Advancing Turbo Roundabouts in the United States: Synthesis Report

FHWA Safety Program

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U.S. Department of Transportation
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A turbo roundabout has the same general operating characteristics as modern roundabouts but utilizes notably different geometrics to address conflicts associated with common crash types in multilane roundabouts. International experience suggests turbo roundabouts are adaptable to the U.S. context, providing an effective roundabout solution for higher-volume intersections. The goal of this document is to synthesize existing published resources (e.g., reports, papers, presentations, videos, and tools) on the topic of turbo roundabouts from international and domestic sources. The synthesis has three major sections: 1) geometric design, 2) capacity and operational performance, and 3) safety performance. The synthesis provides specifics regarding the treatment of various users, including motorists, pedestrians, cyclists, heavy vehicles, and motorcyclists. The synthesis also includes sections on education and public outreach approaches targeting non-technical audiences. The geometric design of a turbo roundabout is governed by the horizontal swept path of a design vehicle and a fastest path analysis for a passenger car. Key geometric designs include selection of turbo roundabout type and determination of functional combinations of the inner radius, cross section elements, and spirals within the turbo block. Turbo roundabout capacity is dependent on type but is generally similar in magnitude to modern multilane roundabouts. Methods in the HCM 2010 produced reasonable estimates of turbo roundabout capacity in Poland. Research available to-date also indicates that, with smaller radii and raised lane dividers, the reduced vehicle speeds and elimination of weaving in a turbo roundabout is expected to produce fewer and less severe crashes than multilane roundabouts and significantly fewer and less severe crashes than other traditional control types.</td></tr>
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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 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 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 (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

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

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List of Abbreviations

AADT	average annual daily traffic
ADA	Americans with Disabilities Act
ARR	Australian Road Research
CMF	crash modification factor
HCM	Highway Capacity Manual
PAR	potential accident rate
PDO	property damage only
pce	passenger car equivalents
ROW	right-of-way
SPF	safety performance function
SSAM	Surrogate Safety Assessment Model

Advancing Turbo Roundabouts in the United States: Synthesis Report

Introduction

Implementing modern roundabouts saves lives and reduces serious injuries resulting from intersection and intersection-related crashes. As planned points of conflict, crashes attributed in some way to intersections contribute significantly to traffic fatality and injury numbers in the U.S. Approximately half of all crashes and half of fatal and serious injury crashes occur at or near intersections. In the single year of 2017, more than 9,000 people were killed in intersection and intersection-related crashes (NHTSA, 2017). In stark contrast, there were a total of 46 fatalities at roundabouts built in the U.S. over the nine-year period spanning 2005 to 2013, a time period in which the total number of roundabouts in the U.S. grew from a few hundred to a few thousand (Steyn et al., 2015). Roundabouts reduce the number and severity of intersection conflicts by eliminating crossing conflicts and lowering operating speeds through the intersection. Eliminating or reducing the number of conflict points eliminates or reduces the chances of crashes from occurring. In addition, research on energy transfer in multiple-vehicle crashes and the human body's tolerance to resulting forces shows that the smaller conflict angles and lower speeds at roundabouts will result in lower probabilities of fatalities and serious injuries in crashes that do occur. Such results are evident in roundabout safety performance to-date. A review of three-star, four-star, and five-star crash modification factors (CMFs) in FHWA's CMF Clearinghouse shows that 90 of 105 roundabout CMFs indicate reductions in expected crash frequencies from implementing both single and multilane roundabouts for all, angle, and rear-end crashes, as well as fatal and injury crashes of all types (Rodegerdts et al., 2010). As one telling example, the CMF Clearinghouse includes "five-star" CMFs of 0.28 for fatal crashes and 0.56 for injury crashes attributed to converting traditional at-grade intersections to roundabouts (see table 1).

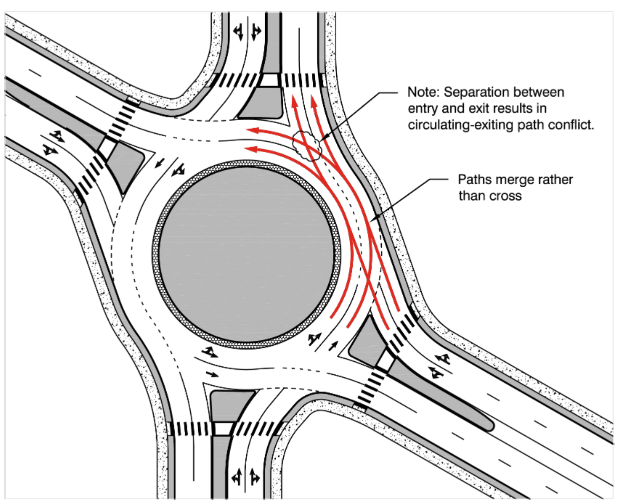
Table 1. CMFs for converting intersections to roundabout.

Crash Severity	"Five-Star" CMF	Prior Condition	Proposed Condition	Source
Fatal crashes	0.28	Yield-, Stop-, or Signal-Controlled Intersection	Single or Multilane Roundabout	Elvik, 2017
Injury crashes	0.56	Yield-, Stop-, or Signal-Controlled Intersection	Single or Multilane Roundabout	Elvik, 2017

Implementing roundabouts requires agency and stakeholder buy-in and support, which can sometimes be difficult to obtain, even with their proven safety performance record. FHWA has invested heavily in advancing roundabout planning, design, and analysis practices; delivering training; and developing educational and outreach materials to advance the consideration and use of roundabouts (FHWA, 2018). This has led to tremendous progress in roundabout implementation throughout the U.S. and resulting safety and operational performance benefits.

Though single-lane roundabouts make up most of the roundabouts in the U.S., multilane roundabouts have become more common. Some constructed multilane roundabouts have experienced higher frequency of low severity crashes. This has led to some negative public perceptions for multilane roundabouts that may slow the growing momentum of their use. For example, a multilane roundabout in Madison, Wisconsin received negative publicity when a local news organization identified it as the top crash site in the city. Another multilane roundabout in Appleton, Wisconsin received attention from local press in 2017 when it experienced 30 reported crashes in the first two months after opening. While these articles typically provide caveats noting that most of the crashes are minor, they still shed negative light on roundabouts from a public perception perspective.

The FHWA *Roundabout Technical Summary* describes conflicts between exiting and circulating vehicles at multilane roundabouts within the context of discussing larger separations between entries and subsequent exits (see figure 1). The *Technical Summary* notes that this situation arises because entering vehicles have more opportunity to begin traveling next to circulating traffic as opposed to crossing the path of exiting vehicles. This is a conflict that is unique to multilane roundabouts. Adapting the descriptions of operational configuration and driver behavior from Gustafson (2018), the larger separations may make drivers in the outer lane incorrectly think that it is up to drivers in the inside lane to select a gap in the outside lane before exiting the roundabout. In other words, the geometry (specifically the larger separation) may imply a “concentric roundabout,” even though the marking is for a “crossing roundabout.”



Source: FHWA

Figure 1. Graphic. Exit-circulating conflict of roundabout design.

An examination of multilane roundabouts in Minnesota (Leuer, 2016) observed two common crash types:

1) Crashes resulting from entering traffic not yielding to traffic within the roundabout.
2) Crashes resulting from drivers changing lanes inside the roundabout because they selected the incorrect lane on the approach.

Leuer (2016) noted that unfamiliar drivers may tend to select the outside lane of a multilane roundabout (even when turning left) since they expect to exit the roundabout from the outside lane. Additional evidence for this possible explanation was uncovered in a driving simulator study, which showed that (Molino et al., 2007):

- More drivers correctly chose the right lane (94.8 percent) than the left lane (82.3 percent) when asked to make different movements through a multilane roundabout.
- For the movements through a multilane roundabout where either lane was an option, only 44 percent of drivers correctly understood that either lane was an option.

Some countries have implemented a modified version of a multilane roundabout, known as a turbo roundabout (see figure 2). A turbo roundabout has the same operating characteristics as modern roundabouts but utilizes notably different geometrics to address the conflicts associated with the common crash types in multilane roundabouts. In describing turbo roundabout operational principles, Fortuijn (2009b) outlined the following key turbo roundabout features:

- A second lane is inserted opposite of at least one entry lane.
- Traffic approaching the roundabout on at least one leg must yield to traffic in two, and no more than two lanes on the roundabout.
- Smooth flow is encouraged by a spiral alignment.
- Mountable raised lane dividers discourage lane changing within the roundabout.
- Each segment of the roundabout includes one lane from which drivers can choose whether to exit or continue around the roundabout.
- At least two exit legs are two-lane.
- The diameter of the roundabout is kept small to encourage lower speeds through the roundabout.
- Approach legs are at right angles to the roundabout.
- Roundabout shields cut off views of the horizon for approaching vehicles.
- Mountable aprons offer sufficient width for longer vehicles.

The spiral road geometry and separated lanes of turbo roundabouts require drivers to choose the proper lane prior to entering the roundabout in order to leave the roundabout in the desired direction. Figure 3 and figure 4 show that the turbo roundabout eliminates the conflicts associated with the common crash types in multilane roundabouts. At the two-lane exits of a turbo roundabout, drivers in the inside lane execute a “turn” to exit the roundabout, as in concentric roundabouts described by Gustafson (2018). However, the turbo roundabout eliminates the requirement in concentric multilane roundabouts of exiting drivers in the inside lane having to first cross the outside lane. This is done by physically forcing drivers in the outside lane to exit (Gustafson, 2018). A crash-based safety evaluation suggests conversion of an intersection from yield-control, signalized, or old-style rotary to a turbo roundabout is associated with a 76 percent reduction in injury crash frequency (Fortuijn, 2009b).

Figure 2. Photograph. Aerial view of turbo roundabout in Delft.

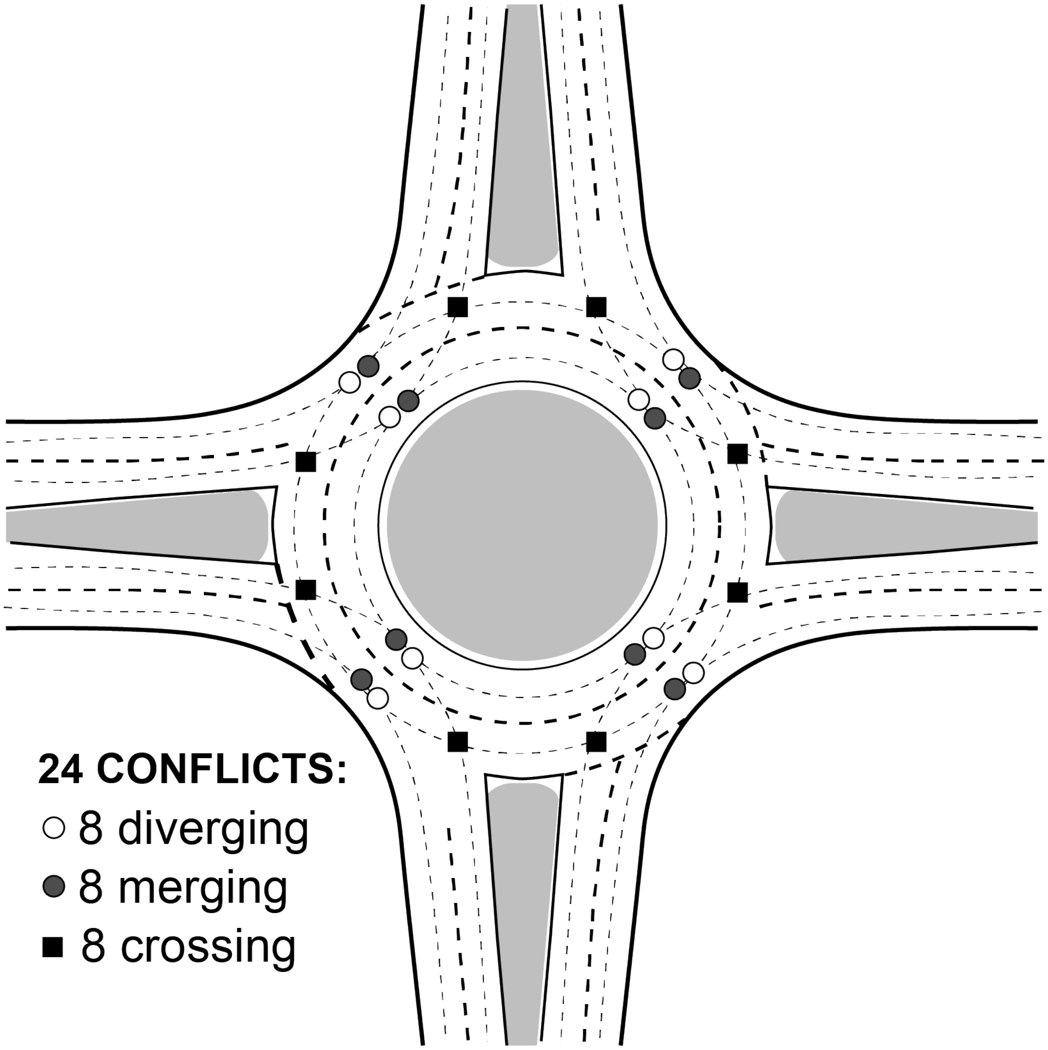


Figure 3. Graphic. Conflict point frequency for multilane roundabouts. Image based on Vasconcelos et al., 2014.[1]

