lane-changing conflicts within the circulatory roadway and exit area.	High.

Possible geometric countermeasure treatments that seem to have medium-to-high potential for effectiveness are listed in table 38, along with their potential benefits.

Table 38. Menu of geometric treatments with medium-to-high effectiveness potential.

Treatment	Potential Benefits	Potential for Effectiveness
Modify entry geometry, including entry radius, entry width, or entry alignment.	Adjusted entry geometry may be desirable for a variety of reasons, depending on specific site conditions. Possible benefits include improved entry speed control to enhance driver yielding, improved lane alignment, and adjusted driver view angles.	Medium to high.
Modify exit geometry, including exit radius, exit width, or exit alignment.	Adjustment to exit geometry may be desirable for a variety of reasons, depending on specific site conditions. Possible benefits include improving exit alignment to reduce exit lane changing and reducing the size of conflict areas.	Medium to high.
Geometric modification: Modify the transition from one approach lane to two entry lanes at the roundabout.	At some roundabouts, an entry lane is added to either the left or right using a standard taper. This configuration prioritizes approaching vehicles into one entry lane. Depending on network origin-destination travel patterns, the lane being given priority could result in drivers selecting the incorrect lane for their movement or create imbalanced lane use. Adjusting which entry lane is being prioritized or making modifications to use a flared approach that removes lane priority are possible strategies for achieving more balanced lane use and improving lane selection.	Medium to high.
Geometric modification: Modify the transition from two exiting lanes to one downstream lane through use of a zipper-style merge (custom; subject to approval for experimentation).	Compared to the common strategy to end the outside lane and merge vehicles to the left, a zipper-style merge avoids priority being given to one exit lane, which has the potential to influence lane imbalances on upstream entries as familiar drivers take positions to avoid needing to change lanes along their travel paths. The zipper-style merge has the potential to enhance operation of the upstream entry and reduce possible failure-to-yield crashes associated with an absence of vehicles in the outside circulating lane. Right turns from incorrect lanes were also potentially influenced at some sites by the outside lane on the adjacent exit ending near the roundabout, which may be improved with use of a zipper-style merge.	Medium.

ACKNOWLEDGEMENTS

For the following figures, the original map is the copyright property of Google® Maps™ and can be accessed from https://www.google.com/maps; all north arrows, road names, labels, lines, dimensions, and/or other annotations were added to the maps by FHWA:

- Figure 1 and figure 2.
- Figure 6 through figure 14.
- Figure 36 through figure 47.
- Figure 49 through figure 51.
- Figure 53 through figure 56.
- Figure 59.
- Figure 61.
- Figure 63 through figure 65.
- Figure 67 through figure 71.
- Figure 78.
- Figure 84 through figure 98.
- Figure 100 and figure 101.

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