[1] Gustafson (2018) offered new definitions for conflict point types that he concludes are more universally applicable to roundabout conflict areas: 1) crossing conflict: a conflict point where two through movements intersect, with two input traffic streams and two output traffic streams, 2) joining conflict: a conflict point where a through movement terminates at another through movement, with two input traffic streams and one output traffic stream, and 3) separating conflict: a conflict point where a through movement originates by departing from another through movement, with one input traffic stream and two output traffic streams.

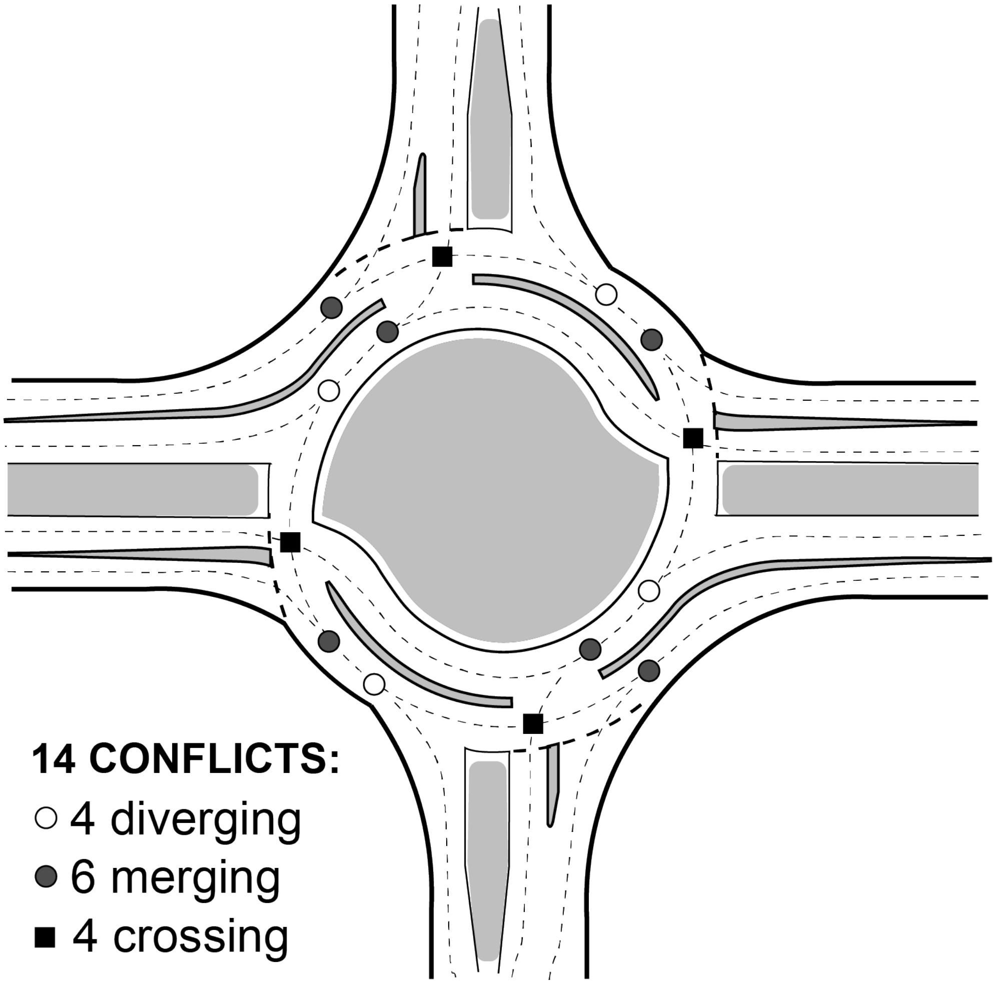


Figure 4. Graphic. Conflict point frequency for turbo roundabout. Image based on Vasconcelos et al., 2014.

Fortuijn (2009b) described five common turbo roundabout geometries (see figure 5 through figure 9): the basic, knee, egg, spiral, and rotor. All, through different center island geometry, reinforce the key turbo roundabout principles and features, and reduce conflict points. Variants shown in the figures include:

- Egg – similar to a basic turbo roundabout, but with only one approach lane on minor approaches.
- Basic – inside lane added on major approaches, two lanes on each approach.
- Knee – the inside lane is only added on one approach, two lanes on each approach.
- Spiral – three circulatory lanes, inside lane only added on two approaches, two approaches with three lanes and two approaches with two lanes.

- Rotor – three circulatory lanes, inside lane added on each approach, three lanes on each approach.

International experience suggests turbo roundabouts are adaptable to the U.S. context. Adoption of the turbo roundabout in the U.S. should resolve some of the issues at multilane roundabouts, providing an effective roundabout solution for higher-volume intersections. The goal of this document is to synthesize existing published resources (e.g., reports, papers, presentations, videos, and tools) on the topic of turbo roundabouts from international and domestic sources. The synthesis is organized into three major sections: 1) geometric design, 2) capacity and operational performance, and 3) safety performance. The synthesis provides specifics regarding the treatment of various users, including motorists, pedestrians, cyclists, heavy vehicles, and motorcyclists. The synthesis also includes sections on education and public outreach approaches targeting non-technical audiences.

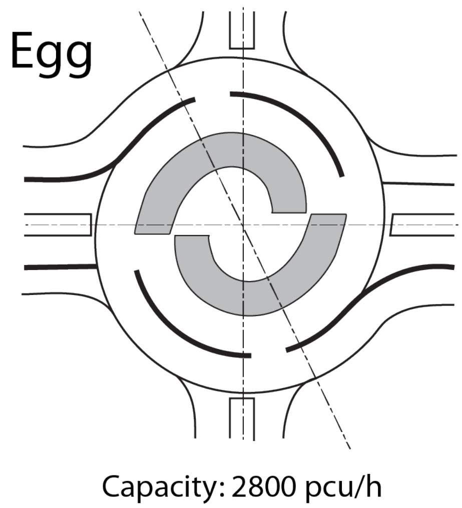


Figure 5. Graphic. Various turbo roundabout center island geometries: egg. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009b.

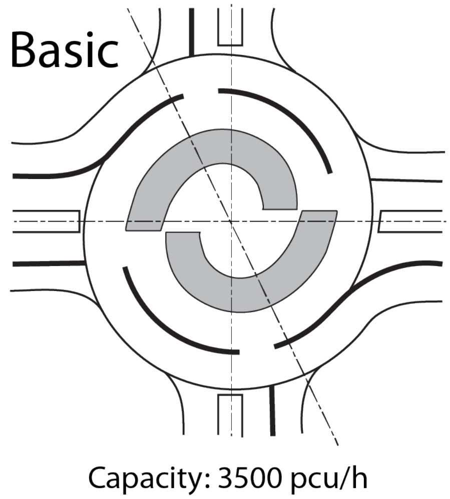


Figure 6. Graphic. Various turbo roundabout center island geometries: basic. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009b.

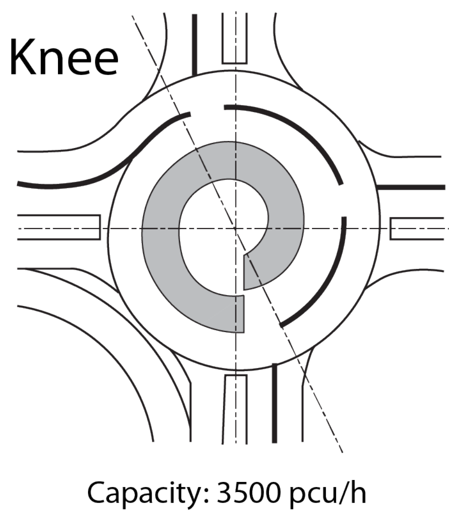
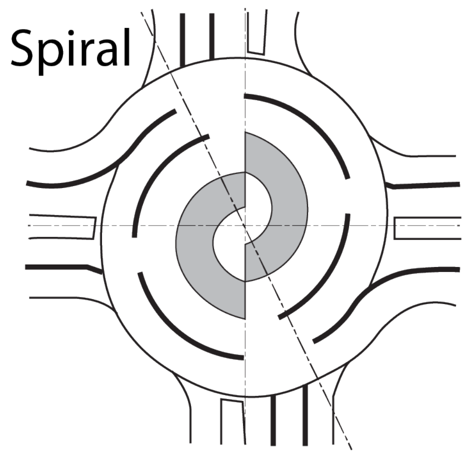
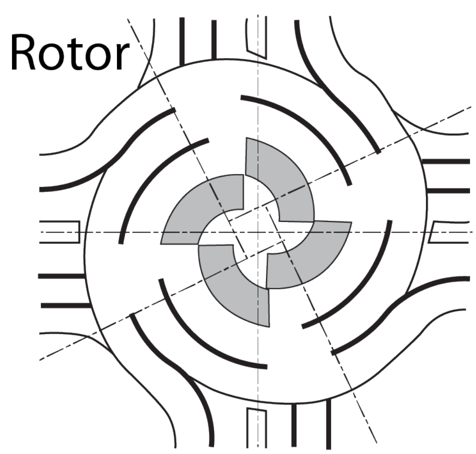


Figure 7. Graphic. Various turbo roundabout center island geometries: knee. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009b.



Capacity: 4000 pcu/h

Figure 8. Graphic. Various turbo roundabout center island geometries: spiral. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009b.



Capacity: 4500 pcu/h

Figure 9. Graphic. Various turbo roundabout center island geometries: rotor. Image based on Dzambas et al., 2017 with capacity value from Fortuijn, 2009b.

Geometric Design

The turbo roundabout was invented in the Netherlands in 1996 (Fortuijn, 2009b) with the initial design guidelines developed by the Dutch Information and Technology Platform (CROW, 2008; Overkamp & van der Wijk, 2009). These documents define turbo roundabouts by the following features:

- A turbo roundabout has at least two lanes for some portions of the circulatory roadway.
- The driver performs circulatory lane selection on the approach.
- The turbo roundabout entrances are yield control; yielding vehicles yield to no more than two lanes of conflicting traffic.
- Raised lane dividers within the circulatory roadway physically discourage weaving and lane changing.
- Exiting from the roundabout can only occur from the lane where the vehicle entered the roundabout.

Fortuijn (2009b) described these features, along with additional notable elements shown in figure 10.

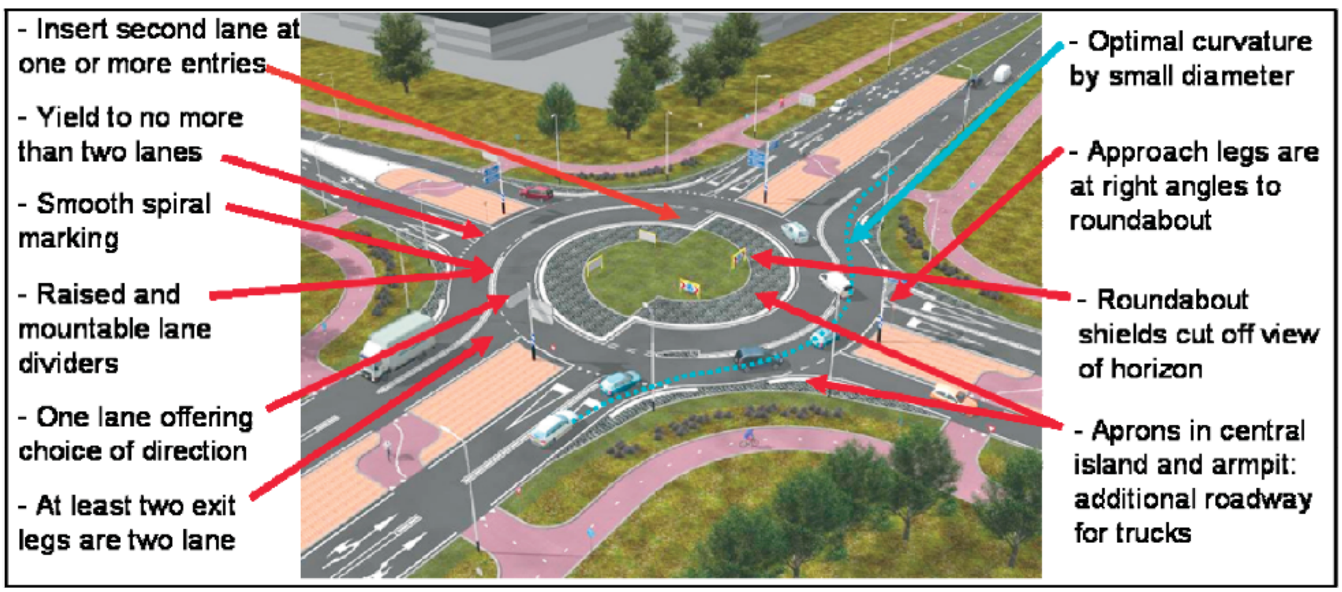


Figure 10. Graphic. Turbo roundabout features.

The geometric design of a turbo roundabout is governed by the horizontal swept path of a design vehicle and a fastest path analysis for a passenger car. The geometric design process consists of iterating through different combinations of the inner radius, cross section elements, and spirals within the turbo block. Designers select the inner radius value, lane widths, edgeline offsets, and lane divider widths, and then design the radii that produce the desired spirals. Designers perform swept path analyses with the selected design vehicle. If there is a violation in the swept path analyses (the wheel track of the design vehicle leaves the designated travel lane), designers adjust the inner radius and/or cross-sectional elements as needed and the turbo block is redesigned.

Inner Radius

The inner radius, R1 in figure 11, serves as the radius of the central island, the radius of the inside travel lane, and is the base value for the rest of the geometrics in a turbo roundabout. In principle, the smaller the inner radius, the lower the speed with which a vehicle will navigate the roundabout. Dzambas et al. (2017) found standard inner radius values for the Netherlands, Slovenia, and Serbia, of 10.5 m (34.4 ft) for a “mini” turbo roundabout, 12 m (39.4 ft) for a “regular” turbo roundabout, 15 m (49.2 ft) for a “medium” turbo roundabout, and 20 m (65.6 ft) for a “large” turbo roundabout. Croatian values were found to be 0.05 m less for the mini, medium, and large designs.

Turbo Block

Turbo roundabouts create a smooth, spiraled vehicle path by shifting the centers of the radii defining the locations of the inside and outside lanes along a translation axis. The combination of these circles and the translation axis is referred to as the turbo block (Fortuijn, 2009b). Figure 11 is an example of a turbo block for a basic four-leg, two-lane turbo roundabout.

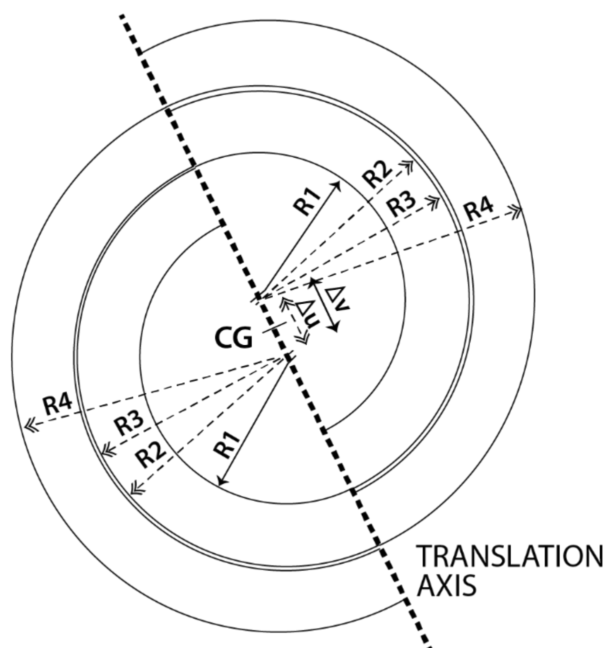


Figure 11. Graphic. Sample turbo block. Image based on Dzambas et al., 2017.

According to Fortuijn (2009b), the orientation of the translation axis is based on the major approaches (those with two lanes) and should provide similar curvature for all through vehicle movements. Overkamp and van der Wijk (2009) stated the correct position for a translation axis is where “the distance between the right edge of each entry leg and the inner curve of the outer lane of the roundabout after one quarter turn [are] more or less equal” (p.70). Dzambas et al. (2017) recommended an orientation of “five minutes until five” (right side is rotated 57.5-degrees around the center below the x-axis) for a four-leg intersection and “ten past eight” (the left side is rotated 65-degrees around the center below the x-axis) for a three-leg approach in situations where the major road is in an East-West orientation (x-axis). The translational axis should be rotated based on the orientation of the major road approaches. An additional check from Overkamp and van der Wijk (2009) is that the outside edge of the minor entrance should intersect the outside edge of the outer lane after the translation axis.

The turbo block in figure 11 contains four radii, where:

- R1 is to the inside edge of the inside lane.
- R2 is to the outside edge of the inside lane.
- R3 is to the inside edge of the outside lane.
- R4 is to the outside edge of the outside lane.

The difference between R1 and R2 is the width of the inside lane plus the widths of the inside edgeline and the edgeline delineating the raised lane divider. The difference between R2 and R3 is the width of the lane divider. The difference between R3 and R4 is the width of the outside lane plus the widths of the edgeline delineating the raised lane divider and the outside edgeline. When meeting at the translation axis, R1 should eventually join with R2 and R3 should eventually join with R4. A close examination shows that R1 has a different arc center along the translation axis than R2, R3, and R4; the reason for this is the presumed difference in widths of the inside and outside lanes (Overkamp & van der Wijk, 2009). The distance between the arc centers on the two sides of the translation axis (e.g., distance between the centers for R1) is called the shift. The shift can differ for the R1 centers and the R2/3/4 centers. The shift for the R1 centers (Δv in figure 11) is equal to the distance between the inside edge of the inside lane and the inside edge of the outside lane. The shift for the R2/3/4 centers (Δu in figure 11) is the distance between the outside edge of the inside lane and the outside edge of the outside lane. If the inside and outside lanes are the same width, the shift value for all radii are the same ($\Delta v = \Delta u$). The location of the center points (also called the arc center biases) is half the distance of the shift from the center of the circle (point CG in figure 11) along the translation axis (Overkamp & van der Wijk, 2009).

Turbo blocks can differ across different types of turbo roundabouts. Overkamp & van der Wijk (2009) provide sample turbo blocks and related details for the star, rotor, and spiral turbo roundabouts. The basic principle is the same; a translation axis is needed for every spiral.

Cross Section Elements

The widths of the cross-section elements of a turbo roundabout, specifically the lane widths, are dependent on the selection of the design vehicle and the inner radius (R1). Guidance from Croatia, Slovenia, Serbia, and the Netherlands recommend wide enough lanes to prevent the design vehicle from tracking over the traversable apron or raised lane dividers in a swept path analysis (Dzambas et al., 2017, Croatian Design Guidance, Slovenian Design Guidance, Serbian Design Guidance, Overkamp & van der Wijk, 2009). Typically, the inside lane of a turbo roundabout is wider than the outside lane to provide more room for the design vehicle to maneuver around the smaller radius path.

Overkamp & van der Wijk (2009) note seven cross section elements that require a defined width:

1. Inner edgeline offset – the distance from the inside edge of the inner lane to the central island, including the inside edgeline pavement marking.
2. Inside lane width – width of the inside lane.
3. Divider inner line offset – the distance from the outside edge of the inner lane to the raised lane divider, including the outside edgeline pavement marking.
4. Raised divider width – the width of the raised lane divider.
5. Divider outer line offset – the distance from the inside edge of the outer lane to the raised lane divider, including the inside edgeline pavement marking.
6. Outside lane width – width of the outside lane.
7. Outer edgeline offset – distance from the outside edge of the outer lane to the edge of the roundabout, including the outside edgeline pavement marking.

The combined width of elements 1, 2, and 3 is considered the width of the inside roadway, while the combined width of elements 5, 6, and 7 is the width of the outside roadway. These values, combined with the inner radius, define R2, R3, and R4 as well as the shift for the turbo block. Overkamp & van der Wijk (2009) provide radii and cross section element widths for four standard inner radius values of a basic turbo roundabout. The design values, provided in table 2, are based on a two-axle truck with a three-axle semitrailer design. Dzambas et al. (2017) found Slovenia and Serbia guidance have the same values, while Croatia uses roadway widths that are 0.05 m wider, which translates to larger R4 values. Turbo roundabouts in the Czech Republic are typically much larger due to significantly larger minimum lane widths for the inside and outside lanes (inside lanes are 2 to 3 meters wider than other countries and outside lanes are 1 to 2 meters wider) (Smely et al., 2015; Skvain et al., 2017).

Table 2. Standard design values for basic turbo roundabouts in the Netherlands. Table based on Overkamp & van der Wijk, 2009.

Feature	Measurement in m [ft]	Measurement in m [ft]	Measurement in m [ft]	Measurement in m [ft]
Inner radius of the inner lane (R1)	10.5 [34.5]	12 [39.4]	15 [49.2]	20 [65.6]
Outside radius of the inner lane (R2)	15.85 [52.00]	17.15 [56.27]	20.00 [65.62]	24.90 [81.70]
Inner radius of the outside lane (R3)	16.15 [52.99]	17.45 [57.25]	20.30 [66.60]	25.20 [82.68]
Outside radius of the outside lane (R4)	21.15 [69.39]	22.45 [73.66]	25.20 [82.68]	29.90 [98.10]
Width, inside roadway	5.35 [17.55]	5.15 [16.90]	5.00 [16.41]	4.90 [16.08]
Width, outside roadway	5.00 [16.41]	5.00 [16.41]	4.90 [16.08]	4.70 [15.42]
Width, inside lane	4.70 [15.42]	4.50 [14.76]	4.35 [14.27]	4.25 [13.94]
Width, outside lane	4.35 [14.27]	4.35 [14.27]	4.25 [13.94]	4.05 [13.29]
Lane divider between driving lanes	0.30 [0.98]	0.30 [0.98]	0.30 [0.98]	0.30 [0.98]
Shift of inner arc centers along the translation axis	5.75 [18.87]	5.35 [17.55]	5.15 [16.90]	5.15 [16.90]
Shift of outer arc centers along the translation axis	5.05 [16.57]	5.05 [16.57]	4.95 [16.24]	4.75 [15.58]
Overrun area (truck apron) width	5.00 [16.41]	5.00 [16.41]	5.00 [16.41]	5.00 [16.41]
Fastest path speed for a passenger car in km/h [mph]	37-41 [23.0-25.5]	37-39 [23.0 – 24.2]	38-39 [23.6 – 24.2]	40 [24.8]

Central Islands

Central islands in turbo roundabouts are similar to central islands in modern roundabouts. They are bordered by a traversable apron. Dzambas et al. (2017) found differences in guidelines for the apron: Overkamp & van der Wijk (2009) recommend a width of 5 m and a design that allows vehicles longer than 22 m to travel through the inner lane. Croatia, Slovenia, and Serbia indicate the purpose of the apron is for emergency vehicles and for emergency stops, recommending values between 2.0 and 2.5 m. One specific use of the central island is considered important in the Netherlands, where the space is used to mount, what Fortuijn (2009b) calls a “roundabout shield” that serves two purposes: blocking the horizon and directing the driver to turn right. A sample roundabout shield is shown in figure 12. This sign is especially important as approaches to turbo roundabouts have a radial entry with no flare and come into the circle at a right angle. These signs convey a sense of obstruction to the driver (Fortuijn, 2009b). Fortuijn (2009b) noted that the sign “must be collision-friendly, and the central island of the roundabout must not be provided with a raised edge. A study of the literature shows that [these points are] not always appreciated by researchers from outside the Netherlands.”

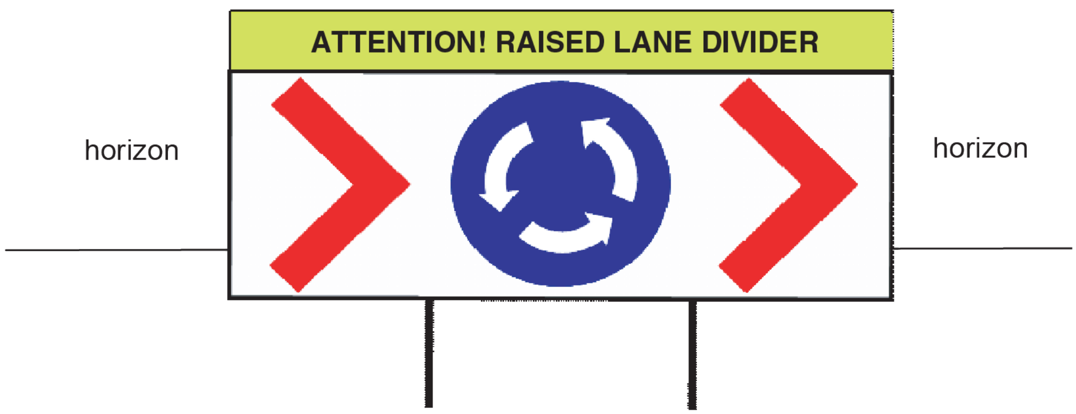


Figure 12. Graphic. Roundabout shield used in the Netherlands.

The geometry of the central island is affected by the addition of the inside lane at major approaches. Originally, this was done in the Netherlands using smooth curvature matching an entering vehicle’s path. However, this led to circulating vehicles entering the added lane, an undesired movement in turbo roundabouts. The country therefore adopted a flat lane addition approach (Overkamp & van der Wijk, 2009). The differences in the original and revised approaches to the inside lane addition are shown in figure 13 and figure 14.The shape of the central island will depend on the turbo roundabout type.

Figure 13. Photograph. Old design for starting the inner lane used in the Netherlands.

Figure 14. Photograph. New design for starting the inner lane used in the Netherlands.

Lane Divider

The raised lane divider is a key feature of turbo roundabouts and is a significant deviation from modern multilane roundabouts in the U.S. Overkamp & van der Wijk (2009) highlight the advantages of the raised lane divider, including reductions in weaving, operating speeds, and the number of conflicting traffic streams for some entering vehicles. The dividers should be sized and constructed to encourage the desired behavior from drivers, while still being mountable and forgiving to striking vehicles (Fortuijn, 2009b). Dutch lane dividers vary depending on needs. Overkamp & van der Wijk (2009) provided examples of lane dividers with no modifications and with modifications for snow plowing and intersections heavily trafficked by lowboys (or low-loaders). Figure 15 and figure 16 illustrate these examples. Though most countries who have adopted turbo roundabouts use them, some countries, such as Germany (Brilon, 2015) and Poland in some cases (Macioszek, 2015), choose not to use these dividers over concerns that include motorcycle safety, snow plowing, and maintenance. A review of materials for this synthesis did not uncover any formal evaluations to verify these concerns. The first known application of a turbo roundabout in North America at Victoria International Airport in Canada used a flat lane divider with a textured pavement treatment (see figure 17). The width in figure 17 is 1.2 meters from white line to white line.

Some countries, such as the Netherlands, Croatia, and Slovenia, include a widened, traversable object at the start of the lane divider. Overkamp & van der Wijk (2009) call this feature a “frog” and say its purpose is to call attention to the lane divider and prevent circulating vehicles from changing lanes. An example frog is pictured in figure 18. There are small differences in the specific dimensions across national guidelines (Dzambas et al., 2017).

Approach Geometry

For standard multilane roundabouts, NCHRP 672 defines three types of approach geometry:

1. Radial – the centerline of the approach intersects with the center of the roundabout.
2. Offset Left – the centerline of the approach passes through the roundabout to the left of the center.
3. Offset Right – the centerline of the approach passes through the roundabout to the right of the center.

Turbo roundabouts are constructed with radial approaches, which have the benefit of reducing changes to the alignment, minimizing roadway area, and maintaining exit curvature to keep vehicle speeds low through exiting the roundabout. Additionally, turbo roundabouts are built with little or no flare and minimal entry radius. Flare is provided in multilane roundabouts to provide adequate entry widths for the design vehicles; using a flare allows for lane width upstream to be kept at a standard width and minimizes the required right-of-way (ROW). The entry radius is typically increased in multilane roundabouts to ease the entry of design vehicles. Minimizing flare and entry radius allows turbo roundabout to achieve greater speed reductions than traditional multilane roundabouts.

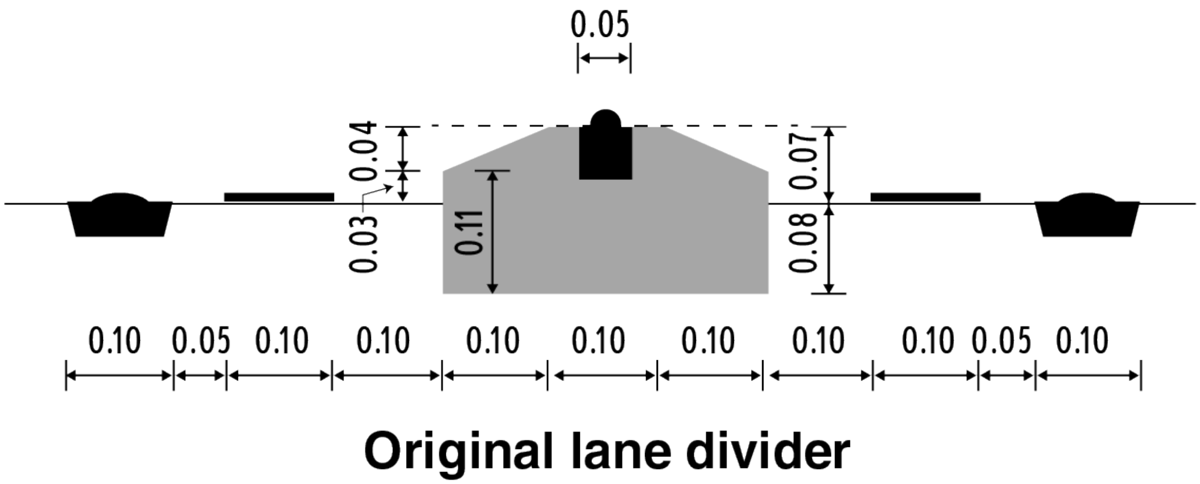


Figure 15. Graphic. Dutch designs of raised lane dividers with no modifications. Image based on Overkamp & van der Wijk, 2009. Note: all measurements in m.

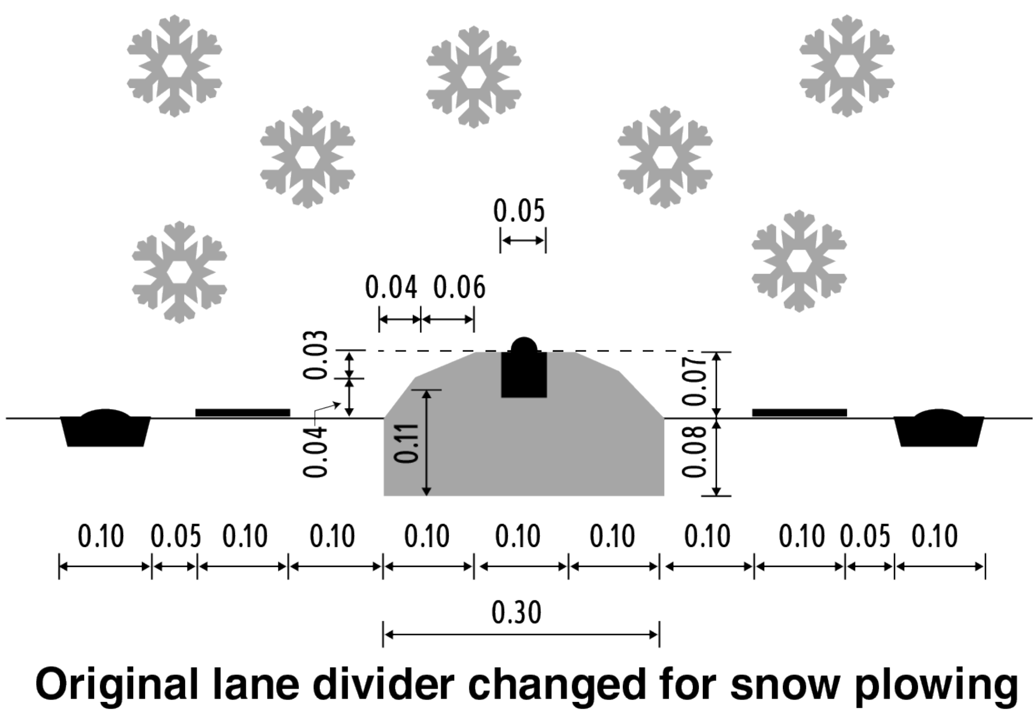


Figure 16. Graphic. Dutch design of lane dividers with modifications for snow plowing. Image based on Overkamp & van der Wijk, 2009. Note: all measurements in m.

Figure 17. Photograph. Lane divider for turbo roundabout at Victoria International Airport.

Figure 18. Photograph. Example “frog”.

Signing and Markings

Due to the turbo roundabout having no lane changes within the circulatory roadway, adequate and informative signing and pavement markings, especially on the approaches, are vital. Dutch guidelines recommend mimicking lane usage arrows on a guide sign 400 m prior to the roundabout entry; an example of the signage is provided in figure 19. This is followed by overhead lane signs supplemented with pavement markings 40 m from the roundabout entrance. Additionally, the Dutch guidelines encourage that the lane usage arrows (examples shown in figure 20 and figure 21) on the signs and the pavement markings be identical (Overkamp & van der Wijk, 2009). No lane use arrow pavement markings are required within the circulatory roadway, as the raised lane divider and spiral directs vehicles to their desired exits (Silva et al., 2013).

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Figure 19. Photograph. Example of guide signage to be placed upstream of a turbo roundabout.

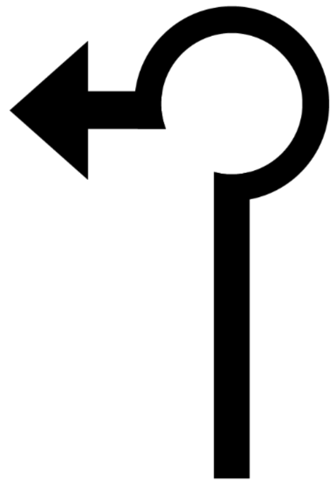


Figure 20. Graphic. Lane use arrows for turbo roundabout entry lane accommodating through and right turn movement as used in the Netherlands, Image based on Overkamp & van der Wijk, 2009.

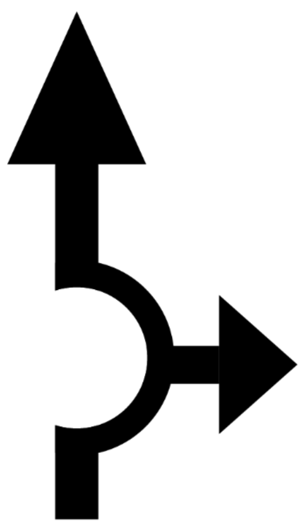
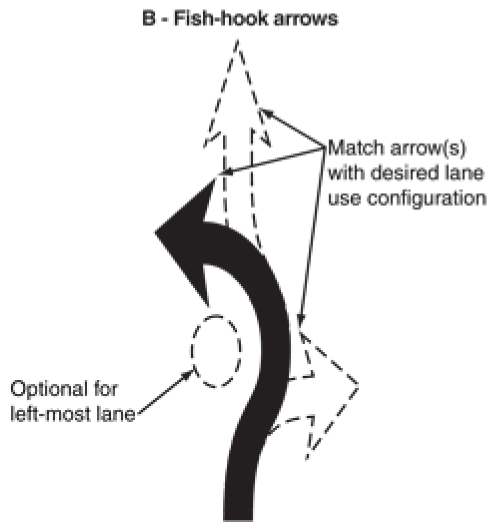


Figure 21. Graphic. Lane use arrows for turbo roundabout entry lane accommodating left turn movement as used in the Netherlands, Image based on Overkamp & van der Wijk, 2009.

Some countries do not use the Dutch arrow design, rather they use the “fishhook” design shown in figure 22, drawn from the U.S. *Manual on Uniform Traffic Control Devices* (FHWA, 2012). For instance, Poland does not have specialized turbo roundabout arrows and uses traditional intersection arrows at their roundabouts (Macioszek, 2013b). Wankogere et al. (2017) found that U.S. drivers in a simulator preferred the “fishhook” design over the Dutch arrow design, with 55.6 percent of drivers identifying fishhook pavement markings and 62.2 percent of drivers identifying fishhook signs as being “very easy to understand” (the responses for the Dutch arrow design were not reported).



Source: FHWA

Figure 22. Graphic. “Fishhook” lane use arrows for roundabout approaches.

User Considerations

Motorists

Motorist considerations have been addressed to some degree in the previous sections of this synthesis. A selected number of key points are summarized here. When entering a roundabout, drivers are required to 1) select the proper lane for their destination, and 2) yield to vehicles in the circulatory roadway. To make step 1 easier for drivers, designers provide signing and pavement markings along the approaches. Some research has been performed on driver lane-selection process in multilane roundabouts. Molino et al. (2007) found drivers in a simulation were more likely to choose the right lane when the right lane was required for the desired movement (95 percent) than the left lane (82 percent). A review of driver behavior at multilane roundabouts in Minnesota found drivers tended to select the outside lane regardless of the desired movement because the drivers expected to exit the roundabout from the outside lane (Leuer, 2016). For step 2 (yielding to drivers in the circulatory roadway), designers provide adequate sight distance for entering vehicles to identify conflicting vehicles in the circulatory roadway. Leuer (2016) found crashes caused by entering traffic failing to yield to circulating traffic to be common on multilane roundabouts in Minnesota.

Given the key operational characteristic of no lane changing within turbo roundabouts, signing and pavement markings to assist with lane selection on the approach is very important. Information should be provided to drivers far enough from the roundabout entrance to allow them to choose the proper lane. Wankogere et al. (2017) performed a simulator study with U.S. drivers to compare lane selection in turbo roundabouts and multilane roundabouts, finding that drivers chose the correct lane 93 percent of the time approaching turbo roundabouts compared to 81 percent approaching multilane roundabouts.

The radial entry also impacts motor vehicle navigation of the roundabout. Combined with the reduced approach curvature, vehicles arrive at turbo roundabouts nearly perpendicular to the circular roadway, rather than at an angle in modern roundabouts. As a result, a roundabout shield (see figure 12) is used to catch the attention of the driver and block the view of the horizon, guiding the driver to turn right (Overkamp & van der Wijk, 2009). The radial entry also reduces vehicle speeds as it requires both entering and exiting vehicles to navigate curvature, in contrast with an offset approach alignment (Rodegerdts et al., 2010).

Pedestrians

Accommodations for pedestrians at roundabouts are typically limited to the perimeter with crosswalks placed on the approaches with some offset from the circulatory roadway. Rodegerdts et al. (2010) recommend designing pedestrian facilities to discourage crossing to the central island, to minimize the crossing distance on the approaches, and to provide enough distance from the circulatory roadway to the crosswalks to allow drivers to focus separately on the vehicle-pedestrian and the vehicle-vehicle conflict. In addition, the authors provide the following guidelines:

- Provide a splitter island on each approach in line with the crosswalk with an appropriate width for the context, e.g., a minimum width of 6 feet for a two-stage accessible crossing.
- Place crosswalks at least one vehicle length from the circulatory roadway to prevent vehicle queues from spilling into the roundabout.
- Crosswalks can either be placed perpendicular to the curb line or to the centerline of the splitter island:
    - Perpendicular to the outside curb line produces the shortest individual lane crossing distances and better facilitates construction of sidewalk ramps that are compliant with the Americans with Disabilities Act (ADA).
    - Perpendicular to the approach minimizes total crossing distance but creates skew between the pedestrian path and vehicle path.
- The crosswalk path through the splitter island should be cut down to pavement height.
- ADA ramps should connect crosswalks to the sidewalk.
- Sidewalks along the perimeter should be separated from the roundabout by planter strips. The sidewalk path can either follow the curvature of the roundabout or have a direct connection between each approach's crosswalk.
- Sidewalks should have a minimum width consistent with the July 2013 NPRM version of the Public Right-of-Way Accessibility Guidelines (PROWAG) published by the U.S. Access Board.

Keeping pedestrian crossings on the approaches is also recommended for turbo roundabouts in the Netherlands (Fortuijn, 2003). The crossings consist of a splitter island of at least 3 m in width to provide adequate time for pedestrians to identify conflicting vehicles in the second stage of their crossing.

Cyclists

At a roundabout, a cyclist can either mix with motor vehicle traffic or, when available, utilize separated facilities. The decision as to which treatment is adopted is based on context, weighing factors such as cyclist volume, motor vehicle volume, complexity of the roundabout, adjacent infrastructure and land use, and available right-of-way.

In general, cyclists mixed with vehicular traffic should feel comfortable in roundabouts because vehicle speeds are typically slowed to a similar range as cyclists (Rodegerdts et al., 2010). NCHRP 672 includes the following guidelines for bicycle accommodation at roundabouts:

- Limit roundabouts to single-lane when possible because cyclists have issues with weaving vehicles in multilane roundabouts.
- Smaller radii can limit vehicle speeds which increases comfort for cyclists.
- Bicycle lanes on approaches should be terminated 100 ft before the edge of the circulatory roadway and before any crosswalks. Taper rates for ending the lane vary based on the width of the bike lane.
- On exit lanes, the taper to reintroduce the bike lane should begin after the crosswalk.
- If cyclists are to use the sidewalk, in most situations a minimum 10-foot-wide sidewalk is recommended. Bike ramps should be added where needed. Careful attention should be paid to differentiate between the ADA ramps and bike ramps.

In the Netherlands, separate cycle paths outside of the roundabout are recommended (Overkamp & van der Wijk, 2009). Modifications to the crosswalk and splitter island opening are often made by introducing a chicane to force cyclists to treat the crossing as a two-stage maneuver (see figure 23). When crossing, cyclists have the right-of-way in urban areas, while they must yield to vehicle traffic in rural areas (CROW, 1998). It is common to see grade-separated bicycle facilities in the Netherlands for higher speed multilane and turbo roundabouts with significant pedestrian and/or cyclist volume; an example is provided in figure 24, which contrasts the at-grade crossing in figure 23 (Overkamp & van der Wijk, 2009).

Figure 23. Photograph. Example of a chicane in a splitter island to encourage cyclists to perform a two-stage crossing.

Figure 24. Photograph. Example of a grade separated bicycle facility at a turbo roundabout in South Holland.

Motorcyclists

While roundabouts are beneficial from a motorist safety perspective because they reduce vehicle speeds and the frequency of conflicts, motorcyclists require additional attention with regards to roundabout design. Even low speed crashes involving a motorcycle can result in a serious or fatal injury, especially when riders do not use a helmet or other personal protective equipment. Between 2008 and 2012, motorcyclists accounted for 25 percent of all serious and fatal injuries at roundabouts in Victoria, Australia (Beer et al., 2014). Roadway features that can have a significant impact on motorcycle safety performance at roundabouts include curbing presence/location, surface friction, pavement markings, drainage, sight distance (especially rider conspicuity), radii, the roadside environment, and surface conditions.

Milling et al. (2016) described some issues pertaining to roundabouts that can be harmful to motorcyclists. These included wet pavement from sprinkler systems for landscaping on the central island or the perimeter, curbing on the roundabout, adverse crown on the circular roadway, insufficient surface friction (motorcyclists need to “lean” to navigate the geometry of a roundabout), and a lack of design features on the approaches that are tailored to slowing motorcycle speed. Roundabout features that make them more suitable for motorcycles include more forgiving roadsides (include flexible and breakaway signage), a mountable curb when curb is required, high-friction pavement, and adequate superelevation (Beer et al., 2014).

The most applicable motorcyclist concern with respect to turbo roundabouts is the presence of curbing, as curbing is used for the raised lane divider. As mentioned previously, Germany does not include the raised lane divider in their turbo roundabouts (Brilon, 2015) because of concerns for motorcyclists. Some turbo roundabouts are accompanied by signs warning motorcyclists of raised lane dividers within the roadway; the signs are provided 50 meters upstream of the turbo roundabout and are repeated in the central island (CROW, 2008; Overkamp and van der Wijk, 2009).

Freight

The geometric design of roundabouts is often based on a large design vehicle, such as a single-unit truck or multi-unit tractor-trailer combination. Such designs may involve a combination of a larger diameter and/or wider lanes. However, overly generous geometry may encourage higher operating speeds, countering the speed management goals of roundabouts. Therefore, designers seek to balance speed management with accommodating larger vehicles. To achieve a balanced design, modern roundabouts may include a mountable apron along the perimeter of the central island, and sometimes along the radius returns between adjacent legs, which allow vehicles longer than the design vehicle additional room to maneuver when necessary (Rodegerdts et al., 2010).

For the design of turbo roundabouts, most countries seek to design the turbo roundabout so that the wheel path of the design vehicle does not leave the designated travel lane in a swept path analysis (Dzambas et al., 2017). However, turbo roundabouts still provide traversable aprons, along with a “frog” at the beginning of the raised lane divider, to provide forgiveness to vehicles larger than the design vehicle.

Capacity and Operational Performance

The ability to estimate the capacity of turbo roundabout alternatives under U.S. driving conditions will be key to their consideration and adoption. Capacity is "the maximum sustainable hourly flow rate at which persons or vehicles can reasonably be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions" (Transportation Research Board, 2016, p.9-4). The capacity of a roundabout is defined by the capacity of each entering lane. Currently, there are several different methods for determining roundabout capacity. NCHRP Synthesis 488, with 36 responding States, documents use at the time the research was performed. Familiarity with the fundamentals of these various approaches will help with interpreting analyses specific to turbo roundabouts that are reported in the literature to-date.

Analysis of Turbo Roundabouts

Fortuijn and Harte (1997) made initial efforts to estimate turbo roundabout capacity by modifying a capacity model developed by Bovy (1991) to account for distribution of traffic between the circulating lanes in a multilane roundabout (see Figure 25). The Dutch multilane roundabout explorer, *Meerstrooksrotondeverkenner,* incorporated this initial work. Capacity values for various roundabouts and other intersection control types, estimated using these approaches with adjustment factors from Bovy (1991), are provided in table 3.

$$C = \frac{1}{\gamma} * [1500 - \frac{8}{9} * \left(\beta * v_{conflict} \; + \alpha * v_{exit}\right)$$

Figure 25. Equation. Capacity equation. Image based on Bovy, 1991.

Where:

γ = adjustment factor for entry capacity, changes with the number of circulating lanes.

β = adjustment factor for circulating flow, changes with the number of circulating lanes.

α = adjustment factor for exiting traffic, changes as a function of distance along the circulatory roadway between the exiting and entering conflict points.

v_{exit} = traffic volume exiting at the subject approach, in vehicles per hour.

Table 3. Approach capacity comparison table. Table based on Overkamp & van der Wijk, 2009.

Type of roundabout/intersection	Practice capacity[2] in peak hour (+/- 10% of AADT), all entries combined	Theoretical capacity[3] in peak hour (+/- 10% of AADT), all entries combined	Conflicting Traffic[4], $v_{predicted}$
Single-lane roundabout	2,000	2,700	1,350 to 1,500
Multilane roundabout with single entry and exit lane	2,200	3,600	1,500 to 1,800
Multilane roundabout with two entry lanes and single exit lane	3,000	3,600	1,800 to 2,000
Multilane roundabout with two entry and exit lanes	3,500	4,000	2,100 to 2,400
Turbo roundabout with two entry and exit lanes (basic design)	3,500	3,800	1,900 to 2,100
Spiral roundabout	4,000	4,300	2,000 to 2,300
Rotor roundabout (three entry lanes and two exit lanes)	4,500	5,000	2,500 to 2,800
Signalized roundabout (3'2 entry lanes)[5]	8,500	11,000	4,200
Minor road stop- or yield-controlled intersection with left turning lane	1,500	1,800	1,100
Four-leg intersection with traffic signals (entries 3'1 travel lanes)	3,500	4,000	3,800
Four-leg intersection with traffic signals (entries 3'2 travel lanes)	7,500	8,000	3,800

[2] Field observed capacity values under peak hour operations, in passenger cars per hour.
[3] Calculated assuming a ratio of 5 to 2 for major road volume to minor road volume (3 to 2 for spiral and rotor roundabout) and for every three through-vehicles on an approach, one turns left and one turns right. Measured in passenger cars per hour.
[4] Measured in passenger cars per hour.
[5] 3'2 entry lanes implies there are 3 lanes on the major road approaches and 2 lanes on the minor road approaches.

The capacity model was updated by Fortuijn (2009a), who wanted to account for the nonlinear relationship between circulating flow and entry capacity while incorporating the effect of pseudoconflicts. He did this by adding a proportion of exiting traffic to the conflicting volume at the entry, as shown in figure 26 (Rodegerdts et al. [2015] would later mimic this approach with U.S. data). Fortuijn (2009a) asserted that incorporating this effect into the Hagring (1998) model results in a good basis for turbo roundabout capacity models. The Hagring model Fortuijn referred to is described in figure 27.

$$v_{conflict\ \ with\,pseudo} = v_{conflict} + d * v_{exiting}$$

Figure 26. Equation. Modified conflicting traffic volume including the pseudoconflict of exiting vehicles.

Where:

$v_{conflict\ with\ pseudo}$ = the modified conflicting traffic in the circulatory roadway, incorporating the effect of pseudoconflicts.

d = proportional effect of exiting traffic.

$$C = 3600 * \sum_i \left[\frac{\varphi_c * v_{conflict\ ,i}}{1 - v_{conflict\ ,i} * t_{M,i}}\right] * \prod_i \left(1 - v_{conflict\ ,i} * t_{M,i}\right) * \frac{e^{-\sum_i \left(\frac{\varphi_c * v_{conflict\ ,i}}{1 - v_{conflict\ ,i} * t_{M,i}}\right) * (t_{c,i} - t_{M,i})}}{1 - e^{-\sum_i \left(\frac{\varphi_c * v_{conflict\ ,i}}{1 - v_{conflict\ ,i} * t_M}\right) * \frac{3600}{t_{f,i}}}}$$

Figure 27. Equation. The Hagring (1998) capacity model for a roundabout entry lane.

Where:

i = index for the circulatory lane (the sum and product operations should be repeated for each circulatory lane).

$t_{M,i}$ = the minimum headway between free circulating vehicles in circulatory lane *i.*

Fortuijn (2009a) compared observed capacity under saturated conditions in 5-minute intervals at a single-lane roundabout entry with a predicted value at the entry, calculated using the Troutbeck (1984) model. The author used least-squares regression to estimate passenger car equivalents (pce) for light trucks (1.9 pce), heavy trucks (2.4 pce), and the proportional effect of exiting traffic, which was found to range from 0.2 to 0.5. It should be noted that the larger the proportional effect of exiting traffic, the smaller the entry capacity.

Fortuijn (2009a) observed driver behavior on approaches of various orientations at single-lane, multilane, and turbo roundabouts and used these observations to calibrate a microsimulation in VISSIM. Calibration of the microsimulation was implemented using accepted and rejected gaps, follow-up times, and headways in the conflicting traffic stream. After calibrating the simulation, the author found four notable results:

1. Circulating traffic volume has a significant effect on the critical gap within the simulation.

2. The relationship between circulating traffic and entry capacity was linear for single-lane roundabouts and nonlinear for turbo roundabouts.
3. Vehicle distribution between circulating lanes in multilane roundabouts influences approach capacity.
4. Capacity models should consider each circulating lane separately.

Fortuijn and Hoogendoorn (2015) revisited gap acceptance-based capacity models for turbo roundabouts. The authors applied modifications to the Hagring (1998) model, adjusting for variance in driver behavior, the non-exponential distribution of gaps in the circulatory roadway, and correlation in gaps between lanes in the circulatory roadway. The authors also pointed out that Germany sees poor utilization of the left-entry lane in multilane roundabouts, and that drivers are more likely to use this entry lane the longer they will travel within the roundabout, meaning they are most likely when making a left turn and least likely when making a right turn (Brilon and Baumer, 2004). The authors noted Dutch and German turbo roundabouts have higher entry capacities than German multilane roundabouts because of higher left-lane usage.

Other authors would go on to adopt the Hagring model for turbo roundabouts as well (Giuffre et al., 2012; Savric and Lovic, 2017). Silva et al. (2014) used the Hagring model, with M3 distribution parameters calibrated to Portugal by Vasconcelos et al. (2012), to compare turbo roundabouts and multilane roundabouts in a Portuguese context, concluding that turbo roundabouts only show increases in capacity over multilane roundabouts when the proportion of right turns from a minor approach is greater than 60 percent of the approach volume.

Not all turbo roundabouts capacity evaluations employed the Hagring model. Mauro and Branco (2010) estimated turbo roundabout capacity by adapting the capacity formula developed by Brilon and Wu (2006), which is described in figure 28, to turbo roundabout conditions. For each approach, the authors used the capacity model for the relevant number of conflicting lanes. For right-lane entries, the number of conflicting lanes is one and the conflicting traffic is the circulating traffic in the outside lane. The equation varies for left-lane entries. On approaches where the inside lane is created across from the approach (typically a major approach), there is one conflicting lane and conflicting traffic is the circulating traffic in that lane. For left-turn lanes where the inside lane is already present, the number of conflicting lanes is two and the conflicting traffic is the total of circulating traffic in the outside lane and inside lane. Fixed values were used for follow-up time and minimum headways; it is unclear where these values came from. The authors found that multilane roundabouts provide higher approach capacity than turbo roundabouts for major road approaches, while turbo roundabouts provide higher approach capacity when most of the circulating traffic is in the inside lane.

Tollazzi et al. (2016) also adopted this approach to model turbo roundabouts when performing a comparative analysis of innovative roundabout types; they determined turbo roundabouts perform best when most entering vehicles are turning right.

$$C = 3600 * (1 - \frac{t_{min} * v_{conflict}}{3600 * n_c})^{n_c} * \frac{n_e}{t_f} * e^{-\frac{v_{conflict}}{3600} * (t_c - \frac{t_f}{2} - t_{min})}$$

Figure 28. Equation. Roundabout capacity model. Image based on Brilon and Wu, 2006.

Where:

n_c = the number of conflicting lanes at the entry.

t_{min} = minimum headway between vehicles in the circulating lane, in seconds.

Macioszek (2016) used the appropriate HCM equation for each scenario on the turbo roundabout, and, compared with Polish-calibrated capacity equations (Macioszek, 2013a) that are based on Tanner (1962), found the HCM produced reasonable estimates of turbo roundabout capacity compared to Polish models.

Driver Behavior on Turbo Roundabouts

Little research has been done outside of the Netherlands to assess driver behavior at turbo roundabouts. Guerrieri et al. (2018) observed traffic flows at a turbo roundabout in Maribor, Slovenia, and found average critical headways ranging from 4.03 to 5.48 seconds and average follow-up headways ranging from 2.52 to 2.71 seconds. As a basis for comparison, Rodegerdts et al. (2015) founded average critical headways of 4.9 seconds for single-lane roundabouts and ranging from 4.3 to 5.5 seconds for multilane roundabouts; they found average follow-up times of 2.6 seconds for single-lane roundabouts and ranging from 2.1 seconds to 2.7 seconds for multilane roundabouts. Fortuijn (2009a) and Fortuijn and Hoodendoorn (2015) used differing critical headway and follow-up times in their turbo roundabout analyses depending on if it was a major or minor approach and if it was the left or right lane. These are shown in table 4. These are likely lower because Dutch drivers are generally more experienced and comfortable using roundabouts.

Table 4. Values used for gap acceptance. Table based on Fortuijn, 2009a; Fortuijn & Hoodendoorn, 2015; Saric & Lovric, 2017.

Entry Lane Approach	Major Direction Left	Major Direction Right	Minor Direction Left	Minor Direction Right
Critical gap—t_c (s)	3.55	3.80	3.15	3.70
Follow-up time—t_f (s)	2.30	2.30	2.25	2.80

Wankogere et al. (2017) used a driving simulator study to compare U.S. driver behaviors in multilane roundabouts with turbo roundabouts. The study consisted of 46 participants navigating multilane and turbo roundabouts with different signing and pavement marking schemes. The study found that, in turbo roundabouts, a minimum of 92.5 percent of drivers selected the correct lane on the approach compared with 81.4 percent for a multilane roundabout. This is important for two reasons. First, with nearly 20 percent of drivers selecting the wrong lane for a multilane roundabout, weaving within the circulatory roadway is likely to arise, which can lead to crashes and reduced capacity. Second, the increase in correct lane selection for the turbo roundabouts shows the effectiveness of good signing and lane marking schemes on the approach, as well as limits issues with lane changing in the roundabout, which are restricted due to the presence of raised lane dividers.

Summary of Turbo Roundabout Traffic Operations Research

Overall, it appears the identified capacity research for turbo roundabouts is based on evaluating the ability of existing gap acceptance capacity models to estimate turbo roundabout capacity. These models can be calibrated to local conditions using observed driver behavior characteristics, such as critical gap, follow-up time, and bunching of circulatory vehicles. Several of these studies stated that, at least in some conditions, turbo roundabouts have higher capacity than multilane roundabouts, although the difference is not substantial (Bulla and Castro, 2011; Fortuijn and Hoogendoorn, 2015; Giuffre et al., 2012; Mauro and Branco, 2010; Saric and Lovric, 2017; Silva et al., 2014). Most likely, this arises from the lane dividers within the circulatory roadway, which limit lane changing within the roundabout and reduce the number of conflicting vehicles that a portion of entering vehicles need to concern themselves with. Having to only focus on one circulating lane is important, as the HCM 6th edition states "some drivers who choose to enter the roundabout via the right entry lane will yield to all traffic in the circulatory roadway due to their uncertainty about the path of the circulating vehicles" (p.22-25). With raised dividers between the inside and outside lane of the circulatory roadway, drivers entering from the right entry lane can confidently only search for gaps in the outside circulating traffic.

Another potential reason for improved capacity in turbo roundabouts could be the right-angle approach of entry lanes. Skewed entries, particularly for older drivers, can present challenges when assessing gaps (Staplin et al., 2001). It is not unreasonable to expect that a less skewed approach may see higher capacity as it will be easier for drivers to judge gaps. A third reason for the higher capacity could be better utilization of the inside lane by movements for which it is an option. Turbo roundabouts have tighter entry radii values, which, according to the U.K. models, will result in lower capacity because of the associated decrease in entry speeds. With these counterbalancing effects in place, HCM approaches for multilane roundabouts, with conflicting vehicle counts specific to the turbo roundabout, will likely result in reasonable estimates for the first turbo roundabouts in the U.S. as demonstrated in Poland by Macioszek (2016).

Safety Performance

Modern roundabouts have a well-documented history of reducing crash frequency and severity at intersections upon installation (Rodegerdts et al., 2010). Traditional four-leg intersections have 32 vehicle-vehicle conflict points, while modern single-lane roundabouts have 8 vehicle-vehicle conflict points. Where a single-lane roundabout does not provide sufficient capacity, multilane roundabouts can be considered. As discussed in the introduction to this synthesis, some constructed multilane roundabouts have experienced higher frequency of low severity crashes. The introduction also provided multiple reasons for this observation centered around an analysis of conflict points and driver behavior. The remainder of this section focuses on safety performance of turbo roundabouts in general, and relative to multilane roundabouts, based on analyses of crash data and safety surrogates.

Evaluation of Crash Data

Because turbo roundabouts are relatively new, observational study designs and statistical analyses of crash data on turbo roundabouts are limited both in quantity (i.e., few studies have been performed with few sites) and quality (with regards to whether they used more reliable methodologies described by Gross et al., 2010). Fortuijn (2009b) performed a before-after analysis of seven intersections with varying traffic control (signalized, stop-control, yield-control, and old-style rotary) that had been converted to single lane and turbo roundabouts. After accounting for priority selection (the improved sites had a history of elevated crash frequency compared to the national average), national safety trends, and the effects of statistical averaging, Fortuijn (2009b) found that converting from yield-control, signalized, or old-style rotary to a turbo roundabout reduced injury crashes by 76 percent. The sample size, however, was limited to only seven sites and Fortuijn (2009b) noted that the precise reduction in the frequency of injury crashes after installing a turbo roundabout is still uncertain.

Another evaluation of crash data at turbo roundabouts investigated the impact of the raised lane divider on crash types. Macioszek (2015) compared observed crashes at turbo roundabouts in Poland with raised lane dividers with observed crashes at turbo roundabouts in Poland with lanes divided by solid white lines. Table 5 provides Macioszek's (2015) reported differences between the distribution of crash types on turbo roundabouts with and without the raised lane divider. With no raised lane divider, percentages showed that sideswipe crashes accounted for more than half of the crashes at the intersections. While turbo roundabouts with raised lane dividers saw a lower proportion of crashes that are sideswipe, those in Macioszek's (2015) sample saw larger percentages of fixed object crashes, which were related to the presence of raised lane dividers. Another difference noted by Macioszek (2015) is the different distributions of observed injury outcomes. Turbo roundabouts with raised lane dividers showed that 45 percent of injured persons were classified as "seriously injured" and 55 percent were classified as "slightly injured." At turbo roundabouts with solid painted lines dividing the lanes, 65 percent of injured persons were classified as "seriously injured" and 35 percent were classified as "slightly injured". Both intersections had similar distributions of crash contributing factors, with a plurality of crashes attributed to failure to yield the ROW. Additionally, while the authors presented no supporting data in the paper, their conclusion states that turbo roundabouts without the raised lane dividers had a higher crash frequency than those with a raised lane divider.

Table 5. Differences in percent of total intersection crashes by type on turbo roundabouts with raised and painted lane dividers. Table based on Macioszek, 2015.

Crash Type	Raised Lane Divider (% of total)	Solid White Line (% of total)
Sideswipe	24	56
Hit Fixed Object	30	6
Vehicle-Pedestrian	0	2
Overturn	5	1
Rear End	33	34
Other	8	1

Kiec et al. (2018) used traffic and crash data from nine turbo roundabouts in Poland to estimate a safety performance function (SPF). Average annual daily traffic (AADT) volumes at these turbo roundabouts ranged from 5,000 to 26,530 vehicles per day. Five of the turbo roundabouts had a raised lane divider and four did not. The authors used four years of data to estimate the models. They estimated SPFs for all crashes (i.e., all types and severities) and for PDO crashes of all types. Figure 29 and figure 30 represent the SPFs estimated from the data. Kiec et al. (2018) also tried to include average vehicle speed in the model, but it proved not to be statistically significant at the 90-percent confidence level. A review of the equations shows that, for a given traffic volume, the lack of a raised lane divider is associated with 59-percent more total crashes and 64-percent more PDO crashes when compared to a turbo roundabout with a raised lane divider.

$$N_{PR,All} = -7.707 * AADT^{0.884} * e^{(0.461*NoDivider)}$$

Figure 29. Equation. SPF for all crashes on turbo roundabouts in Poland. Image based on Kiec et al., 2018.

$$N_{PR,PDO} = -7.369 * AADT^{0.841} * e^{(0.492*NoDivider)}$$

Figure 30. Equation. SPF for PDO crashes at turbo roundabouts in Poland. Image based on Kiec et al., 2018.

Where:

$N_{PR,\ All}$ = the number of annual predicted crashes at a turbo roundabout, in crashes per year.

$N_{PR,\ PDO}$ = the number of annual predicted PDO crashes at a turbo roundabout, in crashes per year.

AADT = annual average daily traffic entering the roundabout, in vehicles per day.

NoDivider = indicator variable for the lack of raised lane divider; 1 if no raised lane divider, 0 otherwise.

Safety Surrogates

Some researchers have evaluated turbo roundabout safety performance using alternative measures of safety, or safety surrogates. For example, Vasconcelos et al. (2013) used microsimulations of roundabouts developed in AIMSUN and the Surrogate Safety Assessment Model (SSAM) to compare the safety performance of single-lane, two-lane, and turbo roundabouts. SSAM utilizes vehicle trajectories from microsimulation models (such as AIMSUN) to predict crash frequency at a location as a function of traffic conflicts per hour (Gettman et al., 2008). For their turbo roundabout analysis, Vasconcelos et al. (2013) used time-to-collision to determine if an event would be classified as a conflict (the threshold was typically less than or equal to 1.5 seconds). Once a conflict was identified, potential severity was estimated as a function of the difference in vehicle speeds. The three roundabout types proposed for a subject intersection in Coimbra, Portugal were modeled using this technique, finding that the turbo roundabout had the fewest predicted daily conflicts and a lower percentage of severe conflicts than the multilane roundabout.

Bulla-Cruz and Barrera (2016) also used SSAM to compare safety performance between a two-lane roundabout and turbo roundabout. The authors built a microsimulation of an existing two-lane roundabout and a proposed turbo roundabout at the same intersection in Bogota, Colombia using VISSIM. After calibrating the microsimulation to the observed conditions at the existing two-lane roundabout, the authors found the turbo roundabout was predicted to have 72-percent fewer conflicts than the two-lane roundabout.

Mauro et al. (2015) took a different approach to conflict analysis that they based on the “potential conflict” approach developed by Ha & Berg (1995). The process consists of identifying all maneuvers required by vehicles to traverse an intersection and identify which maneuvers could result in a crash given certain traffic conditions. The method had been previously extended to single-lane and multilane roundabouts (Mauro & Cattani, 2004; Mauro & Cattani, 2005). After reviewing crash data for single-lane and multilane roundabouts, Mauro et al. (2015) identified four conflicts at roundabouts and how to calculate the potential conflicts that can occur:

1. Failure to yield to circulating traffic with or without stopping.
    a. The number of expected conflicts at an entry is a function of entering volume, the probability of a driver attempting to enter, circulating traffic volume, and the probability of the accepted gap between circulating being “dangerous”, which the authors described as being between 3 and 5 seconds, or insufficient, which is 2 seconds or less.
2. Loss of control by an entering vehicle.
    a. The number of expected conflicts at an entry is a function of entering traffic volume, the probability of an entering vehicle losing control, and the probability of no circulating vehicles being present for the entering vehicle to collide with.
3. Rear-end on an approach.

    a. The number of expected conflicts at an entry is a function of entering traffic volume and the probability of a queuing vehicle failing to stop in time to avoid a rear end crash.
4. Crash when exiting a two-lane roundabout from the inside lane.
    a. The number of expected conflicts at an exit is a function of circulating traffic in the inside and outside lane, exiting traffic volume, and the number of gaps that could result in a collision, which are defined as 2 seconds or less.

Determining the number of crashes from the number of conflicts requires estimating a calibration factor (c_i) for each conflict type. In the method developed by Ha & Berg (1995), this is done by observing traffic flow and collecting traffic data for roundabouts. Observed traffic data can be used to tally the number of each conflict type. The number of observed crashes resulting from the conflict type divided by the number of conflicts is the calibration factor, as shown in figure 31.

$$c_i = \frac{N_{crashes,i}}{N_{conflicts,i}}$$

Figure 31. Equation. Calculation of calibration factor for conflict I. Image based on Mauro et al., 2015.

Where:

c_i = the calibration factor for conflict type *i.*

$N_{crashes,\, i}$ = the number of observed crashes at the intersection resulting from conflict type *i.*

$N_{conflicts,\, i}$ = the number of observed conflicts of type *i*.

Summing the number of predicted crashes, calculated as the product of the calibration factor (c_i) and the number of conflicts ($N_{conflicts,\, i}$) for each conflict type, results in the potential accident rate (PAR). Mauro et al. (2015) applied this methodology to compare the potential safety performance of two-lane and turbo roundabouts, with traffic volume based on assumed average annual daily traffic (AADT) values for each leg (10,000 vehicles per day on major legs and 2,000 vehicles per day on the minor legs) and using German roundabout capacity equations (FGSV, 2006). Known capacity is required for estimating the probability of a failure to yield crash occurring. Calibration factors for various crash types and severities were estimated using data from three single-lane and three multilane roundabouts in Italy; the calibration factors were applied to turbo roundabouts. Five combinations of origin-destination were developed to evaluate how differences in desired movements can affect safety performance. For the turbo roundabout, no conflicts were expected for the exiting conflict as the spiral allows all exits to occur from the outside lane. Across the many combinations of traffic distributions, the authors found that turbo roundabouts are expected to have 40- to 50-percent fewer total crashes and 20- to 30-percent fewer injury crashes than two-lane roundabouts. A sensitivity analysis with regards to traffic volume found that as traffic volumes increased, this difference is expected to increase.

Chodur and Bak (2016) used video data to compare driver behavior at seven turbo roundabouts in Poland with regards to both lane compliance and speed. For lane compliance, the authors reviewed vehicle trajectories to identify vehicles that made an incorrect movement or took an incorrect path. As mentioned previously, some turbo roundabouts are built with the raised lane divider while others are built without. Where the raised lane divider is present, some movements are highly unlikely and are usually limited to areas where the curb is not present. Overall, the results indicated noncompliant behaviors at turbo roundabouts are rare, illegal lane changes mainly occur at the exit area, and tracking over the lane divider is primarily limited to turbo roundabouts without the raised lane divider. The authors assume that fewer intrusions across lane lines will result in fewer related crashes within the circulatory roadway.

When analyzing speed, Chodur and Bak (2016) broke vehicle paths into five sections:

1. Approach.
2. Entry.
3. Conflict.
4. Circulating.
5. Exit.

Comparisons were drawn between speeds in the inside and outside lanes. On average across the seven turbo roundabouts, vehicles in the inside lane were observed traveling 5.0 km per hour (3.1 mph) faster than vehicles in the outside lane. This difference changed to 1.2 km per hour (0.75 mph) *slower* in the circulatory roadway, as expected given vehicles in the inside lane are required to traverse a tighter radius.

Keic et al. (2018) performed additional video analysis of turbo roundabouts in Poland with the goal of using vehicle speed as a safety surrogate measure. Kiec et al. measured vehicle speeds on the approach, entrance, circulatory roadway, and the exit for the nine study roundabouts. Average vehicle speeds for turbo roundabouts with raised lane dividers, without raised lane dividers, and incorrect vehicle paths when navigating turbo roundabouts without raised lane dividers were compared, with the lowest speeds generally occurring for turbo roundabouts with raised lane dividers. The authors then used three existing models for roundabouts that relate circulating vehicle speed to safety performance at a roundabout approach (see figure 32 through figure 34 and corresponding references). Based on these equations and the fact that vehicle speeds are, on average, higher on turbo roundabouts with no raised lane divider than those with raised lane divider, the authors concluded that turbo roundabouts without raised lane dividers can be expected to experience more crashes.

$$N_{PR,App} = 6.12 * 10^{-8} * v_{entering}^{0.47} * v_{conflict}^{0.26} * AS_{Conflict}^{2.13}$$

Figure 32. Equation. Crash prediction model for roundabout approaches in New Zealand. Image based on Turner et al., 2009.

$$N_{PR,All} = 7.70 * 10^{-8} * AADT^{0.5094} * AS^{4.3314}$$

Figure 33. Equation. Crash prediction model for roundabout approaches in the U.S. Image based on Chen et al., 2013.

$$N_{PR,All} = 1.50 * 10^{-13} * AADT^{2.8623} * AS^{0.6339}$$

Figure 34. Equation. Crash prediction model for roundabout approaches in Italy. Image based on Chen et al., 2013.

Where:

$v_{entering}$ = the entering vehicle flow at a roundabout approach, in vehicles per hour.

$N_{PR,\ App}$ = the predicted annual crashes for a roundabout approach, in crashes per day.

$v_{conflict}$ = the conflicting vehicle flow at a roundabout approach, in vehicles per hour.

AADT = annual average daily traffic, in vehicles per day.

$AS_{conflict}$ = the average speed of circulating conflicting traffic at the approach, in km per hour.

AS = the average speed of traffic for the subject roundabout approach, in km per hour.

Summary of Safety Findings

The turbo roundabout was developed outside the U.S. as an alternative to the traditional multilane roundabout to deal specifically with crashes observed at those roundabouts. With smaller radii and raised lane dividers, the reduced vehicle speeds and elimination of weaving was expected to produce fewer and less severe crashes. Though very little research based on an analysis of crash data has been done, it appears initial, but limited, findings supports these hypotheses. Fortuijn (2009b), Macioszek (2015), and Kiec et al. (2018) all showed turbo roundabouts provide improved safety performance compared to multilane roundabouts, specifically with regards to the benefits of the raised lane divider. Surrogate measures, whether derived from microsimulation (Vasconcelos et al., 2013; Bulla-Cruz and Barrera, 2016; Mauro et al., 2015) or field observations (Chodur and Bak, 2016; Kiec et al., 2018), also suggest turbo roundabouts are expected to produce fewer and less severe crashes than a comparable multilane roundabout.

Education and Public Involvement

Traditional public engagement typically focuses on the solution before providing the need; however, turbo roundabout design projects may benefit from a reverse approach. Given the unique geometry and limited knowledge of turbo roundabouts in the U.S., traditional public outreach methods for roundabouts will need to be modified for marketing turbo roundabouts. For guidance, the project team reviewed the education and outreach efforts as well as examples of video simulations where turbo roundabouts were initially introduced in the Netherlands and other countries. In countries outside the U.S., when turbo roundabouts are proposed, transportation agencies educate the public about the design through demonstrated success prior to implementation (or during project development) and ongoing education through the use of signage after installation.

Demonstrated Success

Demonstrating how to navigate a turbo roundabout design is key to gaining the public's acceptance of a turbo roundabout. Practitioners have used real-time video and computer-generated simulations to promote and educate turbo roundabouts to different audiences. These strategies are likely best used prior to project installation and throughout the project development phases.

Real-time video demonstrates to the public how different vehicles and traffic flows can navigate a turbo roundabout. Videos are typically captured by drone footage or traffic cameras and demonstrate real-world situations of different roadway users traveling through a turbo roundabout, illustrating the ease of navigation to the viewer. Real-time demonstrations are helpful for the public to view how traffic maneuvers in a turbo roundabout.

Transportation agencies have used real-time videos in Pula, Croatia, Rosmalen, Netherlands and Europe to illustrate the design and traffic flow through a turbo roundabout (Zgrablic, 2015; Pmverhulst, n.d.). Agencies have also used real-time videos to show to the public what a turbo roundabout would look like in their community and demonstrate that other communities have had success using a turbo roundabout. To effectively reach the public real-time videos can be packaged as marketing pieces to provide more context.

Simulations, much like real-time videos, are helpful for engineering and public audiences because they allow viewers to visualize and analyze a turbo roundabout in greater detail. Simulations are capable of providing more context on turbo roundabout capacity and design; therefore, the content is easily tailored to either a technical engineering audience or the lay person (TU Delft, 2009). Transportation agencies like Royal HaskoningDHV, who specialize in engineering on an international scale, have used simulations to combine animated navigational viewpoints of a turbo roundabout, such as aerial, driver, and pedestrian perspectives (Royal HaskoningDHV, 2015).

While some simulations are created with both engineering and public audiences in mind, some are created solely for an engineering audience. TU Delft, a public technological university located in Delft, Netherlands, overlaid an interviewed Fortuijn, who conceptualized the turbo roundabout design, with a computer-simulation to explain the different types of turbo roundabouts and their respective capacity models for an engineering audience (TU Delft, 2009).

Signage

Marktstate (2010) created a guide describing the different types of signs a road user may encounter when navigating turbo roundabouts for the Regional Traffic Safety Organization of Limburg to distribute to the public. In addition, describing the signage's importance and meaning, the guide emphasized the importance of driver awareness to the signs as they approach a turbo roundabout so they will choose the correct lane (Marktstate, 2008). One sign of particular interest specific to turbo roundabouts warns motorcyclists of the raised dividers between the lanes in the turbo roundabout.

Key Findings

The key to successful public education on turbo roundabouts is providing key messages through the right medium to the right audience. Videos developed for professionals emphasized specifics regarding design capacity, operations, and speed and has been successfully shared through social media platforms like LinkedIn that allow professionals to engage with one another about ideas. These videos are most useful to promote awareness and acceptance of the design and to encourage implementation. For the public, it is important to share material that is easily digestible and provides a real-life connection. Practitioners have used both computer-generated and real-time videos to demonstrate the key concepts at public presentations and posted publicly as online resources prior to project installation.

Once a project is complete, videos are useful for ongoing driver and public education. Signage also becomes more important at the project location to direct drivers to select the correct lane.

The next step in this process is a technical summary, where the research team will propose ways to update and tailor existing outreach materials to appropriate audiences.

Summary and Next Steps

As turbo roundabouts increase in implementation worldwide, a growing body of literature supports the geometric, operational, and safety benefits of the design with relation to other alternatives. The specific design features of turbo roundabouts provide the greatest improvements over traditional multilane roundabouts. Notable design features include:

- Radial entry which improves sight distance.
- Minimized central island radius and entry radius to reduce vehicle speeds.
- Raised lane divider to prevent weaving in the circulatory roadway.
- Roundabout shields which block the horizon and direct drivers to turn into the roundabout.
- Mountable aprons on the central island and the beginning of the raised lane divider to ease navigation by heavy vehicles.
- Spiral design so vehicles do not have to cross lanes to exit the roundabout.

In terms of capacity, the turbo roundabout allows for volumes close or equal to a modern multilane roundabout while providing similar safety benefits to single lane roundabouts. While there are some empirical models based on geometry (Kimber, 1980), most roundabout capacity models are based on gap acceptance theory models derived for stop-controlled approaches. For all models, capacity is estimated at the approach level, either as a whole or the sum of each entrance lane. While much attention has been paid to potential differences in models for turbo roundabouts and multilane roundabouts, specifically in relation to the distribution of headways within the circulatory roadway, turbo roundabout capacity can be estimated through slight adjustments for driver behavior of existing capacity models. As Macioszek (2016) showed, the HCM 2010 produced similar capacity estimates of Polish turbo roundabouts as locally estimated models.

Given that safety is possibly the biggest selling point of a turbo roundabout in place of a multilane roundabout, it is important to discuss what has been found with regards to safety performance of the design. The safety of turbo roundabouts has been evaluated using both crash based analyses and safety surrogate analyses. Some notable findings include:

- Conversion from yield-control, signalized, or old-style rotary intersections to turbo roundabouts is expected to result in a 72-percent reduction in injury crashes (Fortuijn, 2009b).
- In Poland, turbo roundabouts with raised lane dividers were found to have fewer total crashes, PDO crashes, and a smaller percentage of injury crashes classified as “seriously injured” than turbo roundabouts with only a solid white line (Macioszek, 2015; Kiec et al., 2018).
- Surrogate analyses suggest turbo roundabouts are expected to have lower crash frequency and less severe crashes than multilane roundabouts.

Public education and involvement are needed when constructing a unique design such as a turbo roundabout. It is important to create outreach materials that focus on signage and how different users navigate the roundabout design. The key to determining the most effective type of public outreach material is determining the message. There are a variety of platforms Federal, State, and local agencies can use when exposing the public to a turbo roundabout design. One of the most effective forms of outreach is citing examples of demonstrated success, through videos—in either real-time or computer-simulations—to show different perspectives and how different road users can easily turbo roundabout.

The next task for this project is the preparation of an annotated outline for a technical summary on turbo roundabouts, similar in nature to FHWA's Roundabouts Technical Summary and Mini Roundabouts Technical Summary. The Technical Summary will present turbo roundabouts for a U.S. context, drawing on what was learned in this synthesis and merging it with other fundamental design and operational principles of roundabouts as contained in NCHRP Report 672. Comparisons will be drawn with single-lane and multilane roundabouts as well as signalized and stop-controlled intersections to highlight potential safety and operational benefits. Special attention will be paid to any documented safety analyses, noting both before and after conditions as available. It is anticipated the technical summary will have the following structure:

- Section 1: Characteristics of Turbo Roundabouts
- Section 2: Benefits of Turbo Roundabouts
- Section 3: User Considerations
    - Motorists
    - Pedestrians
    - Bicyclists
    - Motorcyclists
    - Freight
- Section 4: Location Considerations
    - Common Site Applications
    - Site Constraints
- Section 5: Safety Analysis Methods and Results
- Section 6: Operational Analysis Methods and Results
- Section 7: Design Considerations
    - Horizontal Design
    - Pedestrian Design Treatments
    - Bicycle Design Treatments
    - Sight Distance and Visibility
    - Vertical Design
    - Pavement Markings and Signs
    - Lighting
    - Landscaping
    - Other Design Details and Applications
- Section 8: Costs
- Section 9: References

Special attention will be paid to explaining design concerns for pedestrians, cyclists, and motorcyclists, all of which are vulnerable in a turbo roundabout. Additionally, because of the importance of lane selection on the approach at turbo roundabouts, good signage techniques will be highlighted in the summary.

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